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INTEGRATED ICHNOLOGICAL-SEDIMENTOLOGICAL MODELS: APPLICATIONS TO THE SEQUENCE STRATIGRAPHIC AND PALEOENVIRONMENTAL INTERPRETATION OF THE VIKING AND PEACE RIVER FORMATIONS, WEST-CENTRAL ALBERTA

BY
JAMES ANTHONY MACEACHERN

A THESIS SUBMITTED TO THE FACULTY OF
GRADUATE STUDIES AND RESEARCH IN PARTIAL
FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA

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(SIGNED) David Bechtel DATE: April 3/94
D.J. Bechtel

(SIGNED) DATE: Apr. 6/94
Dr. S. George Pemberton

MAGIC AND LOSS - The Summation

When you pass through humble
when you pass through sickly
When you pass through
I'm better than you all
When you pass through anger and self deprecation
and have the strength to acknowledge it all
When the past makes you laugh and you can savor the magic
that let you survive your own war
You find that the fire is passion
and there's a door up ahead not a wall

As you pass through fire as you pass through fire
try to remember its name
When you pass through fire licking at your lips
you cannot remain the same
And if the building's burning move towards that door
but don't put the flames out
There's a bit of magic in everything
and then some loss to even things out

Lou Reed

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Dr. S. G. Pemberton - Supervisor

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Dr. R. B. Rains

Date Mch 31/94

DEDICATION

This thesis is dedicated to my grandparents, Henry and Matilda Edelmayer. Their contagious love of the natural world around them and their fascination with paleontology infected me at an early age. I would not be who I am, nor where I am today, if not for their dynamic spirits. All my love.

James

ABSTRACT

Siliciclastic facies from the Albian Viking and Peace River formations were studied in detail from 239 cored wells within a study area ranging from Township 40 to 73, and Range 3W5 to 13W6 (Alberta-British Columbia border). The area lies south of the Peace River Arch and encompasses 16 fields which produce hydrocarbons from the Viking or Peace River formations.

The substrate-controlled *Glossifungites* ichnofacies commonly demarcates sequence boundaries, erosional flooding surfaces and amalgamated (FS/SB) surfaces. Within the study area, forced regression shorefaces, parasequences, high energy parasequences, incised valley fills and transgressive-stillstand cycles can be differentiated.

Four softground trace fossil assemblages, namely the *Zoophycos*, *Cruziana*, *Skolithos* and mixed *Skolithos-Cruziana* ichnofacies, are integrated with sedimentology in order to generate models characterising storm bed (tempestite), shoreface, estuarine incised valley fill, and transgressive deposits. Shoreface deposits are divisible into offshore, lower, middle and upper shoreface, and foreshore environments, based on the interpreted ethology of the ichnogenera. Tempestites constitute the bulk of most lower-middle shoreface successions. The degree of storm domination on the lower and middle shoreface constitutes the principal variation observed in most successions. Three intergradational shoreface types can be recognised. Strongly storm-dominated shorefaces (*e.g.* the Cadotte Member in the Elmworth field) consist of erosionally amalgamated tempestites. Moderately storm-dominated shorefaces (*e.g.* the Viking Formation in the Kaybob field) consist of stacked tempestites with bioturbated tops. Weakly storm-influenced shorefaces (*e.g.* the Viking Formation in the Giroux Lake field) are thoroughly bioturbated.

Five Viking Formation wave-dominated estuarine incised valley deposits were studied from the Crystal, Willesden Green, Cyn-Pem, Sundance and Edson fields. The ichnology of these deposits demonstrates brackish water conditions, fluctuating salinities and episodic though generally high sedimentation rates, which contrasts markedly with juxtaposed fully marine deposits. The upper Viking Formation comprises a complex transgressive systems tract across the entire study area. Transgressive erosion deposits (lags and distal ravinement deposits) can be differentiated from those reflecting rapidly rising sea level (shelfal shales and tidal sand ridges) and progradational (stillstand) cycles (offshore-lower shoreface deposits).

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No thesis is exclusively the result of an individual's effort, and a large number of colleagues and institutions warrant mention for their contributions. This thesis is the product of 5 years of financial and scientific indulgence on the part of my supervisor Dr. S. George Pemberton. Not only has George managed to keep me supplied with research funds and a salary, he has also been a wealth of ichnological and trace fossil-related biological information. Not enough can be said in praise of George, who has consistently encouraged my research endeavours. All the work presented in this thesis is the result of direct collaboration with George and builds upon his previous work, much of it unpublished. I thank him for permitting me to include many of his insights into my own research. He is, without doubt, the finest supervisor I have had the privilege to work with.

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Sandstone at the Bearpaw-Horseshoe Canyon transition, Drumheller, Alberta, where many of the animal-sediment relationships discussed in the thesis were pointed out. Tom also generously provided his own data from the Harmon and Cadotte members of the Peace River Formation, and shared his paleogeographic and depositional model for Cadotte shoreface deposition employed in Chapter VI. Finally, Tom also drafted a number of the figures in Chapter VI. A forthcoming paper, addressing the ichnology and sedimentology of shoreface depositional systems will be co-authored with both Tom and S.G. Pemberton.

Indraneel Raychaudhuri has been a constant source of inspiration and joy over the three years we worked together, and is the co-author of the paper constituting Chapter II. Many of the ideas regarding the applications of the *Glossifungites* ichnofacies to genetic stratigraphic analysis has come through the stimulating collaboration with Indy. His perceptive discussions and excellent research abilities have led to many of the geological insights regarding ichnologically-demarcated stratigraphic discontinuities.

Howard G. Brekke is thanked for his untiring assistance in the logging of core in the Kaybob and Fox Creek fields during the course of his B.Sc. thesis. This data was integral in the writing of Chapter VII. Howard also assisted me in the logging of core from the Crystal, Willesden Green, Sundance and Edson fields, in the course of data collection for a paper of the ichnology of valley fill successions in the Viking, constituting Chapter IX. Howard also supplied data concerning tempestites in the Bluesky Formation, collected during the course of his M.Sc. research, which was employed in Chapter IV. Finally, he also designed several of the drafted figures presented in the thesis. Jeffry C. Peterson kindly supplied data regarding tempestites in the Cardium Formation, collected during the course of his B.Sc. thesis, which augmented the data base in Chapter IV. Special thanks are also due to Louis Leote for his assistance in the interpretation of the Giroux Lake area (Chapter VIII), during work on his B.Sc. thesis. David J. Bechtel provided valuable collaboration in the study of transgressive deposits in the Viking Formation. He assisted in the logging of core and co-authored the paper constituting Chapter X. Dave's capable assistance in data collection and interpretation is gratefully acknowledged.

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LIST OF ABBREVIATIONS

SEDIMENT GRAIN SIZES

vf	very fine	f	fine
vfL	lower very fine	fL	lower fine
vfU	upper very fine	fU	upper fine
m	medium	c	coarse
mL	lower medium	cL	lower coarse
mU	upper medium	cU	upper coarse
vc	very coarse		
vcL	lower very coarse		
vcU	upper very coarse		

S.I. UNITS

mm	millimetres
cm	centimetres
m	metres
km	kilometres

BURROW ABUNDANCES

vr	very rare
r	rare
m	moderate
c	common
a	abundant

PHYSICAL SEDIMENTARY STRUCTURES

HCS	hummocky cross-stratification
SCS	swaley cross-stratification
QPL	quasi-planar lamination
IHS	inclined heterolithic stratification
FA	facies association

SEQUENCE STRATIGRAPHIC TERMS

SB	sequence boundary
FS	flooding surface
LE FS	low energy (non-erosive) flooding surface
HE FS	high energy (erosive) flooding surface
HE MxFS	high energy (erosive) maximum flooding surface
TSE	transgressive surface of erosion
IT	initial transgressive surface
FS/SB	amalgamated sequence boundary and flooding surface
WR	wave ravinement surface
TSR	tidal scour ravinement surface

CHAPTER I

INTRODUCTION

The concepts of functional morphology, a basic premise employed by ecologists and paleoecologists in environmental reconstruction, is equally applicable to ichnology (the study of organism-sediment relationships). In fact, ichnofossils (or trace fossils) are unique in that they represent not only the morphology of the trace-making organism but also its ethology (behaviour) and the physical characteristics of the substrate. Additionally, the same tracemaker may create a variety of different biogenic structures in response to different environmental conditions. Nothing, perhaps, is as sensitive to environmental conditions and changes in the environment than the biota inhabiting it. Variables such as bathymetry, temperature and salinity, sedimentation rate, amounts of sediment deposited or eroded, oxygenation of water and sediment, and substrate coherence and stability have a profound effect on the resulting ichnofossil morphologies and hence, can be used in determination of original biological, ecological and sedimentological conditions (Frey and Seilacher, 1980). If the researcher is not only adept at identifying trace fossils, but fluent in the interpretation of the behaviours indicated by the ichnological assemblages, then much additional information regarding the original depositional conditions of a rock interval can be acquired. Most of this additional information is distinctly different from that gained from primary physical structures alone.

Unfortunately, ichnology has only recently been recognised as a valuable tool in the reconstruction of ancient depositional environments. Pertinent studies of ichnology and its applications to the ancient record are commonly absent or constitute exceedingly minor components of most major sedimentological reference texts, the most obvious being edition 1 of Facies Models (Walker, 1979), Terrigenous Clastic Depositional Systems: Applications to Petroleum, Coal, and Uranium Exploration (Galloway and Hobday, 1983), Sedimentary Structures: Their Character and Physical Basis (Allen, 1984), Sedimentology: Recent Developments and Applied Aspects

(Brenchley and Williams, 1985) and Sedimentary Environments and Facies (Reading, 1986). This seems rather surprising, since Depositional Sedimentary Environments (Reineck and Singh, 1975) and the second edition of the book (Reineck and Singh, 1980) both contained, for their time, significant references to biogenic structures and their value to the interpretation of the ancient record. Further, in the spirit of the Senckenberg Institute in Willemshaven (from which Reineck hailed), considerable mention was made regarding the study of modern tracemaking organisms (*i.e.* neo-ichnology). Succeeding texts appear to have ignored, for the most part, the significance of ichnological research, and to a great extent, kept ichnology out of the grasp of most sedimentologists. This oversight was finally addressed in edition 2 of Facies Models (Walker, 1984), although the subject still remained isolated from the actual development of facies models themselves, by restricting ichnology to a discrete chapter (Frey and Pemberton, 1984). In essence, this is akin to restricting discussion of primary physical sedimentary structures to a single chapter. The philosophical paradigm proposed in the first chapter of Facies Models (Walker, 1984) regarding the establishment of a "facies model" would suggest that the ichnology of any depositional facies is as important an element as the lithology, the physical structures, and the facies' position in the depositional succession. Facies Models: Responses to Sea Level Change (Walker and James, 1992) regarded ichnology as a "tool or concept", intrinsically important to *each* depositional environment, although still restricted to a discrete chapter. Despite the increasing interest in trace fossils by sedimentologists, most studies continue to limit discussion of ichnology to the identification of easily recognised genera. Ichnological analysis, when applied to the interpretation of the ancient record, is far more complex than the mere recognition of a few ichnogenera. Instead, a highly specialised science, using modern biology, paleontology and geology, in order to recognise ichnological facies (ichnofacies; *cf.* Seilacher, 1967), discriminate assemblages, interpret general assemblage behaviours and predict environmental causes to explain the character of the preserved trace fossil suite. Few non-ichnologists have managed to employ ichnology effectively to interpret the ancient record.

In spite of this general state of affairs, much excellent work integrating ichnology and sedimentology has been accomplished by ichnologists themselves, the most notable being Adolf Seilacher, James Howard, Robert

Frey, Richard Bromley, Peter Crimes and George Pemberton. Trace Fossils (Crimes and Harper, 1970), and Trace Fossils 2 (Crimes and Harper, 1977) presented a wide range of papers, many of which outlined trace fossil applications to facies interpretation. As well, the Society of Economic Paleontologists and Mineralogists sponsored a short course on trace fossils resulting in the publication of SEPM Short Course 5 (Basan, 1978), which for some time was employed by many as the principal source of trace fossil information. SEPM Short Course 15 (Ekdale *et al.*, 1984) was a timely and valuable addition to the literature, stressing trace fossil assemblages in a variety of depositional settings. A volume of papers devoted to the applications of trace fossils to paleoenvironmental interpretation followed shortly thereafter (Curran, 1985). It is interesting to note that the first publication devoted exclusively to the integration of ichnology with sedimentology and stratigraphy for the interpretation of the rock record in the subsurface was not published until 1992 (Pemberton, 1992).

The present thesis builds on the work of these "pioneers", mainly through the establishment of integrated ichnological-sedimentological models. The models explain the character of several discrete depositional settings and provide criteria for their recognition in the ancient record. This thesis also attempts to apply ichnological analyses to recent innovations in sedimentology and stratigraphy; in particular, sequence stratigraphy, and the recognition of variability in shoreface character, estuarine incised valley fill deposition and transgressive depositional systems.

This thesis centres around the Viking Formation and the Peace River Formation, the latter mainly restricted to the Harmon-Cadotte members (*cf.* Chapter VI), although data from numerous stratigraphic intervals of various ages have been employed in the establishment of the ichnological models proposed. The study area comprises Townships 47-72, Ranges 14W5-13W6 and contains in excess of 3800 wells, at least 217 of which possess core through the Peace River or Viking formations. Additional cores were studied from outside the thesis area as well, in order to refine the models. A total of 239 cored intervals were logged in the course of the study. Much of the southwest corner of the area is barren of well data, owing to the presence of the disturbed belt and Jasper National Park. The Viking Formation is Upper Albian in age. The Peace River Formation ranges from approximately Middle to early Late

Albian in age. The stratigraphic relationships of these intervals are discussed in the pertinent chapters.

This thesis does not include a chapter devoted to the conceptual framework of ichnology. In general, it is assumed that the reader has a working knowledge of ichnology. Several excellent summaries of the principles of ichnology are available, to which the reader is directed (Frey, 1975; Ekdale *et al.*, 1984; Frey and Pemberton, 1984; Bromley, 1990; Pemberton *et al.*, 1992a, b).

This thesis is arranged with conceptual chapters followed by case studies. The conceptual chapters tend to employ data from a number of stratigraphic intervals of various ages. Some of these data have been collected from literature study, but where possible, first hand observations were employed. The aim of utilising a variety of data sources was to establish general principles with a wide range of application to the ancient record. In this manner, the integrated ichnological-sedimentological models proposed in the thesis conform to the suggestions for general facies models: the distillation of general principles from a variety of local studies (Walker, 1984; 1990). The case study chapters following the conceptual chapters center on the thesis interval and generally, are restricted to the study area in order to demonstrate the utility of ichnological analysis to discrete studies.

Chapter II introduces the reader to the *Glossifungites* ichnofacies, one of three substrate-controlled assemblages, which is found to delineate stratigraphic discontinuities. Work by Pemberton and Frey (1985), Vossler and Pemberton (1988) and Saunders (1989) highlighted the presence of the *Glossifungites* suite at stratigraphic breaks. Chapter II demonstrates the utility of the assemblage to the developing concept of sequence stratigraphy by employing examples ranging from Ordovician to Holocene in age. The chapter deals with the specific discontinuities and their genetic stratigraphic significance, which are commonly demarcated by the *Glossifungites* suite. Chapter III follows from this by illustrating the ways in which ichnology can be utilised in sequence stratigraphic analysis, using Cretaceous intervals of the Western Canada Sedimentary Basin as examples. Where possible, the examples employed are restricted to the Viking Formation. Trace fossil analyses are seen to enhance sequence stratigraphic studies in two main ways. The first is through substrate-controlled ichnofacies and the second is through ichnologic successions (analogous to lithofacies successions). The application of the general principles presented in Chapters II and III constitute the main paradigms for the sequence stratigraphic interpretations of the Viking Formation in Chapters VII, VIII, IX and X.

Chapter IV is a conceptual paper which introduces the reader to storm bed or tempestite deposition and the effects that such deposition has upon the resulting ichnological signature in the rock record. Storm beds constitute a fundamental building block of most shoreface successions observed in the Cretaceous of North America. The general model proposed conforms well with the model of Pemberton and Frey (1984), and is based on a number of stratigraphic intervals of various ages, although it concentrates on the Cretaceous of the Western Interior Seaway of North America. In addition, a discussion of the preservation potential of tempestites is presented which questions the practicality of relatively simplistic quantitative approaches.

Chapter V is also a conceptual paper, building on the tempestite model of Chapter IV. Chapter V is concerned with the establishment of an ichnological-sedimentological model of shoreface deposition, directly applicable to the Cretaceous of the Western Interior Seaway of North America. The model facilitates the subdivision of the shoreface environment into a number of subenvironments. From this, the relative significance of storm influence is seen as the most important factor in characterising the preservational record of most of these shoreface successions. Three main shoreface models: strongly storm-dominated, moderately storm-dominated and weakly storm-affected shorefaces, are proposed.

Chapters VI, VII and VIII are case studies directly related to the conceptual papers presented in Chapters IV and V. Chapter VI highlights the strongly storm-dominated shoreface succession of the Harmon and Cadotte members of the Peace River Formation. An entire depositional record from offshore transition deposits to backshore deposits is preserved in the study area, permitting characterisation of not only the lower-middle shoreface, but also the nearshore complex. The interval provides data strongly supportive of seasonal storm-domination. Chapter VII highlights an intermediate storm-dominated shoreface succession in the Viking Formation of the Kaybob Field, characterised by a distinctive "laminated-to-burrowed" appearance. From a sequence stratigraphic perspective, the succession also illustrates a forced regression shoreface. Chapter VIII describes a weakly storm-affected shoreface from the Viking Formation of the Giroux Lake Field, characterised by thoroughly burrowed facies with minimal preservation of storm beds. From a sequence stratigraphic perspective, the succession also illustrates a newly proposed "high energy parasequence" model.

Chapter IX combines a conceptual paper and a case study paper, and deals with the relatively anomalous estuarine incised valley fill successions in various Viking Formation fields (*e.g.* Crystal, Cyn-Pem, Sundance, Edson, Willesden Green). The chapter demonstrates the nature of brackish (estuarine) trace fossil assemblages and their differences from fully marine suites, as well as highlighting the appropriateness of a tripartite wave-dominated estuary model (*cf.* Roy *et al.*, 1980; Dalrymple *et al.*, 1992) for the Viking Formation examples. Ichnology is also employed to illustrate the sequence stratigraphic significance of internal discontinuities within the valley fills.

Chapter X is the final paper, and like Chapter IX, is both conceptual and specific in scope. The chapter characterises the ichnology and sedimentology of the widespread transgressive deposits in the upper portion of the Viking Formation. These facies are present throughout much of central Alberta, and demonstrate the highly complex and incremental nature of transgression by the Colorado Sea near the end of Viking Formation time.

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CHAPTER II

STRATIGRAPHIC APPLICATIONS OF THE *GLOSSIFUNGITES* ICHNOFACIES: DELINEATING DISCONTINUITIES IN THE ROCK RECORD[1]

INTRODUCTION

For many years, facies analysts have found it difficult to reconcile sedimentologic observations with existing, generally lithostratigraphic frameworks. In recent years, stratigraphers have moved away from lithostratigraphic analysis and have approached the rock record in terms of genetic stratigraphy. Genetic stratigraphy lies at the core of three main stratigraphic paradigms: Genetic Stratigraphic Sequences (Galloway, 1989a,b), Sequence Stratigraphy (Wilgus *et al.*, 1988; Van Wagoner *et al.*, 1990), and Allostratigraphy (NACSN, 1983; Walker, 1990; Walker and James, 1992). Genetic stratigraphic sequences are based on Cenozoic deltaic strata in the well-studied northwestern margin of the Gulf of Mexico, with the main focus centered on sequences bounded by regionally extensive maximum flooding surfaces (Galloway, 1989a,b). Sequence stratigraphy, which traces its roots back to the intercratonic sequences of Sloss (1963, 1988) and seismic stratigraphy (Vail *et al.*, 1977; Mitchum *et al.*, 1977), employs regional unconformity bounded successions as its fundamental units (*i.e.* "sequences"). The "sequences" of Galloway (1989a,b) correspond to the "parasequences" of Van Wagoner *et al.* (1990). Both genetic stratigraphic sequences and sequence stratigraphy are interpretive paradigms, carrying with them the implication that the nature, genesis and regional significance of the bounding surfaces are understood.

Allostratigraphy is the only formal stratigraphy (NACSN, 1983) that permits subdivision of mappable stratiform sedimentary rock bodies on the basis of bounding discontinuities. Such a stratigraphic paradigm provides a

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[1] A version of this chapter has been published. MacEachern, J.A., I. Raychaudhuri and S.G. Pemberton, 1992. *In*: S.G. Pemberton (ed.), Applications of ichnology to petroleum exploration- a core workshop. Society of Economic Paleontologists and Mineralogists Core Workshop 17: 169-198.

valuable framework within which the sedimentologist/ichnologist may arrange facies observations. The descriptive and objective aspect of allostratigraphic analysis is such that interpretation of the origin of the discontinuity is immaterial, so far as actual subdivision of the rock record is concerned. Speculation as to the nature and origin of the discontinuities can proceed, without invalidating the actual proposed subdivision of the interval into allogroups, alloformations, or allomembers.

No matter which stratigraphic paradigm is utilised, the recognition of stratigraphic breaks is of paramount importance and is commonly a difficult task, particularly in subsurface studies. The stress on discontinuities emphasises processes that are external to the depositional system itself (allocyclic) and which may initiate or terminate deposition of sedimentologically related facies successions (Walker, 1990). Genetic stratigraphy, therefore, creates a framework within which Walther's Law may be applied with greater confidence. Obviously, Walther's Law cannot be applied across discontinuities, but can be applied more reliably to stratigraphic successions between these breaks. Ultimately, delineating the origin of the discontinuity is essential in order to resolve the depositional environments and characterise the allocyclic controls on the depositional systems.

Trace fossils and trace fossil suites can be employed effectively, both to aid in the recognition of various types of discontinuities and to assist in their genetic interpretation. This method requires an integrated approach, employing diverse stratigraphic, sedimentologic, and paleontologic techniques. Although the geoscientist does not employ one discipline to the exclusion of others, in this paper only the ichnological applications to these problems are stressed.

TRACE FOSSILS IN STRATIGRAPHY

In the past, trace fossils were considered to be almost useless in stratigraphy because of their long temporal range, making their biostratigraphic value negligible. This was because trace fossils were regarded in classical paleontological terms, and their utilisation in chronostratigraphy was viewed in only three ways: (1) tracing the evolution of behaviour; (2) as morphologically defined entities (with no assumptions concerning their genesis); and (3) as substitutes for the trace-making organisms (Magwood and Pemberton, 1990).

In contrast, trace fossils are proving to be one of the most important groups of fossils in demarcating stratigraphically important boundaries (MacEachern *et al.*, 1990, 1991a,b, 1992a,b; Savrda, 1991a,b; Pemberton *et al.*, 1992a; MacEachern and Pemberton, in press; Pemberton and MacEachern, in press). Ichnology may be employed to resolve surfaces of stratigraphic significance in two main ways. The first is through the recognition of substrate-controlled ichnofacies. The second is through the careful analysis of ichnologic successions (analogous to lithofacies successions). This paper deals only with the ichnological demarcation of erosional discontinuities, using the substrate-controlled *Glossifungites* ichnofacies.

Ichnology as an Aid in the Recognition and Interpretation of Discontinuities

It is generally regarded that sharp breaks in the vertical stratigraphic record may signify fundamental changes in depositional environments and initiation of new cycles of sedimentation. Nevertheless, many facies contacts are sharp, despite the facies being genetically related. The emplacement of sandy storm beds in the offshore transition zone, for example, yields abrupt basal contacts with the fairweather silty shales, but clearly reflect a penecontemporaneous relationship (*cf.* MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992b). In spite of an erosional contact, the absence of a significant temporal break indicates that such contacts probably do not have genetic stratigraphic significance.

In contrast, gradational facies contacts are generally regarded to imply a more gradual shift in depositional conditions. Nonetheless, intense burrowing, for example, can destroy erosion surfaces through biogenic homogenization, making the contact between two superposed facies appear to be gradational (Raychaudhuri, 1989; Raychaudhuri *et al.*, 1992). The presence of dispersed pebbles or rip-up clasts may be the only preserved evidence of an erosion surface. The action of organisms within the substrate may serve either to **enhance** or **obscure** breaks in the stratigraphic succession. This paper is concerned only with those ichnologic characteristics that serve to enhance the recognition and genetic interpretation of discontinuities.

Substrate-Controlled Ichnofacies

Three substrate-controlled ichnofacies have been established (Figure II-1; Bromley *et al.*, 1984): *Trypanites* (hardground suites), *Teredolites* (woodground suites) and *Glossifungites* (firmground suites). The *Trypanites* ichnofacies was erected by Frey and Seilacher (1980) to encompass the trace fossil suite associated with fully lithified substrates. These are typically associated with rocky coasts (*cf.* Seilacher, 1967), unconformities (Pemberton *et al.*, 1980), hardgrounds, and various other omission surfaces (*cf.* Bromley, 1975). The trace fossils are all borings, which cut across the fabric of the lithified sediment, and are characterised by *Trypanites, Gastrochaenolites, Rogerella* and *Entobia*. The *Teredolites* ichnofacies was established by Bromley *et al.* (1984) to encompass trace fossils which are bored into xylic (wood) substrates in marine settings. These have not been widely recognised yet (*cf.* Table II-1; Savrda, 1991b) and known traces are *Teredolites* (clavate borings of bivalves) *Diplocraterion* and *Thalassinoides* ("coal worms" of J.D. Howard; Frey, pers. comm., 1991).

The *Glossifungites* ichnofacies (redefined by Frey and Seilacher, 1980) encompasses trace fossils associated with semilithified or firm substrates, typically consisting of dewatered, cohesive muds, due either to subaerial exposure, or burial and subsequent exhumation (Figure II-2). In contrast to the *Trypanites* and *Teredolites* ichnofacies, the *Glossifungites* ichnofacies is the most common substrate-controlled suite in siliciclastic intervals. Less commonly, *Glossifungites* suites may be developed in incipiently-cemented sandstone substrates, such as in the Bearpaw-Horseshoe Canyon Fm transition in the Drumheller area, Alberta (Figure II-3 E; Saunders and Pemberton, 1986; Saunders, 1989). Such scenarios may be difficult to discriminate, particularly in subsurface studies.

General Characteristics of the *Glossifungites* Ichnofacies

Firmground traces are relatively easy to recognise in the rock record. They are dominated by vertical to subvertical dwelling structures of suspension feeding organisms (Figure II-2). The most common structures correspond to the ichnogenera *Diplocraterion, Skolithos, Psilonichnus, Arenicolites,* and firmground *Gastrochaenolites*. Dwelling structures of

Woodground	Hardground	Firmground	Softground	Environmental Conditions	
			Scoyenia		Freshwater
			Psilonichnus		
Teredolites	*Trypanites*	*Glossifungites*	*Skolithos*	High Energy	
			Cruziana	Medium Energy	Marine
			Zoophycos		
			Nereites	Low Energy	

Figure II-1. Relationship of ichnofacies to substrate. Softground suites are differentiated on the basis of environmental factors. Woodground, hardground and firmground ichnofacies are differentiated on the basis of substrate type and consistency, and appear to be restricted to marine conditions (modified after Bromley *et al.*, 1984).

AGE	LOCATION	FORMATION	PRE-EROSION TRACE SUITE	EROSION SURFACE TRACE SUITE
Ordovician	Michigan Basin	Glenwood Fm (subsurface)	Dark, phosphatic silt-bearing shale; no visible trace fossils.	*Glossifungites* assemblage consisting of robust *Thalassinoides* .
Sil -Dev unconformity	S. Ontario Canada	Bertie/Bois Blanc Fm contact (outcrop)	Bertie Fm dolomites with *Thalassinoides*.	Karsted surface, with a *Trypanites* ichnofacies, consisting of *Trypanites weisei* and *Gastrochaenolites*.
Mississippian (Visean)	WCSB Talbot Lake	Mounthead Fm (outcrop)	Wackestones & packstones with *Planolites*, *Zoophycos*, *Chondrites*, *Rhizocorallium*, *Teichichnus* & *Thalassinoides*.	*Glossifungites* assemblage consisting of *Skolithos* & *Arenicolites*.
Triassic (Ladinian)	WCSB Elmworth area	Doig / Halfway Fm contact (subsurface)	Calcitic dolomite cemented shaly siltstone, sparsely burrowed with mud-lined *Skolithos* and *Arenicolites*.	*Trypanites* ichnofacies: *Trypanites* subtending from a knife sharp contact.
Jurassic (Pliensbachian)	East Greenland	Kap Stewart/Neill Klinter Fm contact (outcrop)	Unburrowed and rooted delta plain sandstonesand coals	*Glossifungites* assemblage consisting of abundant *Diplocraterion parallelum*. Pebble lag is present.
Jurassic (U. Toarcian?)	East Greenland	Neill Klinter/ Vardekloft Fm contact (outcrop)	Trough cross-bedded and current ripple laminated sandstone with *Arenicolites* & *Diplocraterion habichi*.	? *Glossifungites* assemblage consisting of abundant *Diplocraterion habichi* with associated pebble lag.
Cretaceous (L. Albian)	WCSB NE B.C.	Gething/Bluesky contact (subsurface)	Unburrowed, finely laminated & rooted mudstones & coals (Gething Fm).	*Glossifungites* assemblage consisting of *Skolithos* & *Thalassinoides* with associated pebble lag.
Cretaceous (U. Albian)	WCSB Kaybob S. Field	Mannville Gp /Joli Fou Fm (subsurface)	Unburrowed, rooted palaeosols & coals (Mannville Group).	*Glossifungites* assemblage consisting of *Thalassinoides*. Associated pebble lag.
Cretaceous (U. Albian)	WCSB Chigwell Field	Viking Fm (subsurface)	Silty shales with *Helminthopsis*, *Planolites*, *Terebellina*, *Chondrites* & *Asterosoma*, of the distal *Cruziana* ichnofacies.	*Glossifungites* ichnofacies consisting of *Thalassinoides* with associated pebbles & granules.
Cretaceous (U. Albian)	WCSB Joffre Field	Viking Fm (subsurface)	Silty shales & storm sands: *Helminthopsis*, *Planolites*, *Chondrites*, *Terebellina*, rare *Zoophycos*, *Asterosoma* & *Rhizocorallium*.	*Glossifungites* suite of *Thalassinoides*, *Skolithos*, ? *Arenicolites*/ *Diplocraterion* & with associated pebble lag.
Cretaceous (U. Albian)	WCSB Gilby A Field	Viking Fm (subsurface)	Intensely burrowed muddy siltstones containing *Helminthopsis*, *Terebellina*, *Planolites* & rare *Chondrites*.	*Glossifungites* assemblage of *Skolithos* & ? *Arenicolites*/ *Diplocraterion* associated with sideritised surface & pebble lag.
Cretaceous (U. Albian)	WCSB Kaybob S. Field	Viking Fm (subsurface)	Pebbly & sandy shales with *Planolites*, *Asterosoma*, *Terebellina*, rare *Chondrites*, *Helminthopsis* & *Zoophycos*.	*Glossifungites* assemblage consisting of robust *Arenicolites* shafts.
Cretaceous (U. Albian)	WCSB Kaybob Field	Viking Fm (subsurface)	Burrowed sandy shale: *Teichichnus*, *Helminthopsis*, *Asterosoma*, *Terebellina*, *Planolites*, *Zoophycos*, *Chondrites* with rare *Rosselia* & *Rhizocorallium*.	*Glossifungites* assemblage consisting of *Thalassinoides* & *Skolithos* with associated rip-up clasts and pebbles.
Cretaceous (U. Albian)	WCSB Crystal Field	Viking Fm (subsurface)	Intensely burrowed muddy sandstone with *Terebellina*, *Chondrites*, *Planolites*, *Asterosoma*, *Helminthopsis* & rare *Zoophycos*.	*Glossifungites* assemblage consisting of *Diplocraterion*, *Gastrochaenolites*, *Skolithos* & *Thalassinoides*.
Cretaceous (U. Albian)	WCSB Willesden Green	Viking Fm (subsurface)	Shales & silty shales with *Helminthopsis*, *Planolites*, *Terebellina*, *Chondrites* & *Zoophycos* (distal *Cruziana* ichnofacies).	*Glossifungites* assemblage consisting of *Rhizocorallium*, *Thalassinoides*, *Diplocraterion* & *Skolithos*.
Cretaceous (U. Albian)	WCSB Sinclair Field	Peace River Fm Paddy Mbr (subsurface)	Pebbly shale with intense burrowing, represented by *Chondrites*, *Helminthopsis*, *Terebellina*, *Asterosoma* & *Planolites*.	*Glossifungites* assemblage consisting of *Diplocraterion*, associated with dispersed pebbles.
Cretaceous (Cenomanian)	WCSB Jayar Field	Dunvegan Fm (subsurface)	Largely unburrowed & locally rooted mudstones in shallow water (lacustrine?) & delta plain settings.	*Glossifungites* assemblage consisting of *Thalassinoides* systems.
Cretaceous (Turonian)	WCSB Pembina Field	Cardium Fm (subsurface)	Silty shales with *Planolites*, *Chondrites*, *Helminthopsis*, *Terebellina* & *Zoophycos*, reflecting a distal *Cruziana* ichnofacies.	*Glossifungites* ichnofacies consisting of *Thalassinoides*.
Cretaceous (Campanian)	Wyoming, U.S.	Cody/Shannon contact (outcrop)	Burrowed sandy shale: *Helminthopsis*, *Planolites*, *Chondrites*, *Terebellina*, *Palaeophycus* & *Zoophycos*.	*Glossifungites* ichnofacies consisting of *Thalassinoides* with phosphatised pebbles.
U. Cretaceous (Campanian)	Texas, U.S.	Austin/Taylor Fm contact (outcrop)	Austin Fm marly chalk with *Chondrites*, *Planolites* & *Thalassinoides*. Muddy beds correspond to minor omission surfaces.	*Glossifungites* ichnofacies: *Rhizocorallium*, *Spongeliomorpha*, *Strophichnus* & *Remulichnus* .
Cretaceous (Campanian-Maastrichtian)	WCSB Drumheller Alberta	Horseshoe Canyon Fm (outcrop)	Unburrowed and rooted coaly shales & coals formed within a backbarrier setting.	*Glossifungites* assemblage consisting of abundant *Diplocraterion parallelum* in a back-barrier coaly mudstone.
Cretaceous (Campanian-Maastrichtian)	Drumheller Alberta	Horseshoe Canyon Fm	Unburrowed back barrier coal bed formed within an estuarine setting.	*Teredolites* ichnofacies consisting of *Teredolites clavatus* excavated into a coal.
Cretaceous Tertiary contact	Alabama, U.S.	Prarie Bluff/ Clayton Fm	Burrowed (ichnogenera not disclosed) fossiliferous chalk.	*Glossifungites* assemblage of *Thalassinoides paradoxicus* & *Spongeliomorpha*.
Tertiary (Miocene)	New Zealand Tirikohua Pt	Nihotupu /Tirikohua Fm contact (outcrop)	Weakly burrowed volcanogenic clastics & submarine andesitic pillows (Nihotupu Fm). Rare *Thalassinoides*.	*Glossifungites* ichnofacies: *Skolithos*, *Thalassinoides*/ *Spongeliomorpha* & *Rhizocorallium*.
Pleistocene	Grand Cayman Salt Creek	Ironshore Fm (outcrop)	Structureless, cross-bedded & laminated oosparite with *Ophiomorpha nodosa*, *O. borneensis*, *Skolithos* & *Polykladichnus*.	*Glossifungites* ichnofacies consisting of robust *Ophiomorpha nodosa*

Table II-1. Ichnologically-demarcated erosional discontinuity surfaces. The table outlines outcrop and subsurface examples of substrate-controlled ichnofacies and the interpreted stratigraphic significance of the demarcated discontinuity (modified after MacEachern *et al.*, 1992b).

POST-EROSION TRACE SUITE	INTERPRETATION OF SURFACE
Burrowed sandstone & shale with a shallow water suite of *Planolites, Teichichnus, Asterosoma, Terebellina* & rare *Chondrites*.	Lower facies is a condensed section (R. Dott Jr.,G. Nadon & D. Rodrigues de Miranda, pers. comm., 1991), possibly submarine cemented. A shallowing event with erosion (phosphatic clasts within burrow fill) may indicate lowered relative sea level.
Oriskany sandstone of the Bois Blanc Fm is unburrowed.	Bertie Fm reflects final stages of marine regression. Disconformity at top represents subaerial exposure. Transgression permitted colonisation and boring of FS/SB surface, followed by Oriskany sandstone deposition (Kobluk *et al.*, 1977; Pemberton *et al.*, 1980).
Wackestones & packstones with *Zoophycos, Chondrites, Planolites, Rhizocorallium, Teichichnus* & *Thalassinoides*.	Firmground conditions may reflect submarine cementation of the substrate during reduced rates of deposition in a shallow shelfal setting. Surface may mark a downlap surface on a condensed section separating discrete carbonate shelfal suites.
Unburrowed, carbonate cemented skeletal pebbly sandstones and siltstones.	Disconformity between Doig and Halfway reflects shallowing, subaerial exposure, and lithification of Doig Fm top. Transgression permitted colonisation and boring of contact, followed by Halfway Fm deposition.
Poorly sorted, massive to cross- bedded sandstone with *Diplocraterion, Ophiomorpha, Gyrochorte, Monocraterion* & *Rhizocorallium*.	The contact is interpreted as a transgressive omission surface (?ravinement), separating Sinemurian delta plain deposits from overlying barred shoreline sediments (Dam, 1990).
Muddy sandstone with *Curvolithos, Gyrochorte, Rhizocorallium, Ophiomorpha, Arenicolites, Diplocraterion, Palaeophycus, Cruziana, Taenidium, Thalassinoides* & *Planolites*.	Contact is a transgressive ravinement surface reflecting erosive shoreface retreat. The surface separates underlying subaqueous fan delta deposits from overlying shelf deposits (open shelf - *Curvolithos* ichnocoenose; restricted shelf - monospecific assemblage of *Phoebichnus*)(Dam, 1990).
Bar margin sands: *Asterosoma, Teichichnus, Helminthopsis, Palaeophycus, Terebellina, Planolites* & *Rosselia*. Pro-delta sands/shales: *Teichichnus, Planolites* & *Palaeophycus*.	Subaerial exposure and progradation of coal-bearing delta plain sediments, followed by transgressive ravinement (FS/SB). Colonisation of erosion surface preceded main transgressive lag deposition. Overlying sediments consist of prograding bar margin or brackish water pro-delta of the next progradational cycle (Oppelt, 1988).
Silty shale with a distal *Cruziana* assemblage consisting of *Helminthopsis, Zoophycos, Terebellina, Planolites* & *Chondrites*.	Mannville Group surface was subaerially exposed (lowstand unconformity), subsequently transgressed with associated ravinement (FS/SB) and colonised by a firmground suite. Overlying shales reflect offshore to outer shelf settings (Joli Fou Fm).
Intensely burrowed shaly sandstone with robust *Teichichnus, Asterosoma, Terebellina, Helminthopsis* , *Chondrites* & *Planolites*, reflecting the *Cruziana* ichnofacies.	Erosion surface incised into offshore shelfal deposits during lowstand of relative sea level. Basinward shift deposited a "forced regression" shoreface (Raychaudhuri, 1989). Alternatively, surface may reflect transgressive ravinement followed by stillstand shoreface progradation (high energy parasequence) (Raychaudhuri *et al.*, 1992).
Sparsely burrowed, cross-bedded pebbly & coarse sandstone with rip-up clasts. Mud drapes contain *Planolites*.	Discontinuity cut into offshore deposits during lowstand of relative sea level, abruptly overlain by shoreface sandstones. Reflects basinward shift of lowstand shoreface or its final position due to erosive shoreface retreat (Downing and Walker, 1988).
Unburrowed, pebbly medium-grained sandstones.	Discontinuity incised into offshore deposits during lowstand of relative sea level, with corresponding basinward shift of shoreline. Erosive shoreface retreat resulted in final position of shoreface. Firmground associated with SB or FS/SB (Raddysh, 1988).
Pebbly & sandy shales with *Teichichnus, Terebellina, Asterosoma, Planolites*, rare *Chondrites* & *Helminthopsis*.	Surface is interpreted as one of several stillstand/transgressive ravinement surfaces generated during initial (stepwise?) transgression of the Colorado sea. Transgressive deposits over - and underlie the ravinement surface (MacEachern *et al.*, 1992).
Laminated to burrowed sandstone: *Skolithos, Arenicolites, Ophiomorpha, Teichichnus, Palaeophycus, Asterosoma, Helminthopsis, Chondrites, Rosselia, Planolites* & *Terebellina*.	Surface is a lowstand unconformity (SB) incised into offshore-shelfal deposits and abruptly overlain by a forced regression shoreface. Proximally, surface overlain by middle shoreface deposits related to basinward shift of facies. Distally, progradation produced a gradual coarsening-upward cycle (Pemberton and MacEachern, in press).
Sandstones, interbedded sands & shales with *Teichichnus, Ophiomorpha, Palaeophycus, Diplocraterion, Rosselia, Skolithos, Asterosoma, Terebellina* & *Planolites*.	The surface reflects an incised valley margin, generated during a lowstand of relative sea level. The surface is incised into shelf to lower shoreface deposits and overlain by estuarine deposits, related to transgression (Reinson *et al.*, 1988; Pattison, 1991a&b; Pemberton *et al.*, 1992c).
Sands & shales, containing a brackish suite of *Cylindrichnus, Teichichnus, Planolites, Terebellina, Palaeophycus* & *Asterosoma*.	Lowstand of relative sea level generated an incised valley surface, cut into offshore and shelfal deposits. Valley fill is mainly estuarine, related to ensuing relative sea level rise (Boreen, 1989; Boreen and Walker, 1991).
Pebbly shale with *Helminthopsis, Zoophycos* & *Chondrites*, grading into sandstone & shale with *Asterosoma, Planolites* & *Chondrites*.	Surfaces are interpreted to reflect transgressive ravinement associated with continued (stepwise?) advance of the Colorado Sea. Underlying transgressively-reworked deposits reflect slightly more proximal conditions than the directly overlying sediments.
Sandstones with *Ophiomorpha* (transgressive sheet sand), passing into marine shales with *Zoophycos, Planolites* & *Chondrites*.	Delta plain deposits subaerially exposed during a relative sea level lowstand. Surface was transgressively modified (FS/SB), and underlying facies reworked to produce a transgressive sheet sand (Bhattacharya, 1989; Bhattacharya and Walker, 1991).
Unburrowed conglomerate, capped by shale containing *Helminthopsis, Planolites, Chondrites, Terebellina* & *Zoophycos*.	The surface may correspond to a sequence boundary, overlain by a "forced regression" shoreface (Plint *et al.*, 1986, 1988) or to transgressive modification of the SB by erosive shoreface retreat (FS/SB) (Walker and Eyles, 1991; Walker and Plint, 1992).
Sandstone with *Planolites, Palaeophycus, Schaubcylindrichnus, Terebellina, Rosselia, Diplocraterion, Thalassinoides* & fugichnia.	Contact is interpreted as a sequence boundary incised into offshore to shelfal deposits of the Cody Shale during a lowstand of relative sea level. The surface marks the base of a "forced regression" shoreface (Shannon Sandstone) (Walker and Bergman, 1993).
Taylor Fm clay, deeply weathered & unburrowed.	Deep water chalk capped by shallow water glauconitic, calcareous muds. Disconformity exhumed semiconsolidated chalk (Fürsich *et al.*, 1981) during ravinement (Pemberton, pers.observ., 1991). Overlying condensed section reflects resumed transgression.
HCS & SCS sandstone with *Ophiomorpha, Rhizocorallium, Teichichnus, Conichnus, Skolithos* & *Rosselia*.	The erosion surface is interpreted to reflect transgressive ravinement, separating back barrier deposits from overlying, prograding, storm-dominated shoreface deposits (Saunders and Pemberton, 1986; Saunders, 1989).
Shales of an abandoned tidal channel or inlet, containing *Teichichnus, Arenicolites, Planolites* & *Thalassinoides*.	The surface reflects autocyclic tidal channel incision into a coal. Pholadid bivalves colonised the surface prior to channel abandonment and fill (Bromley *et al.*, 1984).
Sandy glauconitic marls with reworked Cretaceous fossils, containing *Thalassinoides suevicus*.	Prarie Bluff Chalk subaerially exposed and locally incised by valleys during relative sea level lowstand. Subsequent transgression with ravinement permitted colonisation of the FS/SB surface (Savrda, 1991a).
Coarse-grained volcanogenic sandstone similar to proximal turbidites with *Skolithos, Planolites, Scalarituba, Thalassinoides* & fugichnia.	The surface reflects submarine canyon incision into deep water clastics during tectonic uplift of an inter-arc basin margin. Canyon walls are intensely burrowed with a *Glossifungites* suite. Canyon floor overlain by turbidites (Hayward, 1976).
Intraclastic oosparite with *Ophiomorpha, Polykladichnus* & *Conichnus*, passing into oosparite with *Ophiomorpha* & *Skolithos*.	Lagoon formed by eustatic sea level rise 125 000 BP with shallowing cycle during highstand or slow fall of sea level. Lagoonal deposition terminated by marine scouring of tidal channels. Surface is possibly autocyclic (Jones and Pemberton, 1989).

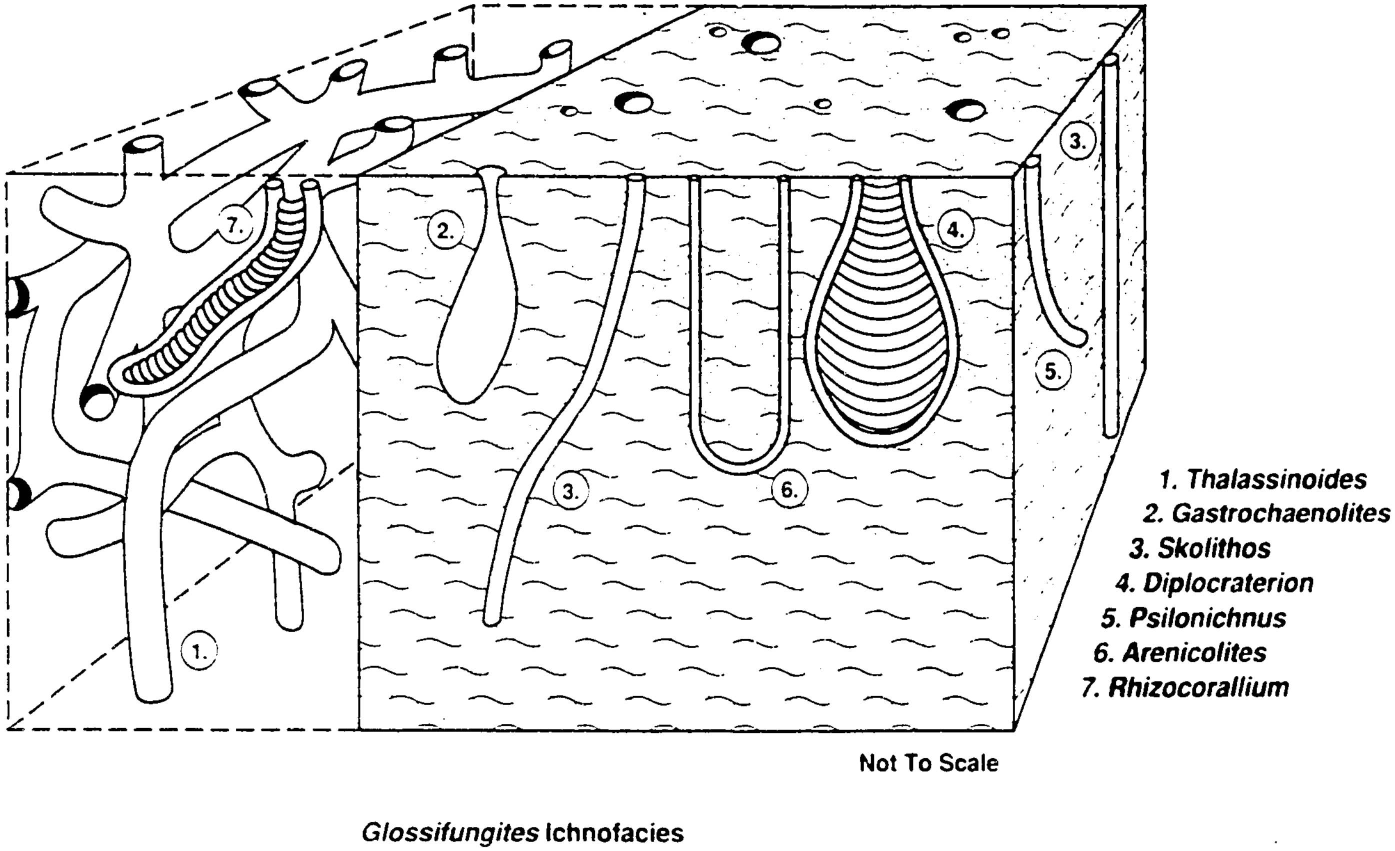


Figure II-2. Trace fossil association characteristic of the *Glossifungites* ichnofacies (modified from Frey and Pemberton, 1984).

deposit feeding organisms are also constituents of the ichnofacies, and include firmground *Thalassinoides/Spongeliomorpha* and *Rhizocorallium*. The presence of vertical shafts within shaly intervals is anomalous, as such structures are not capable of being maintained in soft muddy substrates (Figure II-3 A, B). Their presence suggests the substrate was not soft , but rather, stiff. *Glossifungites* ichnofacies traces are typically robust, commonly penetrating 20-100 cm below the bed junction. Many shafts tend to be 0.5-1.0 cm in diameter, particularly *Diplocraterion habichi* and *Arenicolites*. This scale of burrowing is in sharp contrast to the predominantly horizontal, diminutive trace fossils common to shaly intervals. The firmground traces are generally very sharp-walled and unlined, reflecting the stable, cohesive nature of the substrate at the time of colonisation and burrow excavation. Large structures are exceedingly difficult to maintain in soft muddy substrates, and burrow linings are therefore employed by the tracemaker in an attempt to stabilise the burrow in such material. The absence of linings on *Glossifungites* burrows demonstrates that the substrate was not, in fact, soft, but firm. Many structures, particularly in outcrop, show preserved sculptings or scratch marks on the burrow wall, confirming that construction of the dwelling burrow occurred in a firm substrate (Figure II-3 C). Further evidence of substrate stability, atypical of soft muddy beds is the passive nature of burrow fill. This demonstrates that the biogenic structure remained open after the tracemaker vacated the burrow, thus allowing material from the succeeding depositional event to passively fill the open structure. If the burrow had been excavated in soft mud, the domicile would have collapsed upon burrow vacation, unless lined. The post-depositional origin of the *Glossifungites* suite, in relation to the original softground assemblage, is clearly demonstrated by the ubiquitous cross-cutting relationships observed in the rock record. The final characteristic of the *Glossifungites* suite is the tendency to demonstrate colonisation in large numbers. In several examples, seven to fifteen firmground traces, commonly *Diplocraterion habichi*, have been observed on the bedding plane of a 9 cm (3.5 inch) diameter core; this corresponds to between 1100 to 2300 shafts per m^2 (Figure II-3 B). Similar populations were observed from the modern coast of Georgia (Pemberton and Frey, 1985). Dense populations are typical of many opportunistic assemblages (Levinton, 1970; Pemberton and Frey, 1984).

Figure II-3. Characteristics of the *Glossifungites* Ichnofacies. (A) Offshore silty shales, siderite-cemented near the top, are cross-cut by *Skolithos* shafts of the *Glossifungites* ichnofacies. Note the vertical, sharp-walled, unlined nature of the shafts. Tube diameters reach 0.7 cm. The tubes were passively-filled with pebbly sand from the overlying conglomerate bed. The surface corresponds to a transgressive surface of erosion (TSE). Viking Formation, Gilby A Field, 08-17-40-1W5, depth 1721.5 m. **(B)** Bedding plane view of a dense population (12 shafts) of traces of the *Glossifungites* ichnofacies. *Diplocraterion* (D), *Skolithos* (Sk) and *Arenicolites* (Ar) are present. This density of shafts in a 9 cm diameter core corresponds to more than 1800 shafts per square metre. Note the sharp walls and robust nature of the traces. Viking Formation, Kaybob Field. **(C)** *Diplocraterion parallelum* showing preservation of chelaped scratch marks, indicating the stiff nature of the substrate at the time of burrow excavation. Bearpaw-Horseshoe Canyon Formation transition, Drumheller, Alberta (Saunders and Pemberton, 1986). **(D)** Phosphatic black shale (condensed section) penetrated by a *Thalassinoides* system of the *Glossifungites* ichnofacies, overlain by a progradational cycle. Surface may reflect a non-erosional (incipiently-cemented) downlap surface (R. Dott, G. Nadon, D. Rodrigues de Miranda, pers. comm., 1991). Glenwood Formation (Ordovician), State Foster 1-12 well, depth 3139.7 m, Michigan Basin. **(E)** Abundant firmground *Diplocraterion parallelum* (D) of the *Glossifungites* ichnofacies penetrating sandstone interpreted to have been incipiently-cemented with calcite (Saunders and Pemberton, 1986). The surface is interpreted as a TSE (HE FS). Bearpaw-Horseshoe Canyon Formation transition, Drumheller, Alberta.


A
B
C
1cm
D

Many firmground assemblages are excavated into siderite-cemented horizons within marine shales (*e.g.* Gilby Field, Figure II-3 A, *cf.* Raddysh, 1988; Garrington Field, MacEachern *et al.*, 1992a). It remains uncertain as to whether the siderite cementation is a function of the ravinement, a diagenetic/chemical response to the introduction of sea water below the sediment-water interface (as a function of deep burrow penetration associated with the *Glossifungites* suite itself), or that pre-existing siderite bands formed resistant layers which impeded further ravinement.

The Modern Biological Basis for the *Glossifungites* Ichnofacies.

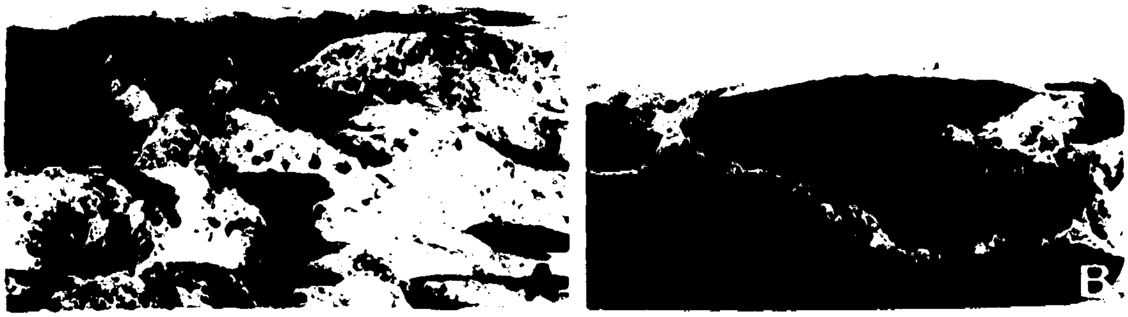
Pemberton and Frey (1985) described a modern occurrence of the *Glossifungites* ichnofacies from the St. Catherines and Petit Chou Islands off the coast of Georgia, where it is predominantly developed in semiconsolidated, partially dewatered, Holocene salt marsh muds. The muds were buried under beach ridges generated as a result of the Holocene transgression. Present day wave and tidal channel erosion has exhumed these stiff muds and allowed their colonisation by one of three intergradational ichnocoenoses: (1) a petricolid assemblage, (2) a petricolid-pholad-crustacean assemblage, and (3) a petricolid-crustacean-polydoran assemblage. These ichnocoenoses comprise the modern *Glossifungites* ichnofacies assemblage observable on the Georgia Coast today. The ichnogenera *Psilonichnus* (unlined crab burrows), as well as largely unlined *Palaeophycus* and *Thalassinoides* constructed by polychaetes and shrimps respectively, occur in both the pre-semiconsolidation softground Holocene salt marsh assemblage, as well as in the semiconsolidated, post-exhumation *Glossifungites* ichnofossil assemblage. The observed relict softground ichnofossil assemblages can be subdivided into relict lebensspuren associated with paleosols, relict shells and ichnofossils of the Holocene salt marsh muds, and the relict lebensspuren of the Pleistocene foreshore sands. The differentiation of softground from firmground burrows are determined by observing their cross-cutting relationships and the distinctive characteristics of the assemblages themselves.

Original softground trace fossils of the paleosols are dominated by vegetative traces, including the dense root systems of saw palmetto (*Serenoa repens*), undifferentiated small vertical rootlets, detrital leaf fronds, *in situ* large lateral roots, and scattered fragments of Bermuda grass (*Cynodon dactylon*). Relict shells and trace fossils of the salt marsh muds include *in situ* shells of the oyster *Crassostrea virginica, in situ* shells of the mussel *Geukensia demissa,* roots and stem-stubble of the cord grass *Spartina alterniflora,* valves of the snail *Littorina irrorata,* crab burrows which belong to the ichnogenus *Psilonichnus,* polychaete worm burrows ascribed to the ichnogenus *Skolithos,* and shrimp burrow systems belonging to the ichnogenera *Thalassinoides* and *Spongeliomorpha. Thalassinoides* is very similar to *Spongeliomorpha,* but *Spongeliomorpha* represents three-dimensional dwelling boxworks that commonly exhibit well-developed chelaped scratches along the burrow walls. The softground assemblage of the foreshore sands consists of burrows identical to those made by the modern shrimp *Callianassa major* and are assigned to the ichnofossil *Ophiomorpha nodosa.*

These three distinctive softground ichnofossil suites have been overprinted by firmground burrows created largely by petricolid and pholad bivalves, and numerous species of crustaceans. The modern *Glossifungites* assemblage comprises petricolid and pholad bivalve burrows amenable to the ichnogenus *Gastrochaenolites,* vertically-oriented polychaete worm burrows, similar to those of the ichnogenera *Skolithos* and *Diplocraterion,* unlined shrimp burrows or shrimp burrows with chelaped sculpted walls representing the ichnogenera *Thalassinoides* and *Spongeliomorpha* respectively, and unlined crab burrows assigned to the ichnogenus *Psilonichnus.* These *Glossifungites* ichnofacies traces typically occur in extremely dense populations, commonly rendering the firm substrate completely pitted (Figure II-4 A; *cf.* Pemberton and Frey, 1985). The burrows remain open and commonly are passively filled with beach sand associated with transgressive shoreline retreat (Figure II-4 B; *cf.* Pemberton and Frey, 1985).

The applications of a modern analogue for the *Glossifungites* ichnofacies to the study of ancient sedimentary rocks are five-fold. The modern example demonstrates the existence of comparable *Glossifungites* ichnogenera to those observed in the ancient, extending at least to Ordovician (Table II-1), suggesting that the nature of firmground colonisation and organism behaviour has remained relatively constant throughout most of the Phanerozoic. The wide occurrence of sharp-walled, unlined structures in the

Figure II-4. Modern *Glossifungites* from the Georgia Coast. (A) Note the dense population of shafts and dwelling structures of the *Glossifungites* suite (the "pits"). Compare this with the populations calculated for Figure II-3B. St. Catherines Island beach (after Pemberton and Frey, 1985). Field of view approximately 5 m. **(B)** A dwelling structure of the tracemaker *Upogebia affinis* (a shrimp) attributable to the ichnogenera *Thalassinoides/ Spongeliomorpha*. Note the sharp, unlined walls of the structure, consistent with the *Glossifungites* ichnofacies. The structure has been passively-filled with beach sand. Petit Chou Island (after Pemberton and Frey, 1985). Field of view is approximately 20 cm.


B

modern suite, currently in a state of passive fill, conforms well with observations from the ancient record. The dominance of vertically-oriented dwelling burrows corresponds to higher energy conditions, associated with the depositional hiatus. This contrasts markedly with the lower energy softground suites which were contemporaneous or penecontemporaneous with marsh mud accumulation. This juxtaposition of organism behaviours, associated with the cross-cutting relationships of the trace fossil suites, has been recognised in virtually every ancient example. The dense populations noted in the Georgia Coast are consistent with observations on bedding planes from outcrop studies (Saunders and Pemberton, 1986; Dam, 1990) and proposed from subsurface analysis (MacEachern *et al.*, 1992b; Pemberton *et al.*, 1992a). Finally, the modern analogue demonstrates that erosional exhumation of the substrate may be relatively complex and not wholly related to allocyclic controls. In the Georgia Coast, original exhumation of the substrate was facilitated by autocyclic tidal channel migration, but colonisation and passive fill, and therefore preservation, are primarily in response to ongoing transgression and erosive shoreline retreat.

THE *GLOSSIFUNGITES* ICHNOFACIES: STRATIGRAPHIC APPLICATIONS

In siliciclastic settings, most firmground assemblages are associated with erosionally exhumed (dewatered and compacted) substrates and, hence, demarcate erosional discontinuities. Depositional breaks, in particular condensed sections, may also be semilithified or lithified (*e.g.* Loutit *et al.*, 1988), presumably at the upper contact (or downlap surface; *cf.* Van Wagoner *et al.*, 1990) and may be colonised without associated erosion. A possible example occurs in the Ordovician Glenwood Formation of the Michigan Basin, where a firmground *Thalassinoides* burrow penetrates a phosphatic shale, interpreted as a condensed section (R. Dott Jr., G. Nadon and D. Rodrigues de Miranda, University of Wisconsin at Madison, pers. comm., 1991; *cf.* Table II-1). In general, however, the recognition of substrate-controlled ichnofacies may be regarded as equivalent to the recognition of erosional discontinuities in the stratigraphic record.

Although certain insect and animal burrows in the terrestrial realm may be properly regarded as firmground (*e.g.* Fürsich and Mayr, 1981) or, more rarely, hardground suites, they have a low preservation potential and constitute a relatively minor element in the preserved record of these associations. The overwhelming majority of *Glossifungites* assemblages originate in marine or marginal marine settings. As such, a discontinuity may be generated in either subaerial or submarine settings, but the colonisation of the surface may be regarded to be marine-influenced, particularly in pre-Tertiary intervals. This has important implications regarding the genetic interpretation of the discontinuity in question.

Finally, the substrate-controlled ichnocoenose, which cross-cuts the pre-existing softground suite, reflects conditions *post-dating* both initial deposition of the underlying unit and its subsequent erosional exhumation following burial (Figure II-5). The *Glossifungites* suite therefore corresponds to a depositional hiatus between the erosional event and deposition of the overlying unit; significant depositional cover precludes firmground colonisation. By observing (1) the softground ichnofossil assemblage (contemporaneous with deposition of the unit), (2) the ichnofacies of the exhumed substrate, and (3) the ichnofossil assemblage of the overlying unit, it is possible to provide considerable insight into the origin of the surface and the allocyclic or autocyclic mechanisms responsible (Table II-1).

Ichnologically-Demarcated Stratigraphic Boundaries

Not all breaks in the rock record have stratigraphic significance. Whether the discontinuity surface is marked by a substrate-controlled ichnofacies or by a pebble lag, its regional extent is not discernible at one outcrop location or in a single cored interval, and careful regional analysis is required. Furthermore, the temporal significance of a break requires biostratigraphic, paleomagnetic, or radiometric analysis.

Three main types of erosional discontinuities having stratigraphic significance are considered: (1) lowstand surfaces of erosion (LSE) (lowstand unconformities or sequence boundaries (SB); *e.g.*, some estuarine arms of incised valley margins, incised submarine canyon margins, bases of forced regression- shorefaces), (2) transgressive surfaces of erosion (TSE, ravinement, high energy flooding surfaces (HE FS), or high energy parasequence boundaries), and (3) co-planar surfaces of lowstand erosion and transgressive

Schematic development of a *Glossifungites* Ichnofacies

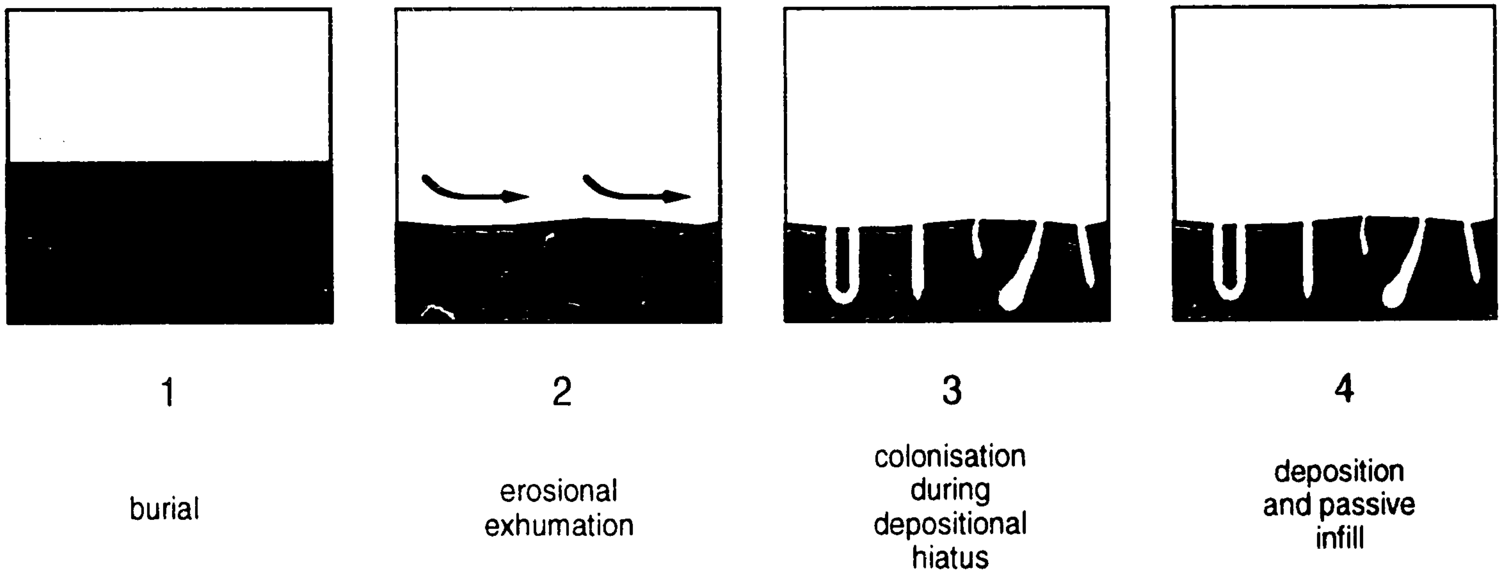


Figure II-5. Schematic development of a *Glossifungites*-demarcated erosional discontinuity. 1) The muddy substrate is buried and dewatered, resulting in a compacted, stiff character. 2) The shaly bed is erosionally exhumed, exposing a firm substrate. 3) Colonisation of the discontinuity surface by tracemakers of the *Glossifungites* ichnofacies proceeds under marine conditions during a depositional hiatus. 4) The structures are passively filled during a succeeding depositional episode.

erosion (E/T surfaces or amalgamated sequence boundaries and flooding surfaces [FS/SB]; *e.g.* many estuarine incised valley margins and transgressed interfluves and subaerial exposure surfaces). There are numerous examples in the ancient record of ichnologically-demarcated erosional discontinuities of these types (Table II-1).

Lowstand Surfaces of Erosion

Subaerial exposure and/or erosion produced during a relative lowstand of sea level permits the widespread development of dewatered and firm or incipiently-cemented substrates. Typically, however, the initial deposits on the unconformity are terrestrial or freshwater in origin. Permanent burial of the surface under these conditions precludes development of a *Glossifungites* assemblage (*e.g.* Savrda, 1991a). Where the lowstand-generated erosion surface lies in a marine or marginal marine setting prior to significant depositional cover, conditions favourable to firmground colonisation exist.

Terrestrial Incised Valleys

In the case of terrestrial incised valleys, colonisation of the erosional discontinuity, under conditions of a relative sea level lowstand, may occur only at the seaward margin of the valley. Here, sediments accumulating as part of the lowstand systems tract may overlie a *Glossifungites*-demarcated valley margin, because fluvial conditions did not extend very far into the valley and marginal marine (estuarine) conditions existed prior to significant deposition. In such a case, the distribution of substrate-controlled ichnofacies may be employed to map the maximum landward limit of marine influence in the valley. More commonly, however, marine conditions are not widespread in the valley until an ensuing transgression. When the transgression is accompanied by ravinement, which removes or redistributes lowstand sediments, colonisation of the exhumed surface by tracemakers of the *Glossifungites* ichnofacies is favoured (MacEachern and Pemberton, in press). As such, these incised valley surfaces are co-planar surfaces of lowstand erosion and transgressive erosion (FS/SB; *cf.* Van Wagoner *et al.*, 1990), and are dealt with below.

Incised Submarine Canyons

In the exceptional case of lowstand incised submarine canyons, the erosional discontinuity lies within a marine setting at the time of its excavation, and colonisation of the walls and floor has a higher probability than in terrestrial valleys. Outcrops of the lower Miocene Nihotupu and Tirikohua formations in Northland, New Zealand, contain a noteworthy *Glossifungites* association related to submarine canyon incision (Figure II-6; Hayward, 1976; *cf.* Table II-1). The underlying Nihotupu Formation consists of volcanogenically derived siltstones, sandstones and subaqueous mass flow conglomerates, together with submarine andesite pillow-pile complexes. The softground assemblage is sparse, characterised by individual occurrences of *Thalassinoides, Planolites* and *Scalarituba*; burrowed horizons occur locally. These deposits are interpreted as turbidites emplaced at bathyal water depths (based on faunal content) within an inter-arc basin on the lower eastern flanks of the west Northland volcanic arc.

The contact with the overlying Tirikohua Formation is sharp and erosional, and exhibits visible relief. The exhumed substrate is demarcated by a *Glossifungites* assemblage, consisting of *Skolithos* (called *Tigillites* by the original author), *Rhizocorallium, and ?Thalassinoides*. Mechanical borings are absent, indicating that the surface was not lithified at the time of colonisation. The stiff and semiconsolidated nature of the underlying sediments at the time of colonisation is demonstrated by the steep trench walls with small overhangs (Figure II-6). The overlying Tirikohua Formation consists of fairly coarse-grained volcanogenic sandstones and conglomerates, deposited as canyon floor and neritic sediment gravity flows, similar to proximal turbidites. These sediments also contain a sparse softground trace fossil suite consisting of *Planolites, Scalarituba, Skolithos, Thalassinoides,* and escape traces. Hayward (1976) interpreted the erosional discontinuity as a submarine canyon wall, excavated into bathyal to neritic inter-arc sediment gravity flow deposits, due to tectonic uplift of the basin margin. Colonisation of the canyon walls by the firmground tracemakers preceded eventual burial by canyon floor and neritic turbidite deposits of the Tirikohua Formation, probably corresponding to late stage relative sea level lowstand or early transgressive fill of the submarine canyon.

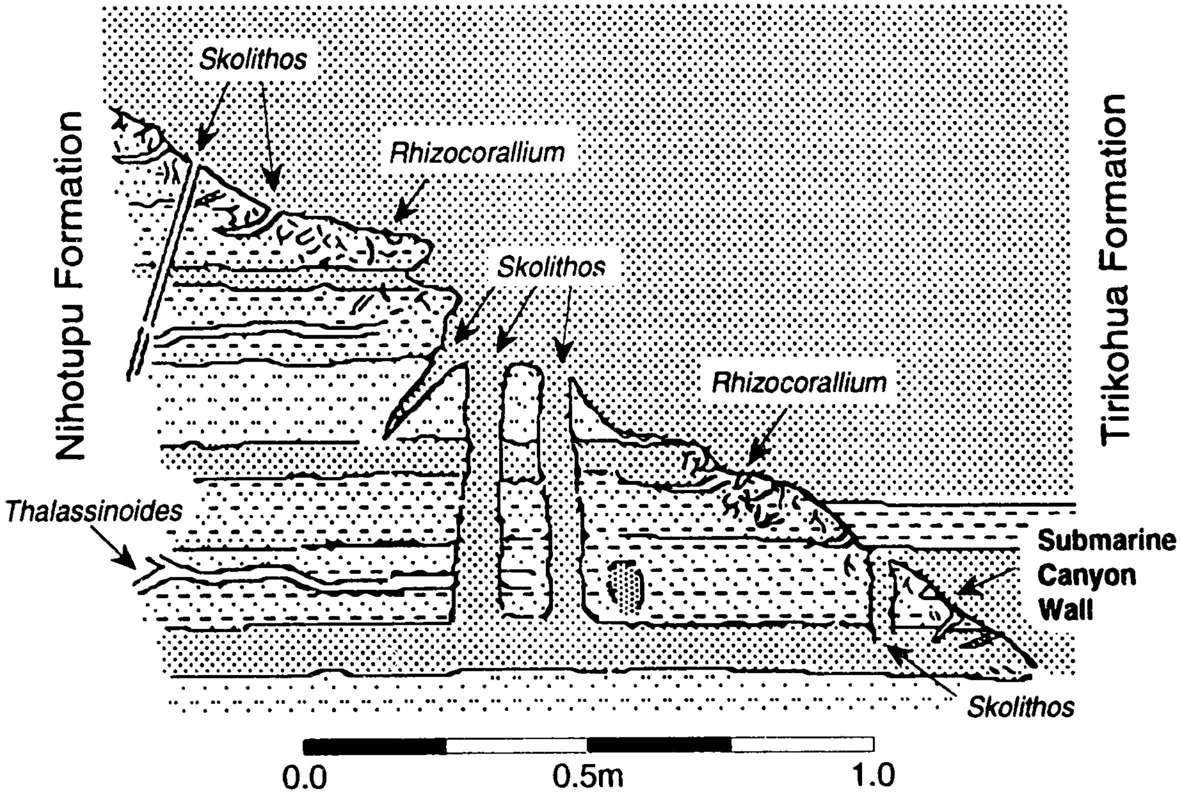


Figure II-6. Lowstand incised submarine canyon wall. This Miocene example from New Zealand shows the canyon wall thoroughly burrowed with a *Glossifungites* assemblage. The stiff, firm character of the substrate is demonstrated by numerous small overhangs and steep slopes (modified after Hayward, 1976).

Forced Regression Shorefaces

The character of sequence boundaries generated during forced regression (*cf.* Plint, 1988; Posamentier and Vail, 1988) differs from many other sequence boundary expressions in that the surface is cut under submarine conditions. During falling sea level, sediments previously lying below fairweather wave base are brought into a zone of persistent wave attack. This produces an erosional sequence boundary which passes basinward into a correlative conformity and landward into a subaerial exposure surface. The rapid basinward shift of the shoreline "forces" a shoreface to prograde rapidly over the sequence boundary, with minimal, if any, record of its passage. The diminished accommodation space associated with the base level fall results in the abrupt establishment of shallow water deposits over deeper water sediments, typically occupying a wave cut terrace at the most basinward position of the shoreline. Depending upon the rate of progradation, this lowstand erosion surface may become colonised by tracemakers of the *Glossifungites* ichnofacies, seaward of the advancing shoreface.

The Albian Viking Formation of the Kaybob field (Figures II-7, II-8 and II-9), central Alberta, produces hydrocarbons from a sharp-based, coarsening upward, NW-SE trending sandstone body, interpreted as a forced regression shoreface (MacEachern *et al.*, 1992b; Pemberton *et al.*, 1992a; Pemberton and MacEachern, in press; see Chapter VII). The lowstand surface (sequence boundary) is incised into thoroughly burrowed silty and sandy shales. The silty shales contain a distal *Cruziana* ichnofacies consisting of *Helminthopsis, Anconichnus, Zoophycos, Thalassinoides, Chondrites, Teichichnus, Terebellina, Planolites,* and very rare *Asterosoma* The distal *Cruziana* ichnofacies is consistent with lower offshore to shelfal deposition (MacEachern and Pemberton, 1992). The sandy shales contain a diverse *Cruziana* ichnofacies consisting of *Helminthopsis, Anconichnus, Chondrites, Zoophycos, Terebellina, Thalassinoides, Asterosoma, Rosselia, Planolites, Teichichnus, Rhizocorallium, Palaeophycus, Siphonichnus, Skolithos, Arenicolites, Diplocraterion* and rare *Schaubcylindrichnus*. This *Cruziana* suite reflects a mixture of grazing, deposit feeding and suspension feeding structures, consistent with upper offshore deposition (MacEachern and Pemberton, 1992).

The lowstand surface (sequence boundary) is locally demarcated by a *Glossifungites* suite of *Skolithos, Thalassinoides* and rare *Diplocraterion,*

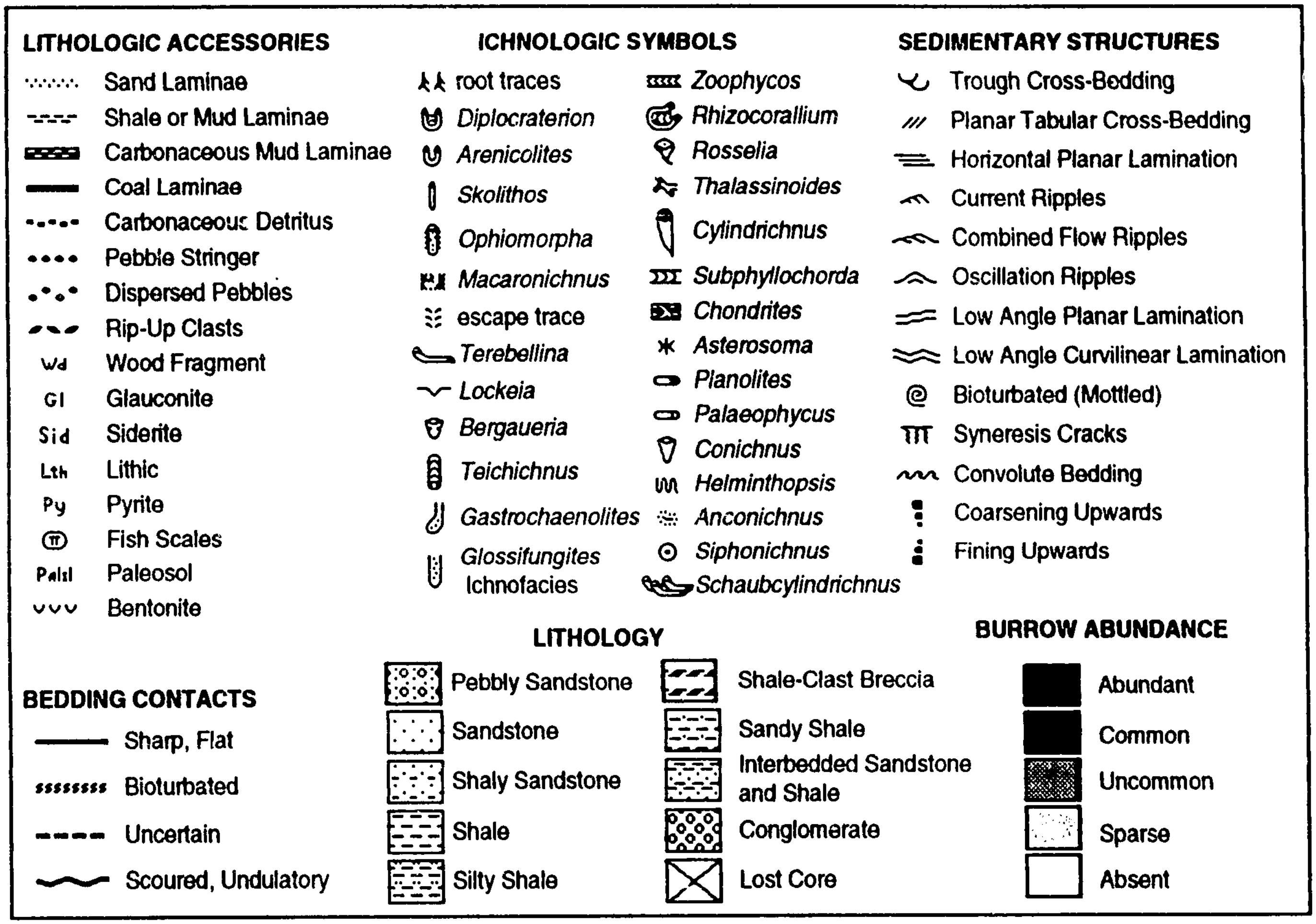


Figure II-7. Legend of Symbols used in Lithologs and Cross-section.

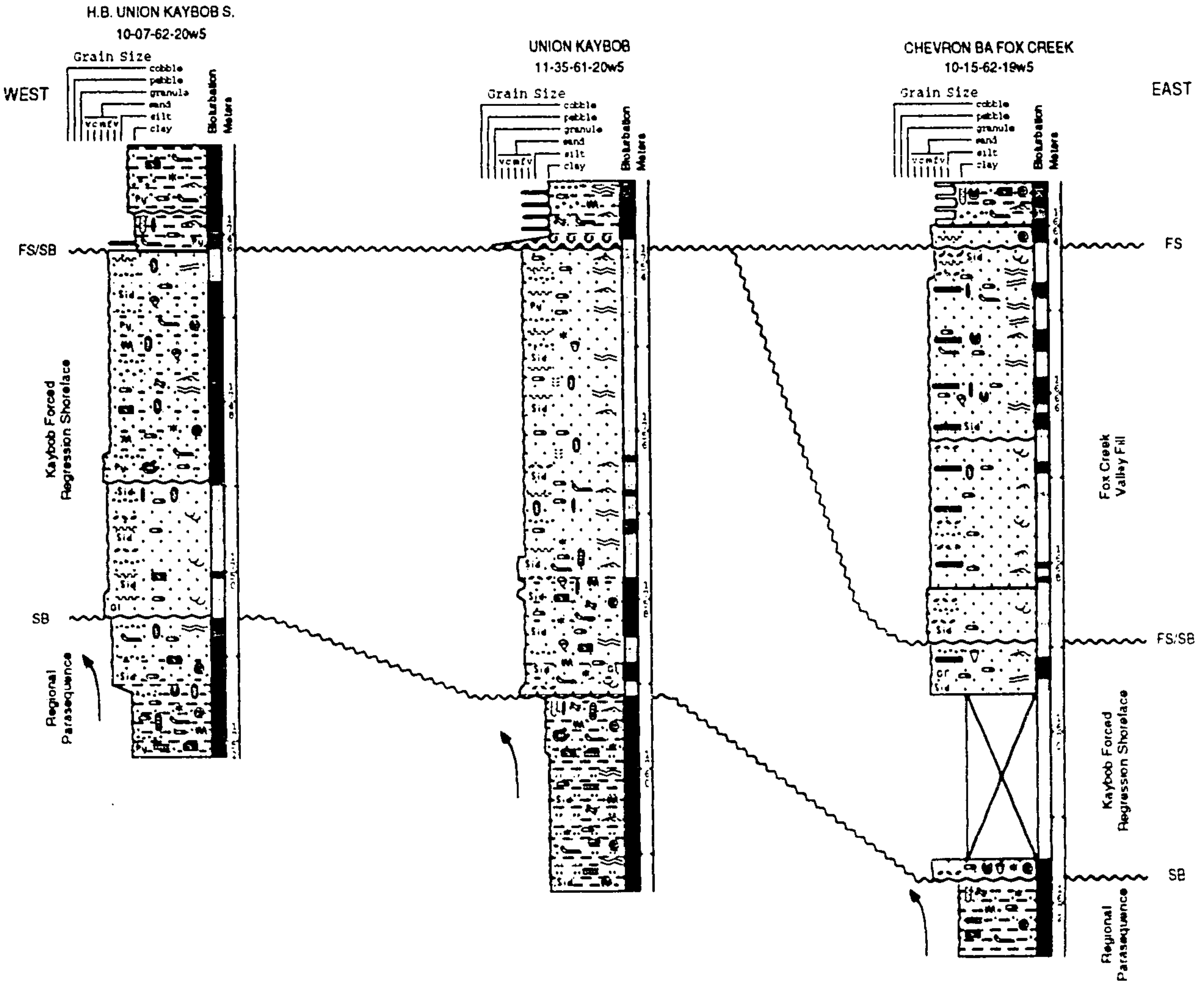
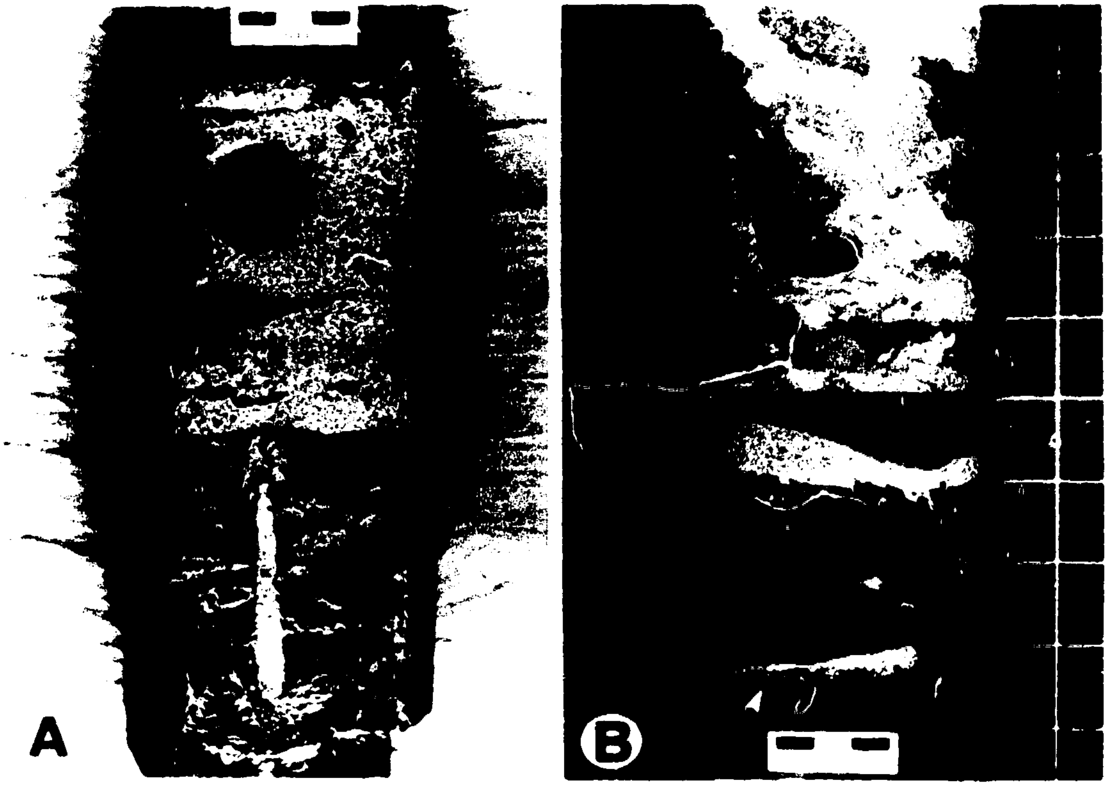


Figure II-8. West-east (proximal-distal) litholog cross-section of the Kaybob forced regression shoreface. The forced regression shoreface overlies a sequence boundary incised into regionally extensive parasequences of the lower Viking Fm. The shoreface is erosionally removed to the east by an FS/SB, defining the base of a proposed incised valley at Fox Creek. Legend of the symbols used in the lithologs occur in Figure II-7.

Figure II-9. Forced Regression Shoreface in the Viking Formation, Kaybob Field. (A) Thoroughly burrowed, upper offshore sandy shale of a highstand parasequence erosionally truncated by lower to middle storm-influenced shoreface sandstones of the Kaybob shoreface. A few rip-up clasts occur above the erosional contact. A sharp-walled, robust *Skolithos* (arrow) of the *Glossifungites* ichnofacies demarcates the surface. The erosion surface is interpreted as a sequence boundary. Kaybob Field, 11-35-61-20W5, depth 1759.1 m. **(B)** Thoroughly burrowed, lower offshore silty shale of a highstand parasequence, erosionally truncated by thoroughly burrowed, lower shoreface muddy sandstone of the Kaybob shoreface. This core lies basinward of the core in A. The erosion surface correlates to the same sequence boundary in A, and is demarcated by *Thalassinoides* (arrow) of the *Glossifungites* ichnofacies. Fox Creek Field, 10-15-62-19W5, depth 1672.0 m.


A
B

passively filled with medium- to coarse-grained sand from the overlying forced regression shoreface (Figure II-9). In proximal positions, the boundary is also manifest by an abrupt increase in grain size and rare chert pebbles. In more basinal positions, the contact is more biogenically disturbed and may also be marked by rare dispersed chert pebbles.

In proximal positions (Figures II-8), upper shoreface sandstones, consisting of thin bedsets of trough cross-stratification with rare, intercalated swaley cross-stratified storm beds, directly overlie the sequence boundary. Softground trace fossils consist of *Arenicolites, Skolithos, Diplocraterion, Palaeophycus, Cylindrichnus,* rare *Conichnus* and escape traces.

In intermediate positions (Figures II-8 and II-9 A), lower to middle shoreface sandstones immediately overlie the sequence boundary. The sandstones consist of alternating storm beds, characterised by swaley cross-stratification and combined flow ripple lamination, and thoroughly burrowed muddy sandstone fairweather beds. The succession is typical of storm-dominated to storm-influenced settings (MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992b). The trace fossil suite consists of fugichnia, *Skolithos, Ophiomorpha, Arenicolites, Palaeophycus, Diplocraterion, Conichnus, Siphonichnus, Planolites, Teichichnus, Terebellina, Rosselia,* with lesser *Asterosoma, Helminthopsis, Chondrites, Cylindrichnus* and *Bergaueria*. This suite reflects a mixture of deposit feeding, suspension feeding and passive carnivore structures, with less abundant grazing structures. In detail, the assemblage shows discrete *Skolithos* assemblages, reflecting initial colonisation of storm beds by opportunistic tracemakers, alternating with proximal *Cruziana* suites, characterised by diverse, unstressed tracemakers (Pemberton *et al.*, 1992a,b; *cf.* Chapters IV and VII). This mixed *Skolithos-Cruziana* ichnofacies is typical of lower to middle shoreface deposition in a moderately storm-dominated setting.

In more basinal positions (Figures II-8 and II-9 B), the sequence boundary is abruptly overlain by thoroughly burrowed lower shoreface muddy sandstones, which contains a proximal *Cruziana* trace fossil suite consisting of *Teichichnus, Asterosoma, Rosselia, Terebellina, Planolites, Chondrites, Rhizocorallium, Skolithos, Diplocraterion, Arenicolites, Ophiomorpha, Cylindrichnus, Palaeophycus,* and rarer *Helminthopsis, Zoophycos, Schaubcylindrichnus* and *Siphonichnus*. This proximal *Cruziana* ichnofacies is dominated by deposit feeding structures, with subordinate numbers of suspension feeding, passive carnivore and grazing structures, and is interpreted to reflect weakly storm-affected distal lower shoreface conditions (*cf.* MacEachern and Pemberton, 1992). Further basinward, the sequence boundary passes into a correlative conformity and is difficult to recognise. The succession in this position demonstrates a gradual coarsening upward profile from offshore-shelfal silty shales to shoreface sandstones without evidence of a break. Successions in this depositional position are difficult to differentiate from the highstand parasequences underlying the correlative conformity (*cf.* Pemberton and MacEachern, in press; Chapter III).

A forced regression setting has also been proposed for the Viking Formation at the Joarcam field (Posamentier and Chamberlain, 1991a,b, 1993; Posamentier *et al.*, 1992). In the few cored intervals from Joarcam studied by the authors, no substrate-controlled suites were observed to demarcate the sequence boundary. Nonetheless, the sharp, erosionally-based character of the shoreface sandstone attests to an abrupt basinward shift of facies, consistent with a relative fall of sea level. The Viking Formation Sunnybrook A and B sandstones (Pattison, 1991a) and the coarse-grained sandstone markers of the upper Viking Formation in the Caroline and Garrington field (Davies and Walker, 1993) have been interpreted as forced regression shorefaces and basinal extensions of forced regressions, respectively (*cf.* Chapter X). Some conglomeratic shorefaces of the Turonian Cardium Formation have also been interpreted as lowstand shorefaces (Walker and Plint, 1992), and contain *Glossifungites* suites of *Thalassinoides* and more rarely, *Skolithos* subtending from the discontinuity (Vossler and Pemberton, 1988; Table II-1). Arnott (1993) has interpreted the "D2" cycle of the Albian Falher D member, Spirit River Group, to reflect a forced regression shoreface in Elmworth area of northwestern Alberta. In addition, Walker and Bergman (1993) have re-interpreted some outcrops of the Shannon Sandstone near Casper, Wyoming to reflect forced regression shoreface deposition rather than offshore bar accumulation. Observation of the Shannon Sandstone where it overlies the Cody sandy shales also shows a *Glossifungites* suite of *Thalassinoides* and associated phosphatic pebbles demarcating the proposed sequence boundary.

Transgressive Surfaces of Erosion

High energy flooding surfaces (HE FS) are manifest as low relief, erosion surfaces cut by wave and current processes, associated with erosional shoreface retreat during transgression. Nummedal and Swift (1987) identified two subcategories of transgressive erosion surfaces: the higher energy ravinement surfaces (*cf.* Stamp, 1921) and the lower energy (distal) offshore marine erosion surfaces. Basinward, high energy flooding surfaces pass into low energy, non-erosional flooding surfaces.

Transgressive surfaces of erosion (*i.e.* ravinement surfaces or HE FS) afford the most elegant means of developing widespread substrate-controlled ichnofacies. This is because the exhumed surfaces are generated within marine or marginal marine environments, favouring colonisation by organisms as the surface is cut, and prior to deposition of significant thicknesses of overlying sediment.

Many of these surfaces are of limited spatial extent and may be discontinuous, limiting their effectiveness in regional correlations. In addition, high energy flooding surfaces commonly produce pronounced stratigraphic breaks in the rock record, which may be easily mistaken for sequence boundaries (Nummedal and Swift, 1987) or amalgamated FS/SB surfaces, unless carefully placed into stratigraphic context.

Ravinement - Stillstand Cycles

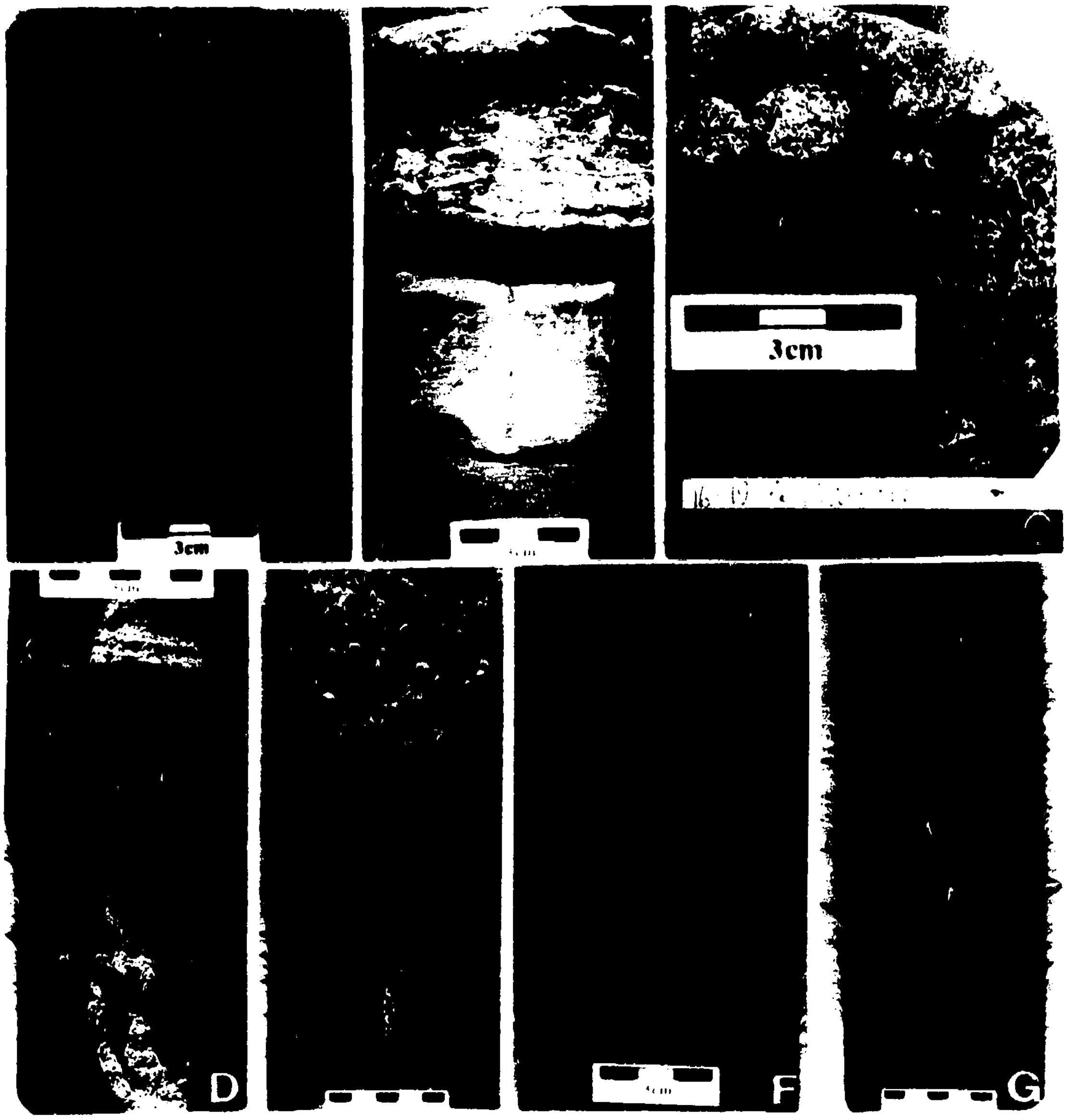
The Lower Cretaceous (Albian) Viking Formation in the subsurface of central Alberta contains several transgressive surfaces of erosion near the top of the interval, recording a complex history of transgression which culminated in maximum flooding of the North American Interior Seaway and deposition of the widespread Colorado shales and equivalents. The recognition of discrete high energy flooding surfaces is difficult on the basis of sedimentology alone, particularly when dealing with the upper Viking Formation, where there exist abundant sharp-based pebble stringers and thin trough cross-stratified coarse-grained sandstones within interbedded sandstones, siltstones and shales. Many of these coarse stringers could reflect veneers on transgressive surfaces but, due to their abundance, picking which ones have stratigraphic significance is highly problematic. However, virtually every high energy flooding surface incised into, or cut across, shaly sediments, shows a *Glossifungites* suite (Figure II-10). Several intervals contain up to seven such ichnologically-demarcated flooding surfaces across 6 meters of section.

Lower cycles of the Viking Formation are truncated and overlain by pebble lags (*cf.* Facies A; MacEachern *et al.*, 1992a) or by highly burrowed pebbly muddy sandstones and sandy shales with thin gritty sandstones interbedded with less intensely burrowed interstratified sandstones, siltstones and shales. All pebble lags are erosionally-based and typically lack discrete physical and biogenic structures. The pebbly muddy sandstones and sandy shales (*cf.* Facies B; MacEachern *et al.*, 1992a) are erosionally-based and, where not biogenically homogenized, contain a proximal *Cruziana* softground suite of *Terebellina, Planolites, Chondrites, Asterosoma, Teichichnus, Cylindrichnus, Rosselia, Siphonichnus, Helminthopsis, Zoophycos,* rare *Diplocraterion* and *Palaeophycus*.

The interstratified sandstones, siltstones and shales (*cf.* Facies C; MacEachern *et al.*, 1992a) range from moderate to low degrees of burrowing, and preserve remnant low angle parallel laminae, combined flow ripple laminae and less common oscillation ripple and current ripple laminae. This facies commonly grades out of the pebbly muddy sandstones and sandy shales. The softground suite consists of *Planolites, Teichichnus, Asterosoma, Chondrites, Terebellina, Cylindrichnus, Rhizocorallium Siphonichnus, Thalassinoides, Helminthopsis, Zoophycos, Anconichnus horizontalis,* rare *Diplocraterion, Skolithos, Arenicolites, Lockeia,* and *Palaeophycus*. The suite corresponds to a *Cruziana* ichnofacies reflecting lower to upper offshore conditions (MacEachern and Pemberton, 1992; MacEachern *et al.*, 1992a).

Glossifungites assemblages are characterised by the ichnogenera *Diplocraterion* (dominantly *D. habichi*; Figure II-10 C, D), *Skolithos* (Figure II-10 B, F), *Arenicolites* (Figure II-10 A), and firmground *Thalassinoides*, and are developed at erosional contacts between the interstratified sandstones, siltstones and shales and the overlying pebbly muddy sandstones and sandy shales. In many cases, the nature of the contact is cryptic, due to biogenic reworking by deeply penetrating structures; the presence of the firmground suite and dispersed pebbles are employed to interpret the existence of a hidden bed junction (*i.e.* concealed bed junction preservation; *cf.* Simpson, 1957). Although these higher energy *Glossifungites* suites clearly cross-cut the lower energy softground suites, most authors have routinely regarded them

Figure II-10. TSE Demarcated by the *Glossifungites* Ichnofacies. **(A)** Thoroughly burrowed, muddy sandstone cross-cut by a robust, medium- to coarse-grained sand-filled *Arenicolites* of the *Glossifungites* ichnofacies, subtending from a TSE. Viking Formation, Kaybob South Field, 07-19-62-19W5, depth 1652 m. **(B)** Siderite-cemented shale, penetrated by a *Skolithos* of the *Glossifungites* ichnofacies, marking a TSE. Gritty, muddy sandstones overlying the surface correspond to transgressive deposits associated with erosive shoreface retreat. Viking Formation, Garrington Field, 16-13-34-03W5, depth 2066.2 m. Scale in centimeters. **(C)** Bedding plane view of sandy shales, cross-cut by firmground *Diplocraterion habichi.* Note the robust, sharp-walled character. Viking Formation, Fenn Field, 16-19-36-21W4, depth 1302.2 m. **(D)** Burrowed sandy shale reflecting distal stillstand deposits, cross-cut by robust *Arenicolites/Diplocraterion habichi* subtending from a TSE, and overlain by sandstone. Viking Formation, Fox Creek Field, 10-15-62-19W5, depth 1664.8 m. **(E)** Silty and sandy shales of regionally extensive Viking parasequences, erosionally truncated by a TSE (VE3 of Boreen and Walker, 1991). The *Glossifungites* suite consists of *Skolithos* filled with conglomeratic sandstone from the overlying transgressive lag. Viking Formation, Willesden Green Field, 07-10-41-07W5, depth 2318.1 m. Scale in centimetres. **(F)** Weakly-burrowed sandstone and shale of a stillstand progradational cycle, erosionally truncated by a TSE (VE4 of Raychaudhuri, 1989). The *Glossifungites* suite is manifest by *Diplocraterion,* filled with pebbly sandstone. Viking Formation, Chigwell Field, 04-02-42-26W4, depth 1439.3 m. **(G)** Thoroughly burrowed sandy shale, cross-cut by abundant (at least 16) firmground *Diplocraterion*, subtending from a TSE. Paddy Member, Peace River Formation, Sinclair Field, 10-03-72-12W6, depth 1733.8 m.


3cm
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D
F
G

as part of the softground assemblage, obscuring the true, original depositional conditions of the facies.

These erosional discontinuities are interpreted as transgressive surfaces of erosion (TSE) or high energy flooding surfaces. The *Glossifungites* assemblages record suspension feeding behaviour associated with the period of higher energy associated with active ravinement. Colonisation of the exhumed surface post-dates the erosive shoreface retreat, but presumably occurs prior to significant deepening. The transgressive lags (*cf.* Facies A, MacEachern *et al.*, 1992a) may correspond to either lowstand lags on a sequence boundary, subsequently transgressively-modified during ravinement, or simply to wave ravinement in proximal positions. Van Wagoner *et al.* (1990) outlines several arguments surrounding the origin of thick pebble veneers on erosion surfaces lying in offshore positions (*cf.* Chapter X); the nature of such surfaces requires detailed regional stratigraphic analysis in order to resolve their genetic stratigraphic significance.

The overlying pebbly muddy sandstones and sandy shales (*cf.* Facies B, MacEachern *et al.*, 1992a) are interpreted as the distal deposits of the continuing ravinement process; the presence of coarse-grained sand and dispersed pebbles record ongoing ravinement in shallower water settings, with the coarser material reworked seaward by storm-initiated or storm-enhanced currents. The associated softground suite supports sediment accumulation in upper to lower offshore settings associated with continuing deepening. The interlaminated sandstones, siltstones and shales are interpreted as upper offshore to distal lower shoreface deposits in a moderately to highly storm-dominated setting (*cf.* Facies C, MacEachern *et al.*, 1992a), recording a shallower water setting than the pebbly shales. The stacking of *Glossifungites*-demarcated, erosionally-based, pebbly muddy sandstones and sandy shales, with gradationally-based interlaminated sandstones, siltstones and shales, supports the interpretation of ravinement followed by short-lived stillstand cycles of progradation. Many of these progradational cycles probably record the distal equivalents of more substantial stillstand progradational shorefaces developed in landward positions.

The regional significance of these ichnologically-demarcated transgressive surfaces requires careful mapping and correlation. High energy flooding surfaces appear localised or amalgamated (co-planar) in several localities, making delineation difficult. The character of the overlying transgressive deposits also tends to vary considerably, even across short distances, complicating the process of determining surface equivalence. In addition, some *Glossifungites* ichnofacies-demarcated surfaces may be autocyclically-generated as well. Regardless, the presence of a substrate-controlled ichnofacies overlain by transgressive deposits provides a more distinctive and reliable means of identifying a surface of **more likely** stratigraphic significance than merely choosing the base of any one of a number of pebble stringers or gritty shales.

Similar TSE have been observed in the Viking Formation of the Garrington (Figure II-10 B), Fenn (Figure II-10 C), Willesden Green (Figure II-10 E), and Chigwell fields (Figure II-10 F) as well as the Paddy Member of the Peace River Formation, in the Sinclair Field of central Alberta (Figure II-10 G). In the Paddy Member, the *Glossifungites* suite typically consists of *Diplocraterion parallelum* and *Skolithos*, although examples of firmground *Thalassinoides* and *D. habichi* have also been observed.

Amalgamated Lowstand Erosion and Transgressive Erosion Surfaces (FS/SB)

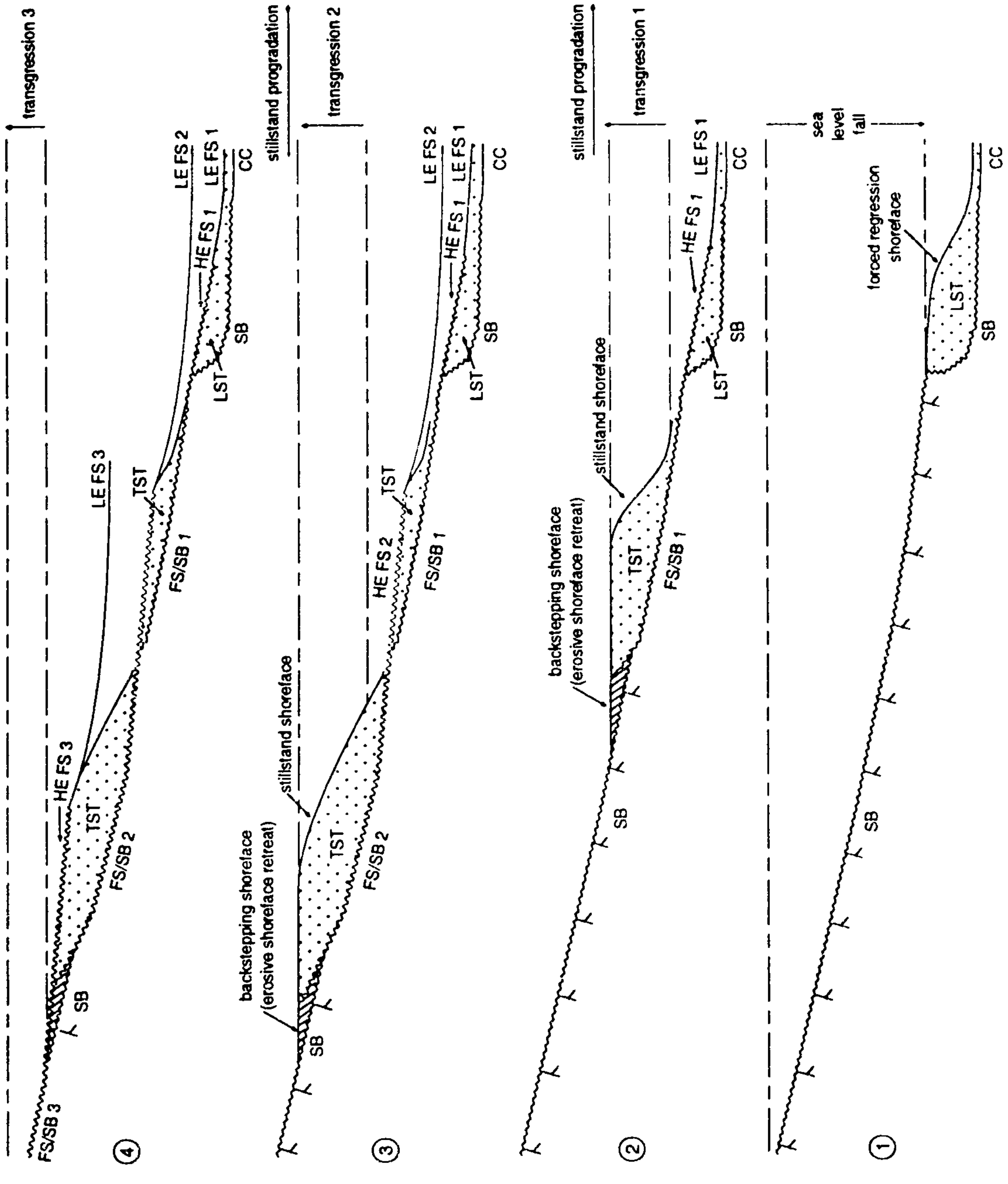
Amalgamated lowstand erosion and transgressive surfaces are commonly colonised by substrate-controlled tracemakers. The lowstand erosion event typically produces widespread firmground, hardground, and woodground surfaces. The following transgressive event, commonly accompanied by erosion (*i.e.* ravinement; *cf.* Stamp, 1921), tends to remove much of the lowstand deposits and exposes the discontinuity to marine or marginal marine conditions, permitting organisms to colonise the re-exhumed substrate.

Transgressively-Incised Stillstand Shorefaces

Several Viking Formation oil and gas fields in central Alberta produce hydrocarbons from NW-SE trending shoreface successions which correspond to areally restricted parasequences, bound above and below by high energy (erosive) flooding surfaces (high energy parasequence boundaries; *cf.* Chapters III and VIII). These successions show a strong genetic affinity with other transgressive intervals. Figure II-11 schematically illustrates the development of these areally restricted parasequences and their relationship

Figure II-11. Schematic Model of Forced Regression and Stillstand Shoreface Development in the Viking Formation. **(1)** Relative sea level fall shifts the shoreline basinward, creating a widespread subaerial exposure surface. At the new shoreline position, a wave-cut notch is generated to a depth corresponding to fairweather wave base (FWWB). Below this, a non-erosional correlative conformity (CC) is developed. The subaerial exposure surface, wave-cut notch and CC are manifestations of the same sequence boundary (SB). The new shoreface, termed a forced regression shoreface, progrades over the SB and is an element of the lowstand systems tract (LST). **(2)** Ensuing transgression (transgression 1) generates a low energy flooding surface (LE FS) below FWWB, and a high energy flooding surface (HE FS), generated by erosive shoreface retreat, at and above FWWB. Continued transgression truncates the top of the forced regression shoreface, and cuts an amalgamated flooding surface and SB (FS/SB). The backstepping shoreface sits on the SB. No evidence of subaerial exposure is preserved on the FS/SB. During a relative stillstand of sea level, a shoreface progrades over the FS/SB. Note that since the FS/SB is cut during rising sea level, initial deposits on the surface may correspond to facies lying basinward of FWWB, in contrast to the forced regression shoreface. **(3)** Resumed transgression (transgression 2) generates an LE FS below, and an HE FS at and above the initial FWWB. Here, the HE FS removes the backstepping shoreface. Erosive shoreface retreat creates a new FS/SB landward of the first stillstand shoreface. The remnant of this shoreface constitutes a parasequence. During a pause in transgression, a new stillstand shoreface is produced seaward of the backstepping shoreface, and progrades over the FS/SB. **(4)** Resumed transgression (transgression 3) generates an LE FS below, and HE FS at and above initial FWWB. In this example, a remnant of the backstepping shoreface and, hence the SB, is preserved. Evidence of subaerial exposure is removed landward of this remnant, as a new FS/SB is cut. The progressive landward-stepping stillstand shorefaces produce a retrogradational parasequence set, reflecting the transgressive systems tract (TST).

The only localities where the initial SB is preserved are underlying the forced regression shoreface, small remnants veneered by backstepping shorefaces, and the CC. Erosive shoreface retreat has removed virtually all other evidence of subaerial exposure. The FS/SB is actually a composite surface, made up of segments of FS/SB (*i.e.* FS/SB1 - FS/SB 3) which are genetically related to specific transgressive events. Each FS/SB therefore correlates to its equivalent HE FS and LE FS, not to the previous FS/SB.


④
FS/SB 3
SB
TST
FS/SB 2
HE FS 3
LE FS 3
TST
FS/SB 1
LST
SB
HE FS 1
LE FS 2
LE FS 1
CC
transgression 3
③
SB
backstepping shoreface
(erosive shoreface retreat)
TST
FS/SB 2
stillstand shoreface
HE FS 2
TST
FS/SB 1
LST
SB
HE FS 1
LE FS 2
LE FS 1
CC
stillstand progradation
transgression 2
②
SB
backstepping shoreface
(erosive shoreface retreat)
TST
FS/SB 1
stillstand shoreface
LST
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HE FS 1
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stillstand progradation
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SB
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SB
forced regression
shoreface
CC
sea
level
fall

to lowstand surfaces and forced regression shorefaces. The lower parasequence boundary corresponds to an FS/SB, generated by erosive shoreface retreat across a subaerial exposure surface. This high energy flooding surface removes all evidence of subaerial exposure in the Viking examples studied. A decrease in the rate of sea level rise or an increase in sedimentation rate permits the progradation of a shoreface over the FS/SB, seaward of the backstepping shoreface. The progradational shoreface constitutes the parasequence, marking a basinward shift of facies during a period of relative stillstand of sea level (*i.e.* a stillstand shoreface). An increase in the rate of transgression (resumed transgression) produces a low energy (non-erosional) flooding surface below fairweather wave base and a high energy flooding surface at and above fairweather wave base. The high energy flooding surface truncates the upper portion of the stillstand shoreface and cuts a new FS/SB landward of the previous one. It is clear that what initially appears to be a single FS/SB is actually a composite surface, generated by multiple, discrete periods of transgressive modification of the sequence boundary. Since each successive stillstand shoreface lies progressively landward of the previous one, these high energy parasequences stack as a retrogradational parasequence set and thus, constitute elements of the transgressive systems tract in sequence stratigraphic nomenclature.

The Viking Formation of the Chigwell field is interpreted to reflect this depositional scenario (Raychaudhuri *et al.*, 1992). The principal sand body overlies highly burrowed silty shales and sandy shales equivalent to those of the regional Viking cycles. The FS/SB surface is rarely preserved as a discrete surface; intense burrowing has largely obliterated it. Instead, dispersed pebbles and *Glossifungites* assemblages consisting of *Thalassinoides* and more rarely, *Diplocraterion*, highlight the presence of the stratigraphic break. In a basinward direction, evidence of a break is largely lacking and the discontinuity appears to have graded into a low energy flooding surface overlying a correlative conformity, which was subsequently biogenically homogenized. The facies overlying the FS/SB correspond to lower-middle shoreface deposition in proximal positions and upper offshore-lower shoreface deposition in distal positions.

A similar stratigraphic scenario has been proposed for other Viking Formation fields, such as Joffre and Gilby (Downing and Walker, 1988; Raddysh, 1988, respectively). The FS/SB of Joffre is demarcated by a

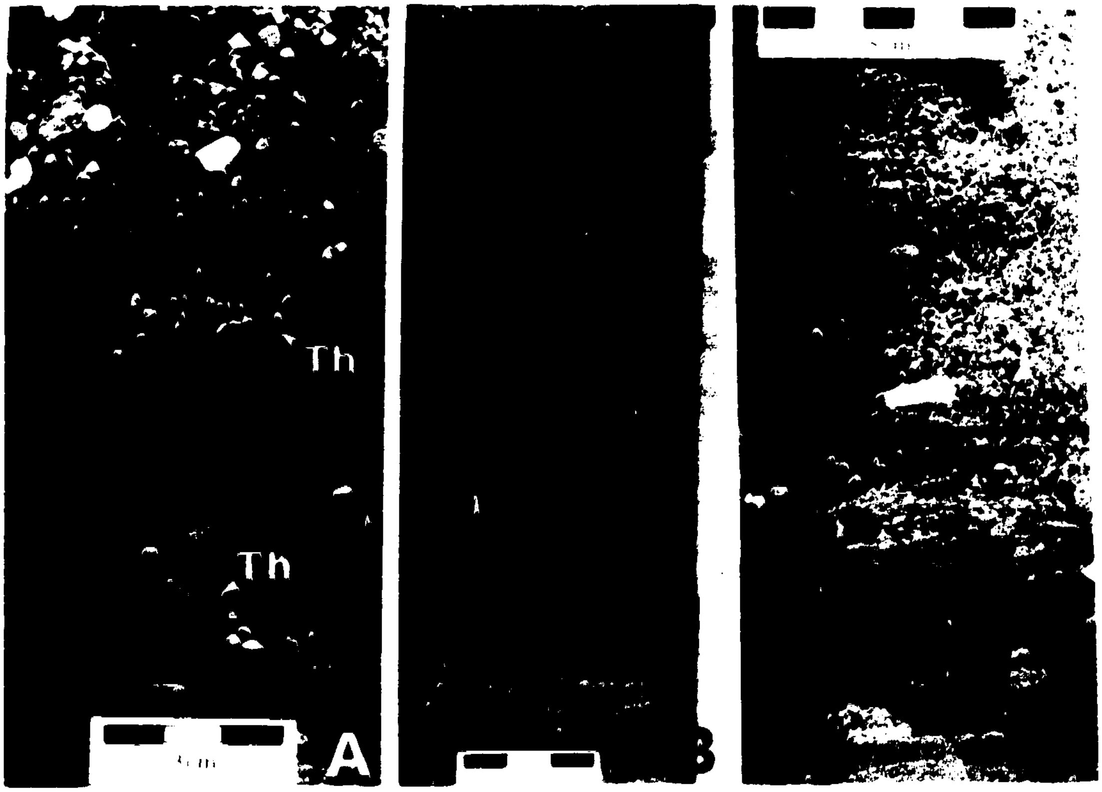
Glossifungites suite of *Thalassinoides/Spongeliomorpha* and *Diplocraterion* (Figure II-12 B, C), whereas the Gilby surface is marked by firmground *Skolithos, Diplocraterion* and *Arenicolites* (Figure II-3 A).

The Turonian Cardium Formation in central Alberta also contains a series of stillstand shorefaces (parasequences) overlying FS/SB surfaces and capped by marine flooding surfaces (*cf.* Walker and Eyles, 1991; Walker and Plint, 1992). In the Pembina field, silty shales lying below the FS/SB contain a diverse trace fossil assemblage, including *Planolites, Chondrites, Helminthopsis, Terebellina, Asterosoma,* and rare *Zoophycos.* This suite reflects a distal *Cruziana* ichnofacies, suggesting offshore to shelfal accumulation (MacEachern and Pemberton, 1992). This facies was probably subaerially exposed, with associated erosional exhumation, during a fall in sea level. The lowstand surface was subsequently transgressed and a high energy marine flooding surface substantially modified the sequence boundary, removing the evidence of subaerial exposure. This FS/SB surface is demarcated by a *Glossifungites* assemblage locally consisting of robust *Thalassinoides/Spongeliomorpha* (Figure II-12 A) and more rarely, *Skolithos,* subtending into the underlying silty shales. The *Thalassinoides* systems are passively filled with pebbles and sand piped down from the overlying structureless conglomerates (Vossler and Pemberton, 1988). The conglomerate body sharply overlies the FS/SB and corresponds to a gravelly shoreface which prograded basinward during a relative stillstand of sea level. The conglomerate largely appears structureless and shows no burrowing except within thin mud interbeds. The gravelly shoreface passes upward into a ?low energy flooding surface overlain by shelfal shales that contain *Helminthopsis, Anconichnus, Planolites, Chondrites, Terebellina, Thalassinoides* and *Zoophycos.*

TSE Across Subaerially-Exposed Surfaces (Interfluves)

Outcrops of Lower Jurassic (Sinemurian to Pliensbachian) sediments in the Jameson Land Basin of East Greenland contain trace fossil suites that mark a transgressive surface of erosion at the contact between the Kap Stewart and Neill Klinter formations (Dam, 1990). The sediments were deposited on the southernmost block of the Mesozoic rift basin of East Greenland. The underlying Kap Stewart Formation consists mainly of unburrowed lacustrine, deltaic, and braidplain deposits. In the vicinity of Constable Pynt, the

Figure II-12. Transgressively-Incised Stillstand Shorefaces (FS/SB). **(A)** Distal, lower offshore shales are truncated by conglomerates of a stillstand shoreface. The erosional discontinuity (E5 of Plint *et al.*, 1988) is marked by a *Glossifungites* suite of conglomerate-filled *Thalassinoides* (Th). The surface is interpreted as a sequence boundary, erosionally-modified during initial transgression (HE FS), and overlain by a stillstand progradational shoreface. Cardium Formation, Pembina Field, 12-09-51-10W5, depth 1596.2 m. **(B)** Storm-dominated, upper offshore, very fine-grained sandstones (distal storm beds) and shales, thoroughly burrowed with *Helminthopsis* (H), *Anconichnus* and *Planolites*. These basinal deposits are erosionally-truncated by a surface interpreted as a TSE (HE FS) (Pattison, 1991a; *cf.* E2 of Downing and Walker, 1988). The erosional discontinuity is marked by pebble-filled *Skolithos* (Sk) of the *Glossifungites* ichnofacies. The surface is overlain by a stillstand shoreface succession. Viking Formation, Joffre Field, 09-15-39-27W4, depth 1550.7 m. **(C)** Thoroughly burrowed silty shales of the lower offshore are cross-cut by sand-filled *Thalassinoides* (Th) of the *Glossifungites* ichnofacies, subtending from a TSE (*cf.* Downing and Walker, 1988). The surface is overlain by a stillstand shoreface succession. Viking Formation, Joffre Field, 14-11-39-27W4, depth 1572.3 m.


Th
Th
A
B

underlying Kap Stewart consists of delta plain rooted sandstones, mudstones, and coals (Figure II-13). An erosional discontinuity and associated pebble lag mark the contact with the overlying Neill Klinter Formation. The contact is penetrated by a monospecific assemblage of abundant *Diplocraterion parallelum*, which subtend into the underlying mudstones and coals, constituting the *Glossifungites* and *Teredolites* ichnofacies, respectively. The overlying deposits consist of pebble conglomerates passing into cross-bedded sandstones containing abundant reactivation surfaces, mud drapes, and shale clasts along foresets. The sandstones contain *Diplocraterion, Ophiomorpha, Gyrochorte, Monocraterion,* and *Rhizocorallium,* and are interpreted as foreshore ridges. The erosional discontinuity corresponds to a ravinement surface cut along a subaerial exposure surface (FS/SB) associated with the early Pliensbachian transgression. Preservation of the omission suite suggests that minimal scouring and reworking of the underlying delta plain sediments occurred during continued transgression and emplacement of the overlying transgressive lag.

The Cenomanian Dunvegan Formation in the subsurface of the Jayar Field, central Alberta, contains a similar FS/SB, cut into rooted and subaerially exposed delta plain deposits (Bhattacharya and Walker, 1991; *cf.* Table II-1). The erosional discontinuity is demarcated by a *Glossifungites* suite of *Thalassinoides*, passively filled with coarse-grained sands infiltrated from an overlying transgressive sand sheet (Figure II-14 C). The discontinuity constitutes the boundary between Allomember B and C of the Dunvegan Alloformation (Bhattacharya, 1989; Bhattacharya and Walker, 1991). Oppelt (1988; *cf.* Table II-1) noted a similar relationship at the Gething/Bluesky contact in northeastern British Columbia. An excellent example of this also occurs at the Mannville Group-Joli Fou Formation contact in the Kaybob Field of central Alberta, where rooted paleosols are cross-cut by robust firmground *Thalassinoides*, passively filled with muddy sand and large sideritic clasts (Figure II-14 A, B). The overlying silty shales record deposition in proximal shelf to lower offshore conditions, with *Planolites, Helminthopsis, Terebellina,* rare *Chondrites* and very rare *Zoophycos*.

Areas marginal to incised valley systems correspond to interfluves which are subaerially exposed during lowstand excavation of the valley and late lowstand valley infill. In the Viking Formation, these interfluves are generated on original fully marine regional Viking Formation offshore to

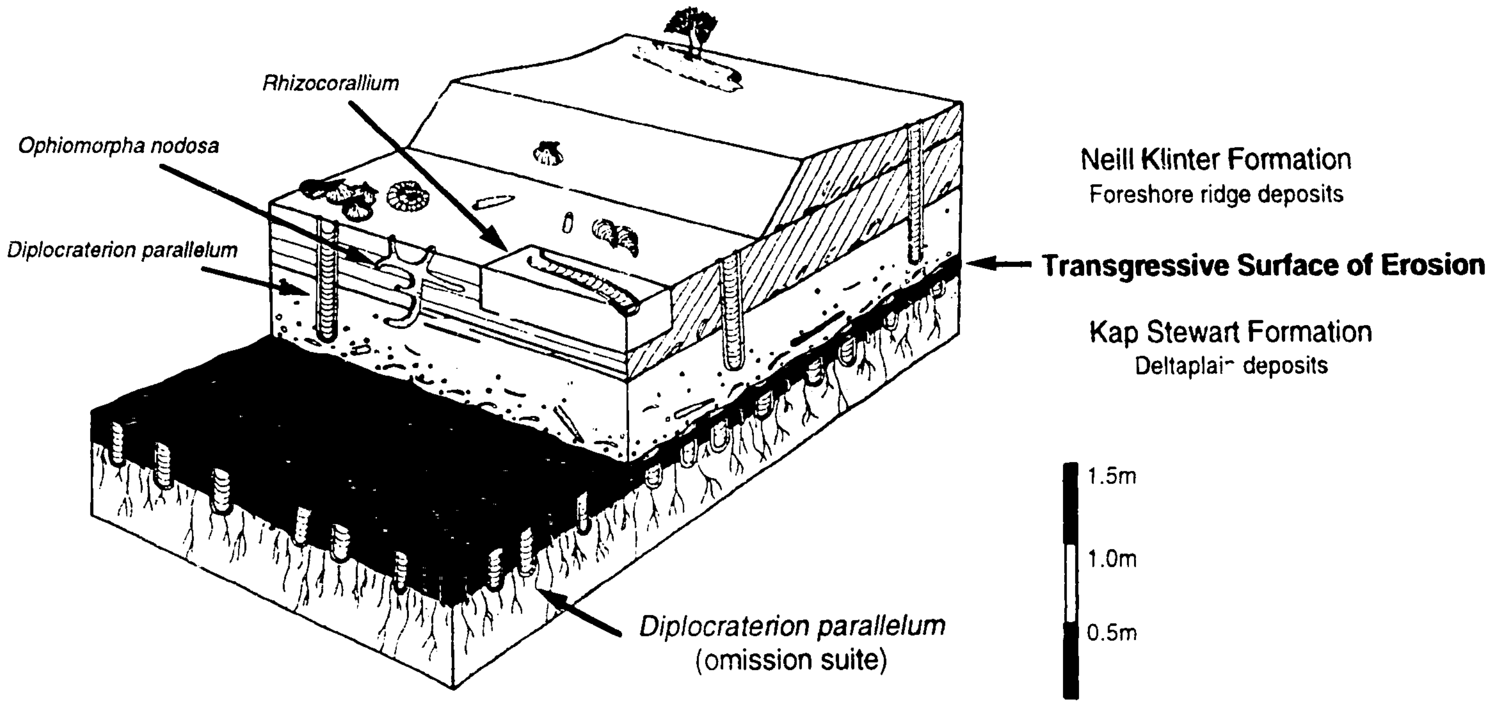
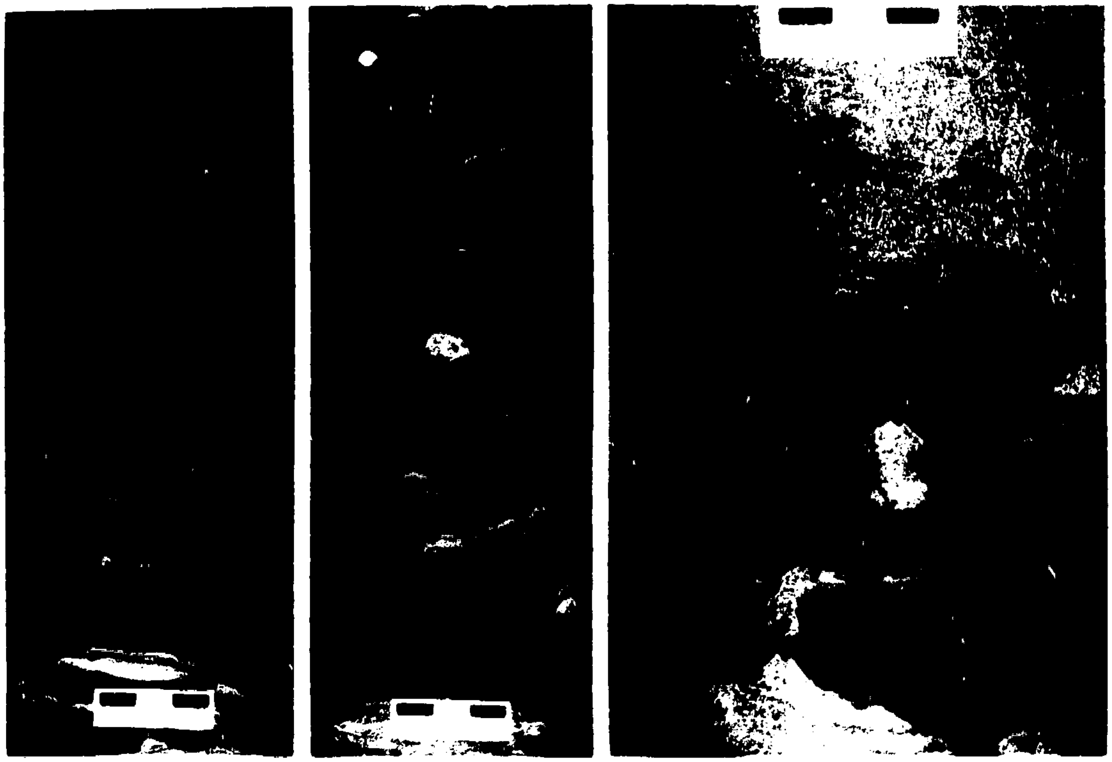


Figure II-13. Co-planar surface of lowstand (subaerial) exposure and transgressive erosion (FS/SB) in the Jameson Land Basin of East Greenland, marked by *Glossifungites* assemblage. Lower Jurassic deltaplain rooted mudstones and coals of the Kap Stewart Formation reflect subaerial exposure, followed by transgressive erosion. A monospecific assemblage of abundant *Diplocraterion parallelum* penetrate the erosion surface, corresponding to the *Glossifungites* assemblage (modified after Dam, 1990).

Figure II-14. Co-planar Surfaces of Lowstand Exposure (subaerial exposure) and Transgressive Erosion (FS/SB), Marked by the *Glossifungites* Ichnofacies. **(A & B)** Rooted paleosol, truncated by a transgressive lag consisting of chert and lithic pebbles, and intraformational detritus. The co-planar surface is demarcated by a robust *Thalassinoides* (Th) network corresponding to the *Glossifungites* ichnofacies. Mannville Group-Joli Fou Formation contact, Kaybob South, 11-03-60-19W5, depth 1894.2 m. **(C)** Rooted and subaerially exposed delta plain deposits truncated by TSE, overlain by a transgressive sand sheet. The erosional discontinuity, corresponding to the contact between Allomember B and C of Bhattacharya and Walker (1991), is marked by a robust *Thalassinoides* (Th) system of the *Glossifungites* ichnofacies. Dunvegan Formation, Jayar Field, 06-11-62-03W6, depth 2523.6 m.



lower shoreface deposits. When the valley is ultimately filled and transgressively overrun, a high energy flooding surface is commonly generated on the interfluve, which removes any evidence of exposure. Differentiating this from pure transgressive erosion is impossible, until placed into regional context. In other localities, the FS/SB may not even appear to reflect deepening, such as where the interfluve is cut into lower offshore or shelfal deposits of a regional Viking parasequence and is overlain by lower or upper offshore shales. In such settings, recognition of the nature of the surface may hinge on the delineation of the associated incised valley fill deposits.

Transgressively-Modified Incised Valley Margins

Five Viking Formation fields, namely Crystal, Willesden Green, Sundance, Edson, and Cyn-Pem, contain facies associations interpreted to reflect estuarine incised valley deposition (Figure II-15; *cf.* Reinson, 1988; Boreen and Walker, 1989; Pattison, 1991b, 1992; Pemberton *et al.*, 1992c; MacEachern and Pemberton, in press). The observed facies types and their distributions indicate that they accumulated in a barrier estuary or wave-dominated embayed estuary setting, in the sense of Roy *et al.* (1980) and Dalrymple *et al.* (1992).

The valley fill deposits demonstrate a tripartite zonation of facies and facies associations, defining three major depositional zones within the estuary (Figure II-16). The bay head delta complex is sand-dominated and formed at the head of the estuary, where much of the sediment is fluvially-derived, though commonly wave reworked. The central basin complex grades seaward out of the bay head delta complex and into the estuary mouth complex, and is a zone of interference between marine and fluvial processes. The central basin corresponds to the lowest energy zone of the estuary. The estuary mouth complex occurs seaward of the central basin and is sand-dominated. Marine processes (waves and tidal currents) are responsible for transport and deposition of the sediment. A fourth depositional complex reflects channel deposition, corresponding to migration of tidal inlets and distributaries, or to periods of channel re-incision and fill.

The FS/SB of the valley margins are excavated into the coarsening upward, regional Viking silty shales, sandy shales and muddy sandstones of the underlying highstand parasequence sets. These intervals contain fully

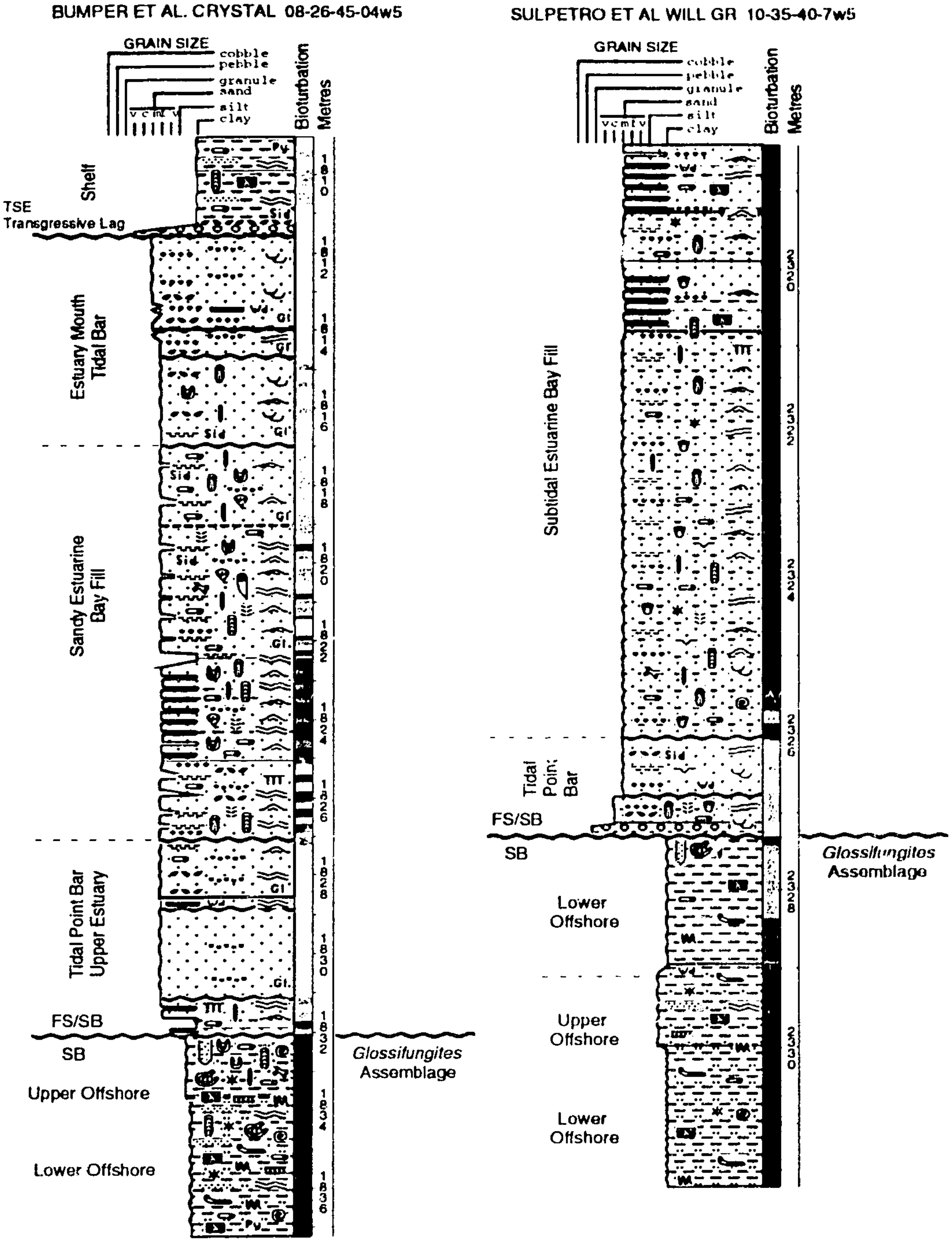


Figure II-15. *Glossifungites*-demarcated co-planar surfaces of lowstand erosion and transgressive erosion (FS/SB) associated with incised valley fills. Lithologs illustrate similar surfaces in the Viking Formation at Crystal and Willesden Green. The legend of symbols used in the lithologs occurs in Figure II-7.

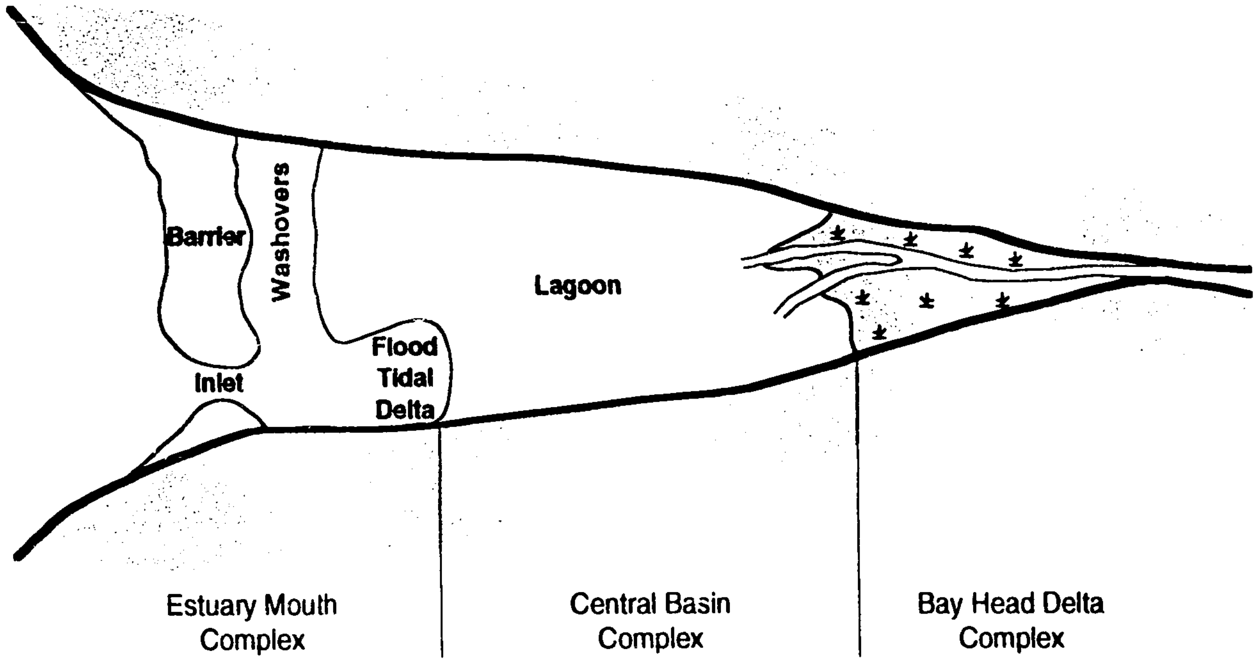


Figure II-16. Conceptual Model for Wave-Dominated, Embayed Estuarine Depositional Systems. The model best explains the distribution of observed facies and facies associations in the Viking Formation incised valley fills. The system demonstrates a tripartite zonation of facies, corresponding to three main depositional complexes: the bay head delta, the central basin and the estuary mouth. The model is based on observations of embayed estuary systems along the New South Wales coast of Australia, by Roy *et al.* (1980). Figure is modified after Dalrymple *et al.* (1992).

marine, high diversity and abundant distal to proximal *Cruziana* softground suites, commonly consisting of *Terebellina, Chondrites, Thalassinoides, Teichichnus, Planolites, Helminthopsis, Anconichnus, Rosselia, Asterosoma, Palaeophycus, Arenicolites, Ophiomorpha, Cylindrichnus, Schaubcylindrichnus, Siphonichnus,* and rare *Zoophycos,* in marked contrast to the stressed assemblages of the valley-fill successions (MacEachern and Pemberton, in press; Pemberton and MacEachern, in press; *cf.* Chapter IX).

In the Crystal Field, the FS/SB is marked by the *Glossifungites* ichnofacies, manifest by numerous sharp-walled, unlined *Diplocraterion* shafts (Figure II-17 B), firmground *Thalassinoides, Diplocraterion habichi,* and firmground *Gastrochaenolites* (Figure II-17 C). In the Willesden Green field, the valley base is locally marked by a *Glossifungites* assemblage consisting of spectacular *Rhizocorallium saxicava* (Figure II-17 D, E), *Thalassinoides* (Figure II-17 F), *Arenicolites, Skolithos* and *Diplocraterion habichi.* The valley surfaces in the Sundance and Edson fields are only rarely demarcated by firmground *Thalassinoides,* while the valley margin at the Cyn-Pem field is locally marked by abundant firmground *Arenicolites* and *Skolithos.*

In many incised valley-fills, determining whether the fill is associated with lowstand (fluvial) conditions, or with the ensuing transgression may, in part, be resolved by trace fossil analysis. In the Viking Formation examples where the base of the incised valley is marked by a *Glossifungites* assemblage, it follows that either the valley did not fill until the ensuing transgression, or the colonised portion of the valley margin occurred only near the mouth of the estuary. This may be resolved by mapping the distribution of trace fossils at the incised lower contact of the valley across the entire field. In contrast, Savrda (1991a) studied the Paleocene Clayton Formation at Moscow Landing, Alabama and found that the incised valley-fill of the lowstand systems tract did not possess a substrate-controlled assemblage at its base (Figure II-18). The basal "Clayton sands", consisting of medium- to coarse-grained, laminated to massive calcite-cemented sandstones with subordinate sandy marls, rested unconformably upon the Upper Cretaceous Prairie Bluff Chalk. The lower 1.6 m of the fill is unburrowed, but the overlying sandy marls become burrowed with abundant softground *Thalassinoides suevicus.* The burrows comprise large, predominantly horizontal boxworks, with diameters of 3-10 cm and burrow segments up to 1 m in length. The upper part of the valley-fill was interpreted as marine or marginal-marine influenced (Savrda,

Figure II-17. Co-planar Surfaces of Lowstand Erosion and Transgressive Erosion (FS/SB) Associated with Incised Valleys. (A & B) Crystal Field, 08-26-45-04W5. **A)** Boxshot (1831.2-1835.8 m) shows thoroughly burrowed, lower offshore silty shales coarsening upward into upper offshore sandy shales of a regionally extensive Viking Formation parasequence, erosionally truncated by interbedded sandstones and shales of the Central Basin complex (arrow). 15 cm scale is present in the lower left of photo. Core is read from base at lower left (B) to top at upper right (T). **(B)** The contact (1832 m) shows a *Cruziana* (softground) assemblage, cross-cut by muddy, sand-filled *Diplocraterion* (D) of the *Glossifungites* ichnofacies. **(C)** The Crystal valley surface is also marked by firmground *Gastrochaenolites* in the 04-01-46-04W5 well, at a depth of 1804.7 m. **(D & E)** Willesden Green Field, 10-35-40-07W5. **(D)** Boxshot (2326.2-2329.8 m) shows a coarsening upward parasequence near the base, capped by a low energy marine flooding surface (LE FS), passing into shelfal to lower offshore silty shales. These are erosionally-truncated by pebbly sandstones and conglomerates of the Estuary Mouth complex (arrow). 15 cm scale is present in the lower left of photo. Core is read from base at lower left (B) to top at upper right (T). **(E)** The contact (2327 m) is marked by robust *Rhizocorallium saxicava* of the *Glossifungites* assemblage. **(F)** The Willesden Green valley surface is marked by *Diplocraterion* and *Thalassinoides* (Th) of the *Glossifungites* ichnofacies in the 11-31-40-6W5 well, at a depth of 2285.8 m. Note the *Ophiomorpha* in the sandstone of the overlying Channel-fill complex, attesting to a marine influence on valley fill.


B
3cm
C
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B
E

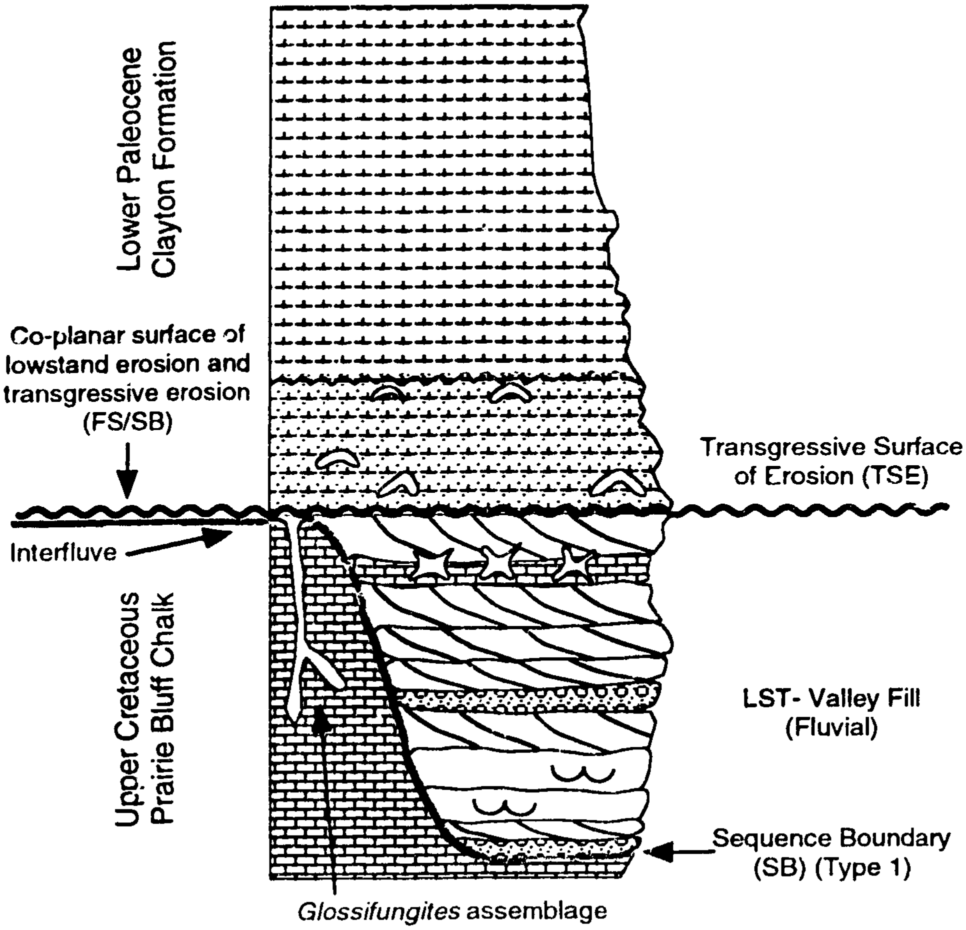

Figure II-18. Lowstand fluvial valley fill with an overlying TSE. The Cretaceous Prairie Bluff Chalk of Moscow Landing, Alabama contains an incised valley complex, initially filled with Paleocene fluvial lowstand deposits of the Clayton Fm. The fill becomes marine influenced upwards, related to ensuing transgression. A TSE is cut across the top of the valley fill and becomes co-planar with the lowstand surface at the interfluve. Only this FS/SB possesses a *Glossifungites* assemblage, consisting of *Thalassinoides paradoxicus* / *Spongeliomorpha* where the firm substrate was subjected to marine conditions (modified after Savrda, 1991a).

1991a), but the initial basal sandy fill may support initial, fluvial, lowstand valley fill. Where the Cretaceous-Tertiary unconformity (identified as a Type 1 unconformity by Savrda, 1991a) is not covered by incised valley-fill deposits, an overlying transgressive surface of erosion is amalgamated with it, and contains a *Glossifungites* suite of *Thalassinoides paradoxicus* and *Spongeliomorpha*, possessing a strong vertical component which penetrate up to 1m into the underlying Cretaceous chalk. This generally corresponds with interfluve areas. The firmground suite appears to be a result of subaerial exposure and erosional exhumation of the chalk during lowstand conditions and subsequent marine colonisation during the ensuing transgression (Savrda, 1991a). The absence of this substrate-controlled ichnofacies at the base of the valley-fill supports initial fluvial deposition within the valley.

SUMMARY

To date, substrate-controlled ichnofacies have been under-utilised as a means of recognising and mapping stratigraphically important surfaces in outcrop and subsurface. Locally, many surfaces are obvious on the basis of sedimentology alone, however, the character of such surfaces can markedly change with geography, making correlation difficult. Substrate-controlled ichnofacies are another useful tool that the stratigrapher can introduce into his repertoire of analytical skills to improve his chances of determining discontinuity equivalence in genetic stratigraphic studies. The *Glossifungites* ichnofacies is proving to be exceedingly important in the recognition and genetic interpretation of erosional discontinuities in marine-influenced siliciclastic intervals. Many of the examples cited in this paper deal with their applications to the Cretaceous of the Western Canada Sedimentary Basin, but the suite has been recognised to demarcate discontinuity surfaces ranging from the Ordovician to the Holocene. In many cases, the current interpretation as to the genesis of the discontinuity has come principally from the introduction of ichnological analysis, centering on the ichnofossil assemblages associated with the underlying deposits, the discontinuity itself, and the overlying units. Although some stratigraphically significant surfaces have required re-interpretation as to their genesis, the recognition of the surface as a discontinuity has not changed; ultimately, this remains the essential element in genetic stratigraphic analysis. The continued integration of substrate-controlled ichnofacies with detailed stratigraphic and sedimentologic analysis will undoubtedly enhance and refine developing genetic stratigraphic paradigms.

Caution must be employed when applying *Glossifungites*-demarcated discontinuity surfaces to regional stratigraphic problems. Some *Glossifungites* suites may mark surfaces which have been generated autocyclically (*e.g.* Bromley *et al.*, 1984; Jones and Pemberton, 1989). Determination of the stratigraphic significance of an erosional discontinuity requires the thorough integration of stratigraphic, sedimentologic, paleontologic, and ichnologic analysis. Ichnology is proving to be an exceedingly useful tool in this endeavour.

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CHAPTER III

THE SEQUENCE STRATIGRAPHIC SIGNIFICANCE OF TRACE FOSSILS: EXAMPLES FROM THE CRETACEOUS FORELAND BASIN OF ALBERTA, CANADA[2]

INTRODUCTION

Stratigraphy, once considered to be a somewhat routine and mundane discipline, consisting mainly of the dry cataloguing of lithostratigraphic units, has recently undergone a dramatic renaissance. During the last decade, stratigraphers have radically altered how the rock record is perceived and therefore interpreted. Once almost exclusively the domain of biostratigraphers and geochronologists, the stratigraphic column has been subjected to new ideas and methods. A synergistic approach has resulted in the development and refinement of new stratigraphic tools such as seismic stratigraphy, allostratigraphy, tephrastratigraphy, magnetostratigraphy, eco-stratigraphy, event stratigraphy, and of course, sequence stratigraphy.

The stratigraphic utility of trace fossils can take on many guises and their significance varies depending on what stratigraphic paradigm one is employing. In the past, trace fossils were considered to be almost useless in stratigraphy because: (a) most have long temporal ranges; (b) they are largely facies dependent; (c) a particular structure may be produced by the work of two or more different organisms living together, or in succession, within the structure; (d) the same individual or species of organism may produce different structures corresponding to different behaviour patterns; (e) the same individual may produce different structures corresponding to identical behaviour but in different substrates, (*e.g.* in sand, in clay, or at sand-clay interfaces); and (f) identical structures may be produced by the activity of systematically different trace-making organisms, where behaviour is similar

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[2] A version of this chapter has been accepted for publication. Pemberton, S.G. and J.A. MacEachern, in press. *In*: J.C. Van Wagoner and G. Bertram (eds.), Sequence Stratigraphy of Foreland Basin Deposits- Outcrop and Subsurface Examples from the Cretaceous of North America. American Association of Petroleum Geologists, Memoir.

(Ekdale *et al.*, 1984). These factors combine to make their biostratigraphic value negligible. Traditionally, it was thought that there were only three ways in which trace fossils could be utilised in chronostratigraphy: (1) tracing the evolution of behaviour; (2) as morphologically-defined entities (with no assumptions concerning their genesis); and (3) as substitutes for the trace-making organisms (Magwood and Pemberton, 1990). In contrast, trace fossils are proving to be one of the most important groups of fossils in delineating stratigraphically important boundaries related to sequence stratigraphy (MacEachern *et al.*, 1991a,b, 1992a,b; Savrda, 1991a,b), allostratigraphy (Pemberton *et al.*, 1992a), and event stratigraphy (Frey and Goldring, 1992; Pemberton *et al.*, 1992b).

Facies analysts have generally found it difficult to reconcile sedimentologic observations with lithostratigraphic frameworks. In recent years, stratigraphers have moved away from lithostratigraphic analysis and have approached the rock record in terms of genetic stratigraphy. Genetic stratigraphy lies at the core of three main stratigraphic paradigms: Genetic Stratigraphic Sequences (Galloway, 1989a,b), Allostratigraphy (NACSN, 1983), and Sequence Stratigraphy (Wilgus *et al.*, 1988; Van Wagoner *et al.*, 1990).

No matter which stratigraphic paradigm is utilised, the recognition of stratigraphic breaks is of paramount importance and is commonly a difficult task, particularly in subsurface analysis. The stress on discontinuities emphasises processes that are external to the depositional system itself (allocyclic) and which may initiate or terminate deposition of sedimentologically-related facies successions (Walker, 1990). Delineation of the origin of the discontinuity is vital in resolving depositional environments and in determining the characteristics of allocyclic controls on depositional systems. Trace fossils and trace fossil suites can be employed effectively both to aid in the recognition of various types of discontinuities and to assist in their genetic interpretation. This method requires an integrated approach, employing diverse stratigraphic, sedimentologic, and paleontologic techniques.

CONCEPTUAL FRAMEWORK OF ICHNOLOGY APPLIED TO SEQUENCE STRATIGRAPHY

Trace fossils (other than borings) are both sedimentologic and paleontologic entities, and therefore represent a unique blending of potential environmental indicators in the stratigraphic record. The conceptual framework of ichnology has been discussed in considerable detail in Ekdale *et al.* (1984) and Pemberton *et al.* (1992a,c). Like physical sedimentary structures, trace fossils reflect many of the effects of environmental parameters prevailing during deposition, and to an appreciably greater extent than body fossils, are a record of the behaviour of active, *in situ* organisms. The behavioural record of benthic organisms, as dictated or modified by environmental constraints, is thus the mainstay of ichnology. Biogenic structures appear in many guises (Frey and Pemberton, 1985), but in paleoenvironmental analysis the main concern is with tracks, trails, burrows, and borings. The ultimate objective is to portray the facies implications of these various structures.

Ethological Classification of Trace Fossils

Unique classification schemes have been developed in order to decipher trace fossils, because they represent behaviour rather than actual body remains. Historically, trace fossils have been classified in descriptive, preservational taxonomic and behavioural terms. Of these, the behavioural (or ethological) scheme is by far the most important; the behavioural record of benthic organisms is dictated and modified not only by genetic preadaptations but also by prevailing environmental parameters.

Ekdale *et al.* (1984), recognised seven basic categories of behaviour; resting traces (cubichnia), locomotion traces (repichnia), dwelling structures (domichnia), grazing traces (pascichnia), feeding burrows (fodinichnia), farming systems (agrichnia), and escape traces (fugichnia). Ekdale (1985) added predation traces (praedichnia) and Frey *et al.* (1987) further emphasised the importance of equilibria (fugichnia) to all other behavioural patterns.

Such fundamental behavioural patterns, although genetically-controlled, are not phylogenetically restricted. The basic ethological categories, for the most part, have persisted throughout the Phanerozoic (Hiscott *et al.*, 1984).

Individual tracemakers have evolved, but basic benthic behaviour has not. For example, deposit feeders are preadapted to quiescent environments where deposited foodstuffs are most abundant; therefore, they do not fare well in turbulent-water settings. The opposite is true of suspension feeders. Similarly, locomotion traces can be preserved only under a strict set of environmental conditions. The ability to discern behavioural trends of benthic organisms represented in the rock record greatly facilitates environmental interpretations.

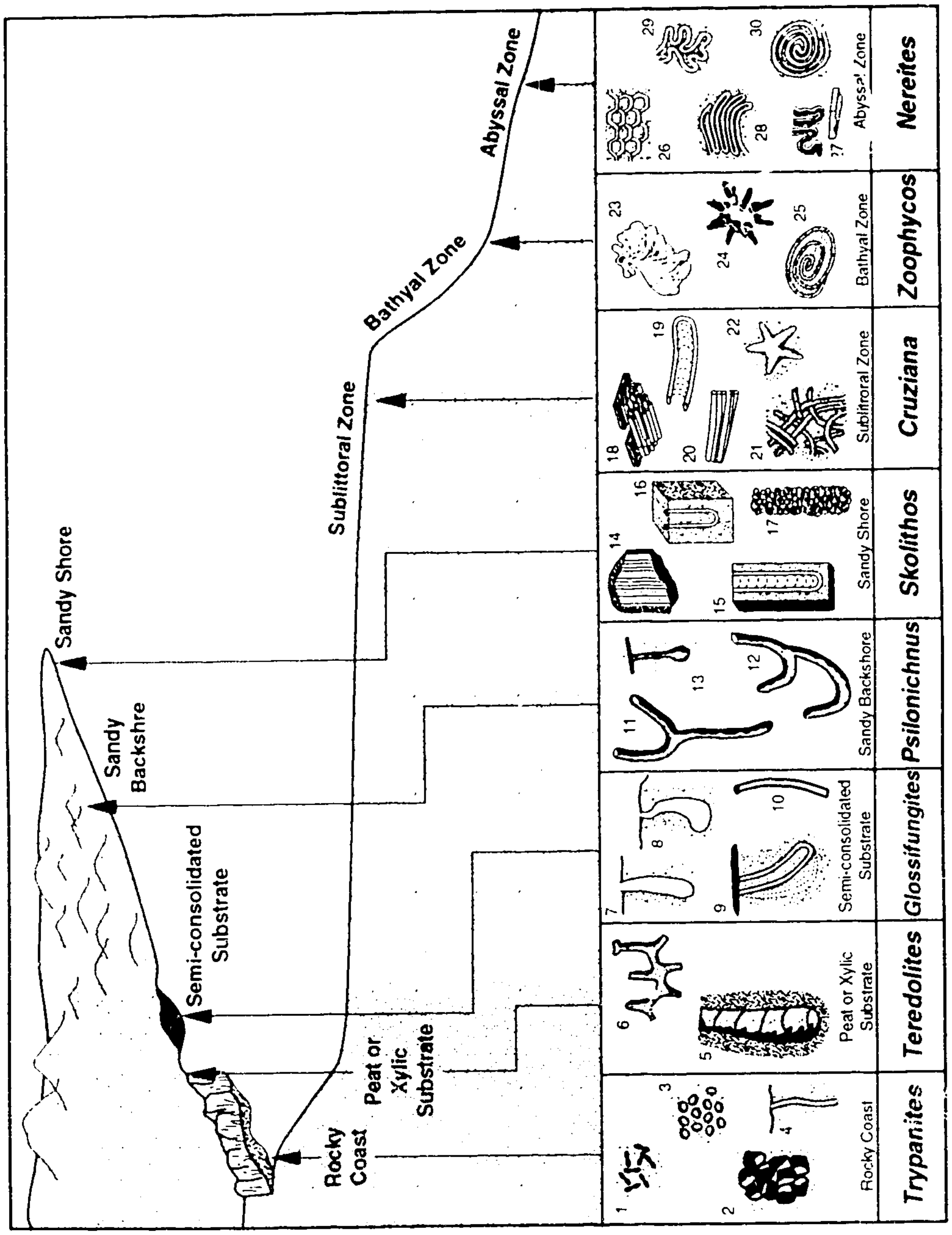
The Ichnofacies Concept

Perhaps the essence of trace fossil research involves the grouping of characteristic ichnofossils into recurring ichnofacies. This concept, developed by Adolf Seilacher in the 1950's and 1960's, was based originally on the observation that many of the parameters that control the distribution of tracemakers tend to change progressively with increased water depth (Figure III-1).

Because of the potential geological value of this bathymetric relationship (Figure III-1), the Seilachernian ichnofacies concept soon came to be regarded almost exclusively (albeit erroneously) as a relative paleobathymeter. Today, these ichnofacies remain valuable in environmental reconstructions, but paleobathymetry is only one aspect of the modern ichnofacies concept (Frey *et al.*, 1990).

Ichnofacies are part of the total aspect of the rock, are the result of the original conditions of deposition, and like lithofacies, are subject to Walther's Law. Further, isolated bored shells or clasts do not in themselves constitute the *Trypanites* ichnofacies. Rather, there should be some semblance of stratification, lateral continuity, and vertical succession, in keeping with the concept of facies. This relation is another strength of ichnology, however; interpretations of ichnofaunas are improved substantially when the traces are studied in the context of the host rocks and their implications.

Figure III-1. Synoptic diagram illustrating recurring marine ichnofacies, placed in a representative, but not exclusive, suite of environmental gradients (*cf.* Seilacher, 1967). Local physical, chemical, and biological factors ultimately determine which traces occur at which sites. Typical trace fossils include 1) *Caulostrepsis*; 2) *Entobia*; 3) echinoid borings, unnamed; 4) *Trypanites*; 5) *Teredolites*; 6) *Thalassinoides*; 7, 8) *Gastrochaenolites* or related ichnogenera; 9) *Diplocraterion* (*Glossifungites*); 10) *Skolithos*; 11, 12) *Psilonichnus*; 13) *Macanopsis*; 14) *Skolithos*; 15) *Diplocraterion*; 16) *Arenicolites*; 17) *Ophiomorpha*; 18) *Phycodes*; 19) *Rhizocorallium*; 20) *Teichichnus*, 21) *Planolites*; 22) *Asteriacites*; 23) *Zoophycos*; 24) *Lorenzinia*, 25) *Zoophycos*; 26) *Paleodictyon*; 27) *Taphrhelminthopsis*; 28) *Helminthoida*; 29) *Cosmorhaphe*; 30) *Spirorhaphe*. Modified from Frey and Pemberton (1985).


Rocky Coast
Peat or Xylic Substrate
Semi-consolidated Substrate
Sandy Backshre
Sandy Shore
Sublittoral Zone
Bathyal Zone
Abyssal Zone
1
2
3
4
Rocky Coast
Trypanites
5
6
Peat or Xylic Substrate
Teredolites
7
8
9
10
Semi-consolidated Substrate
Glossifungites
11
12
13
Sandy Backshore
Psilonichnus
14
15
16
17
Sandy Shore
Skolithos
18
19
20
21
22
Sublittoral Zone
Cruziana
23
24
25
Bathyal Zone
Zoophycos
26
27
28
29
30
Abyssal Zone
Nereites

Archetypal Ichnofacies

Nine recurring ichnofacies have been recognised, each named for a representative ichnogenus: *Scoyenia, Trypanites, Teredolites, Glossifungites, Psilonichnus, Skolithos, Cruziana, Zoophycos* and *Nereites*. These trace fossil associations reflect adaptations of tracemaking organisms to numerous environmental factors such as substrate consistency, food supply, temperature, hydrodynamic energy, salinity and oxygen levels (Frey and Pemberton 1984; Frey *et al.*, 1990). Traces in nonmarine assemblages (other than in the *Scoyenia* settings) are in need of further refinement; the marine softground ichnofacies (*Psilonichnus, Skolithos, Cruziana, Zoophycos,* and *Nereites*) are distributed according to numerous environmental parameters; traces in the firmground (*Glossifungites*), woodground (*Teredolites*), and hardground (*Trypanites*) ichnofacies are distributed on the basis of substrate type and consistency.

Representative occurrences of the various ichnofacies are summarised below, however, each may appear in other settings, as dictated by characteristic sets of recurrent environmental parameters. From the standpoint of ethological requirements of tracemaking organisms, for example, certain intertidal backbarrier environments are not significantly different from certain subtidal forebarrier environments, and may contain virtually identical suites of trace fossils.

Contrary to a popular misconception, the *Scoyenia* ichnofacies is only one of many nonmarine ichnofacies and is, itself, quite distinctive (Frey and Pemberton, 1985; Bromley and Asgaard, 1991). Furthermore, prospects for the recognition of additional archetypal nonmarine ichnofacies remain encouraging. For example, Ekdale *et al.* (1984) and Frey and Pemberton (1987) noted that distinct suites of trace fossils characterise eolian dunes, fluvial overbanks, paleosols, and lake environments.

The *Psilonichnus* ichnofacies is associated with supralittoral/upper littoral, moderate to low-energy marine and/or eolian conditions typically found in beach to backshore to dune environments. The comments by Bromley (1990) and Bromley and Asgaard (1991) notwithstanding, the *Psilonichnus* ichnofacies was founded on fossil examples (Frey and Pemberton, 1987), and is no more theoretical than any other recurrent ichnofacies. The modern ichnocoenoses were emphasised to show the richness that one might reasonably expect to have existed for various ancient ichnofaunas. Furthermore, one of the major tenets of ichnofacies reconstruction is that the name-bearer need not be present in every occurrence of the ichnofacies; thus, just as *Cruziana* are rare in post-Paleozoic occurrences of the *Cruziana* ichnofacies, *Psilonichnus* may well be absent in pre-Mesozoic occurrences of the *Psilonichnus* ichnofacies.

The *Skolithos* ichnofacies is generally associated with high-energy, sandy, shallow-marine environments. The trace fossils are characterised by: (1) predominantly vertical, cylindrical or U-shaped burrows; (2) few horizontal structures; (3) few structures produced by mobile organisms; (4) low diversity, although individual forms may be abundant; and (5) mostly dwelling burrows constructed by suspension feeders or passive carnivores.

The *Cruziana* ichnofacies is typically associated with marine substrates lying below minimum wave base and above maximum wave base. The trace fossils are characterised by a number of features, including: (1) a mixed association of vertical, inclined, and horizontal structures; (2) the presence of traces constructed by mobile organisms; (3) generally high diversity and abundance; and (4) mostly feeding and grazing structures constructed by deposit feeders, except where crawling traces are predominant.

The *Zoophycos* ichnofacies ideally is found in shelfal to bathyal, quiet-water marine muds or muddy sands, lying below maximum wave base to fairly deep water, in areas free of turbidity flows and subject to oxygen deficiencies. The trace fossils are characterised by: (1) low diversity, though individual traces may be abundant; (2) grazing and feeding structures produced by deposit feeders; and (3) horizontal to gently inclined spreiten structures. However, the ichnofacies also may occur in restricted intracoastal settings, particularly in Paleozoic intervals. The ichnogenus *Zoophycos* is present in deeper water environments in Mesozoic and Cenozoic deposits than in Paleozoic deposits (Frey and Pemberton, 1984). Hence, the character of the *Zoophycos* ichnofacies may vary from one part of the stratigraphic column to the next.

The *Nereites* ichnofacies typically is associated with bathyal/abyssal, low-energy, oxygenated marine environments subject to periodic turbidity flows. The trace fossils are characterised by: (1) high diversity but low abundance; (2) complex horizontal grazing traces and patterned feeding/dwelling structures; (3) numerous crawling/grazing traces and sinuous faecal castings; and (4) structures produced by deposit feeders, scavengers, or possibly harvesters (Ekdale *et al.*, 1984). As presently understood, the *Nereites* ichnofacies is restricted primarily to flysch or turbidite successions; sediments in the great expanses of seafloor beyond influence of turbidity flows consist chiefly of bioturbate textures rather than discrete traces (Frey and Wheatcroft, 1989). Hence, there is no well-preserved record of these specific ichnocoenoses.

The remaining three ichnofacies are specialised, substrate-controlled suites and, environmentally, are very general in scope, although typically marine or marginal marine in character. The *Glossifungites* ichnofacies (Figure III-2) develops in firm but unlithified substrates (*i.e.* dewatered muds). Such substrates can dewater as a result of burial and are made available to tracemakers if exhumed by later erosion (Pemberton and Frey, 1985). Exhumation can occur in shallow-water environments as a result of coastal erosion processes or from submarine channels cutting through previously deposited sediments. Other substrates may reflect subaerial exposure prior to onset of marine conditions. Such horizons may prove to be critical sequence stratigraphic breaks in the rock record.

The *Trypanites* ichnofacies characterises fully lithified marine substrates such as hardgrounds, reefs, rocky coasts, beachrock, unconformities, and other kinds of omission surfaces. The ichnofacies may develop even on igneous substrates (Fischer, 1981), and the collective volume of bioeroded sediments may be substantial (Torunski, 1979).

The *Teredolites* ichnofacies, on the other hand, encompasses a characteristic assemblage of borings in mostly marine or marginal marine influenced xylic (woody) substrates. The latter differ from lithic substrates in three main ways (Bromley *et al.*, 1984): (1) they may be flexible instead of rigid; (2) they are composed of organic material instead of mineral matter; and (3) they are readily biodegradable. Woodgrounds may appear in freshwater settings (*e.g.* logjams in fluvial cutoffs), but wood-boring bivalves (shipworms) do not; freshwater examples of this ichnocoenose consist principally of isopod and allied borings. Furthermore, one should discern whether the woodground borings are autochthonous (Arua, 1989) or allochthonous (Dewey and Keady, 1987); only the former are true members of the *Teredolites* ichnofacies. Such assemblages also may be of considerable importance in defining sequence and parasequence boundaries.

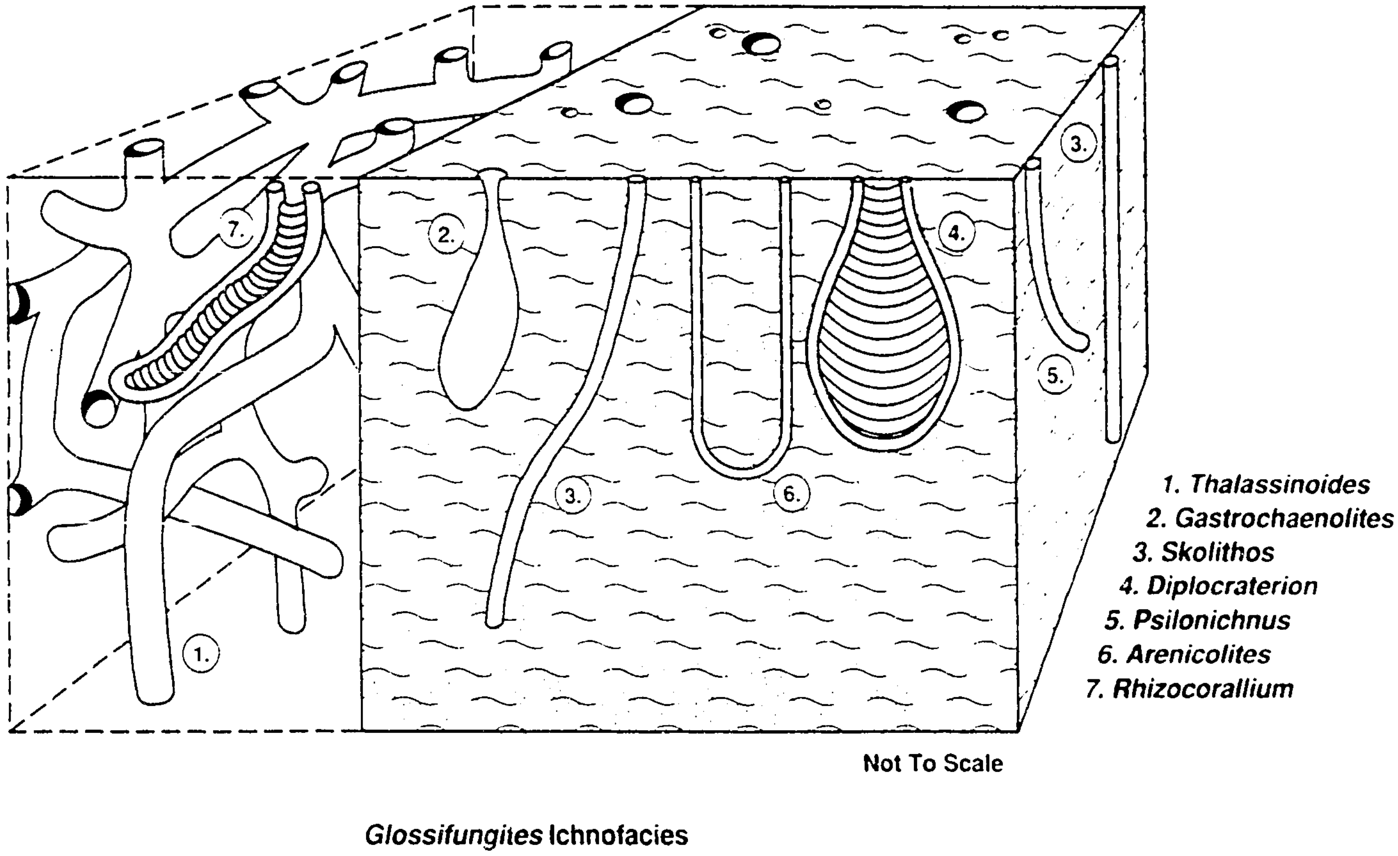


Figure III-2. Trace fossil association characteristic of the *Glossifungites* ichnofacies (modified from Frey and Pemberton, 1984).

Evaluation of the Ichnofacies Models

Ichnofacies stand today as one of the most elegant but also most widely misunderstood concepts in ichnology, especially where paleobathymetry is concerned (Frey *et al.*, 1990). Marine ichnofacies are not intended to be paleobathymeters; rather, they are archetypal facies models based upon recurring ichnocoenoses (Seilacher, 1967, 1978; Frey and Pemberton, 1984, 1985). If a particular ichnocoenose tends to occur repeatedly within a given bathymetric setting, so much the better, but water depth *per se* is rarely, if ever, a governing factor. Ichnofacies, therefore, are best viewed in the context of actual deposition.

One of the most fundamental tenets of modern ichnofacies analysis is that all available evidence - physical, chemical or biological - should be integrated and utilised in interpretations. For bathymetric assessments, those collective observations should be placed in the context of proximality trends, whether emphasised from a sedimentologic viewpoint (Nittrauer *et al.*, 1984; Clifton, 1988) or an ichnological one (Crimes, 1973; Wetzel, 1981; Howard and Frey, 1984). Associations between, and configurations of, biogenic and physiogenic sedimentary structures are powerful combinations in the reconstruction of environmental gradients (Wightman *et al.*, 1987; Moslow and Pemberton, 1988); they are especially useful where otherwise prevalent trends have been modified by episodic events or other environmental fluctuations (Pemberton and Frey, 1984; Frey, 1990; Frey and Goldring, 1992; Pemberton *et al.*, 1992b).

Numerous authors have noted occurrences of certain ichnofacies in settings outside the zone specified in the original paradigm (Figure III-1), and have used these discrepancies as an argument against the validity or usefulness of the overall ichnofacies concept. For instance, if each shoreline involved only a "normal" beach-to-offshore trend, then the classic onshore *Skolithos* ichnofacies would indeed give way to the offshore *Cruziana* ichnofacies, virtually without exception. But in many settings, the nearshore zone includes bays, lagoons, estuaries, deltas and tidal flats, and the offshore zone includes bars, shoals, submarine canyons, or ridges or other features that might disrupt the "normal trend". For similar reasons, the *Skolithos* ichnofacies may appear on proximal parts of deep-sea fans (Crimes, 1977; Crimes *et al.*, 1981) or the *Zoophycos* ichnofacies may appear in silled marine basins or restricted lagoons (Miller, 1991).

In short, the idealised ichnofacies succession works well in "normal" situations (Frey and Pemberton, 1984); yet one should not be surprised to find nearshore assemblages in offshore sediments, and *vice-versa,* if these accumulated under conditions otherwise like those preferred by the trace-making organisms (Frey *et al.,* 1990). The basic consideration rests not with such inanimate backdrops as water depth or distance from shore, or some particular tectonic or physiographic settings, but rather with such innate, dynamic controlling factors as substrate consistency, hydraulic energy, rates of deposition, turbidity, salinity, oxygen levels, toxic substances, the quality and quantity of available food, and the ecologic or ichnologic prowess of the tracemakers themselves. Resulting ichnocoenoses are related to bathymetry only where particular combinations of environmental parameters are aligned with bathymetry.

SUBSTRATE-CONTROLLED ICHNOFACIES AND STRATIGRAPHIC DISCONTINUITIES

Three substrate-controlled ichnofacies have been established (Bromley *et al.,* 1984): *Trypanites* (hardground suites), *Teredolites* (woodground suites) and *Glossifungites* (firmground suites). Although all three suites may indicate the presence of a regional stratigraphic discontinuity, only the *Glossifungites* ichnofacies has been recognised to commonly do so in Cretaceous intervals of the Western Canada Sedimentary Basin. The *Glossifungites* ichnofacies (redefined by Frey and Seilacher, 1980) encompasses trace fossils associated with semilithified or firm substrates (*e.g.* dewatered, cohesive muds), attributable either to subaerial exposure, or burial and subsequent exhumation (Figure III-2). Less commonly, *Glossifungites* suites may be developed in incipiently-cemented sandstone substrates, such as in the Appaloosa Sandstone of the Bearpaw Formation-Horseshoe Canyon Formation transition (Saunders and Pemberton, 1986).

Firmground traces are dominated by vertical to subvertical dwelling structures of suspension feeding organisms (see Chapter II Figure II-3 A,B). The most common structures correspond to the ichnogenera *Diplocraterion, Skolithos, Psilonichnus, Arenicolites,* and firmground *Gastrochaenolites* (Figure III-2). Dwelling structures of deposit feeding organisms are also constituents of the ichnofacies, and include firmground

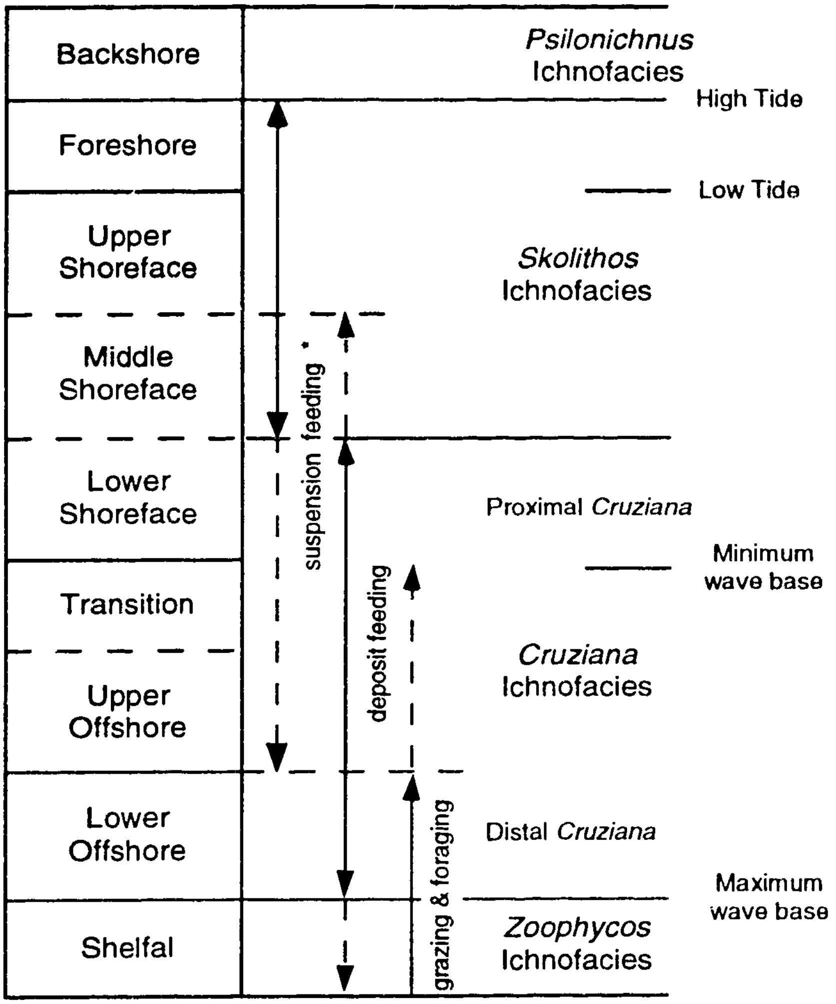
Thalassinoides/Spongeliomorpha (see Chapter II, Figure II-3 C,D), and *Rhizocorallium*. The presence of vertical shafts within shaly intervals is anomalous, as such structures are not capable of being maintained in soft muddy substrates. *Glossifungites* ichnofacies traces are typically robust, commonly penetrating 20-100 cm below the stratigraphic break. Many shafts tend to be 0.5-1.0 cm in diameter, particularly *Diplocraterion habichi* and *Arenicolites*. This scale of burrowing is in sharp contrast to the predominantly horizontal, diminutive trace fossils common to shaly intervals. The firmground traces are generally very sharp-walled and unlined, reflecting the stable, cohesive nature of the substrate at the time of colonisation and burrow excavation. Linings are typically employed by the tracemaker in an attempt to stabilise dwelling burrows in unconsolidated material. Many structures, particularly in outcrop, show preserved sculptings or scratch marks on the burrow wall, confirming that construction of the dwelling burrow occurred in a firm substrate (see Chapter II, Figure II-3 C, D). Further evidence of substrate stability, atypical of soft muddy beds, is the passive nature of burrow fill. This demonstrates that the structure remained open after the tracemaker vacated the burrow, thus allowing material from the succeeding depositional event to passively fill the open structure. The post-depositional origin of the *Glossifungites* suite, in relation to the original softground assemblage, is clearly demonstrated by the ubiquitous cross-cutting relationships observed in the rock record. The final characteristic of the *Glossifungites* suite is the tendency to demonstrate colonisation in large numbers (see Chapter II, Figure II-3 B, E). In several examples, seven to fifteen firmground traces, commonly *Diplocraterion habichi*, have been observed on the bedding plane of a 9 cm (3.5 inch) diameter core. This density corresponds to between 1100 to 2300 shafts per square meter. Similar populations were observed from *Glossifungites* suites on the modern coast of Georgia (Pemberton and Frey, 1985). Dense populations are typical of many opportunistic assemblages (Levinton, 1970; Pemberton and Frey, 1984).

In siliciclastic settings, most firmground assemblages are associated with erosionally exhumed (dewatered and compacted) substrates and, hence, correspond to erosional discontinuities. Although certain insect and animal burrows in the terrestrial realm may be properly regarded as firmground (*e.g.* Fürsich and Mayr, 1981) or more rarely, hardground suites, they have a low preservation potential and constitute a relatively minor component in the preserved record of these associations. The overwhelming majority of these assemblages originate in marine or marginal marine settings, particularly in pre-Tertiary intervals. Consequently, a discontinuity may be generated in either subaerial or submarine settings, but colonisation of the surface corresponds to marine conditions. This has important implications regarding the genetic interpretation of the discontinuity in question. Finally, the substrate-controlled ichnocoenose, which cross-cuts the preexisting softground suite, reflects conditions post-dating both initial deposition of the underlying unit and its subsequent erosional exhumation following burial. The *Glossifungites* suite therefore indicates that a temporal break (*e.g.* depositional hiatus) occurred between the erosional event and sedimentation of the overlying unit; significant depositional cover precludes firmground colonisation. These three aspects of the *Glossifungites* suite makes it useful both in the recognition of the discontinuity and in its genetic interpretation.

PALEOENVIRONMENTAL SIGNIFICANCE OF ICHNOFOSSILS

The application of ichnology to paleoenvironmental analysis goes far beyond the mere establishment of general or archetypal ichnofacies. For instance, shallow-water, coastal marine environments comprise a multitude of sedimentological regimes which are subject to large fluctuations in many physical and chemical parameters. In order to comprehend the depositional history of such zones represented in the rock record, it is imperative to have some reliable means of differentiating subtle changes in these parameters. Detailed investigations of many coastal marine zones have illustrated the value of using biogenic sedimentary structures in delineating such ecological parameters as oxygenation, salinity, and energy levels. For instance, Dörjes and Hertweck (1975) subdivided the coastal zone into three major environments, based primarily on the position of mean high-water, mean low-water, and wave base. Their faunistic investigations of the distribution of benthic organisms also confirmed the importance of minimum and maximum wave base as distinct boundaries separating animal communities (Figure III-3).

Softground ichnofacies tend to be differentiated from one another by variables that typically are depth related. The *Zoophycos* and *Nereites*


ICHNOLOGICAL-SEDIMENTOLOGICAL SHOREFACE MODEL

* Many tube dwellers are passive carnivores rather than suspension feeders.

Figure III-3. Idealised shoreface model of ichnofacies successions, based on observation of Cretaceous strata of the Western Interior Seaway of North America (modified after Pemberton *et al.*, 1992a).

assemblages are more characteristic of deep-water environments, whereas the *Psilonichnus, Skolithos,* and *Cruziana* ichnofacies are represented in nearshore marine environments. For example, in the Cretaceous of the Western Interior of North America the marine shoreface can be zoned ichnologically (Figure III-3). This zonation is based on the food-resources paradigm, which is influenced by relative energy levels. Recent summaries of the ichnology of marine shoreface environments can be found in publications by Frey and Pemberton (1987), Frey and Howard (1990), and MacEachern and Pemberton (1992).

The *Zoophycos* and especially the *Nereites* ichnofacies tend to characterise deep-water environments, including outer shelf, slope, and bathyal to abyssal settings (Figure III-1). For details on ichnology of deep marine deposits, see the papers by Ekdale *et al.* (1984), McCann and Pickerill (1988), and Crimes and Crossley (1991).

It is also important to be able to differentiate autocyclic successions (sedimentary event layers), resulting from *in loco* fluctuations in energy, from allocyclic successions. Only allocyclic successions have sequence stratigraphic significance. Sedimentary event layers represent beds that were deposited during short periods of time and differ in some significant way from the ambient sediment (Wheatcroft, 1990). Event beds include such diverse entities as volcanic ash beds, or tephra deposits (*i.e.* Pedersen and Surlyk, 1983), beds resulting from seismic shocks (*i.e.* seismites, Seilacher, 1969); as well as episodic sedimentation events such as turbidites (Seilacher, 1962); tempestites or storm deposits (Aigner, 1985); phytodetritus pulses (Rice *et al.*, 1986); and inundites or flood deposits (Leithold, 1989). Trace fossils are known to be significant features of most of these deposits.

For instance, tempestites exhibit a characteristic suite of trace fossils that are related to the population strategies of benthic organisms. The general succession of most tempestites consists of: (a) a fairweather resident trace fossil suite; (b) a sharp basal contact, with or without a basal lag; (c) parallel to subparallel laminations (reflecting hummocky cross-stratification, swaley cross-stratification or quasi-planar lamination); (d) common escape structures; (e) the dwelling burrows of opportunistic organisms that colonise the unexploited storm unit; (f) gradational burrowed tops, representative of bioturbation resulting from subsequent burrowing by organisms from higher colonisation levels; and (g) a fairweather resident trace fossil suite indicative of persistent quiescent conditions (Pemberton *et al.*, 1992b).

The use of trace fossils in the interpretation of freshwater deposits is becoming increasingly important. Recent work by Pollard (1988), Maples and Archer (1989), and Bromley and Asgaard (1991), among others, has stressed the abundance and diversity of tracemaking organisms in freshwater environments and emphasised their potential importance in paleoenvironmental reconstructions. Distinct differences in trace fossil types and abundance have been reported from a wide range of freshwater-terrestrial environments, in both ancient and recent settings (Ekdale *et al.*, 1984).

Recently, marginal marine environments (including tidal channels, estuaries, bays, shallow lagoons, delta plains, *etc.*) have been recognised with greater frequency in the rock record. Such environments characteristically display steep salinity gradients, which, when combined with corresponding changes in temperature, turbulence, exposure, and oxygen levels, result in a physiologically stressful environment for numerous groups of organisms. The typical trace fossil suite in such environments reflects these stresses and is characterised by: (1) low diversity; (2) ichnotaxa which represent an impoverished marine assemblage rather than a true mixture of marine and freshwater forms; (3) a dominance of morphologically simple structures constructed by trophic generalists; (4) a mixture of elements which are common to both the *Skolithos* and *Cruziana* ichnofacies; (5) assemblages that are commonly dominated by a single ichnogenus; and (6) diminished size compared to fully marine counterparts (Wightman *et al.*, 1987; Pemberton and Wightman, 1992).

One of ichnology's greatest strengths, the bridging of sedimentology and paleontology, in some respects, can also be its greatest liability. Sedimentologists tend to use a strict uniformitarian approach to paleoenvironmental interpretation and rely heavily on modern analogues. Paleontologists, on the other hand, must temper their observations in the light of organic evolution. Although trace fossils can be considered as biogenic sedimentary structures and are difficult to classify phylogenetically, they are constructed by biological entities and are thus subject, at least to some degree, to evolutionary trends. The ichnologist must keep both in mind and employ trace fossil studies within an actualistic paradigm.

ICHNOLOGICAL APPLICATIONS TO SEQUENCE STRATIGRAPHY

The main applications of ichnology to sequence stratigraphic analysis are two-fold. The most obvious use is in the demarcation of erosional discontinuities having a significant temporal break between the eroding event and the successive depositional event. The second use is more subtle and is concerned with the environmental implications of the trace fossil suites, both softground and substrate-controlled. When these aspects are integrated with sedimentologic and stratigraphic analyses, the result is a powerful approach to the delineation and genetic interpretation of sequence stratigraphic surfaces, as well as to their associated deposits. The Cretaceous of the Western Canada Sedimentary Basin (WCSB) is well-suited to demonstrate the effectiveness of ichnology to sequence stratigraphic analysis (Figure III-4; Table III-1).

Sequence Boundaries

Sequence boundaries are generated during lowstands of relative sea level. In the Cretaceous of the Western Canada Sedimentary Basin (WCSB), sequence boundaries are manifest by subaerial exposure surfaces locally associated with paleosols, erosionally incised valley surfaces, and submarine erosion surfaces related to "forced regressions" (*cf.* Posamentier and Vail, 1988; Posamentier *et al.*, 1992). Although subaerial exposure and/or erosion during lowstands of sea level generates widespread dewatered, firm or incipiently-cemented substrates, such surfaces are unlikely to become colonised by substrate-controlled trace fossil suites unless they are subsequently exposed to marine or marginal marine conditions. As such, most sequence boundaries are not colonised by substrate-controlled suites, unless capped by a marine flooding surface (*i.e.* FS/SB).

Incised Valley Surfaces

At the seaward margins of some incised valley complexes, estuarine conditions prevail prior to transgression, permitting the colonisation of the sequence boundary and deposition of marginal marine facies in what is legitimately part of the lowstand systems tract. Such incised valley surfaces

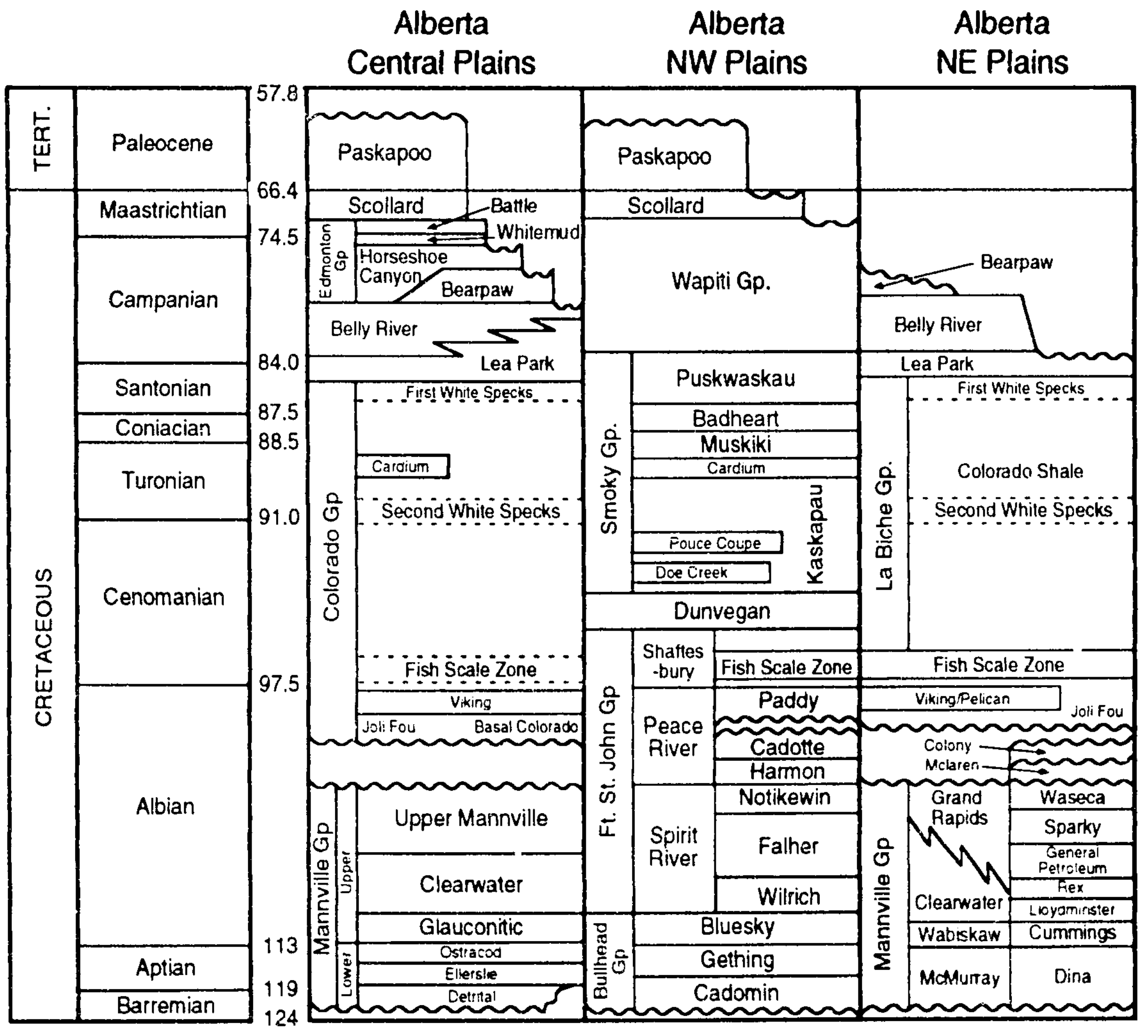


Figure III-4. Stratigraphic chart of Cretaceous intervals occurring in the Western Canada Sedimentary Basin, Alberta, Canada.

AGE	LOCATION	FORMATION	PRE-EROSION TRACE SUITE	EROSION SURFACE TRACE SUITE
Lower Albian	WCSB NE British Columbia	Gething/ Bluesky contact (subsurface)	Unburrowed, finely laminated and rooted mudstones and coals (Gething Formation).	*Glossifungites* assemblage consisting of *Skolithos* and *Thalassinoides* with associated pebble lag.
Upper Albian	WCSB Kaybob S. Field	Mannville Gp /Joli Fou Fm (subsurface)	Unburrowed, rooted paleosols (terrestrial) with coals (Mannville Group).	*Glossifungites* assemblage consisting of *Thalassinoides*. Associated pebble lag.
Upper Albian	WCSB Chigwell Field	Viking Fm (subsurface)	Silty shales with *Helminthopsis*, *Planolites*, *Terebellina*, *Chondrites* and *Asterosoma*, of the distal *Cruziana* ichnofacies.	*Glossifungites* ichnofacies consisting of *Thalassinoides* with associated pebbles and granules.
Upper Albian	WCSB Joffre Field	Viking Fm (subsurface)	Silty shales & distal storm sands: *Planolites*, *Helminthopsis*, *Chondrites*, *Terebellina*, rare *Zoophycos*, *Asterosoma* & *Rhizocorallium*.	*Glossifungites* assemblage consisting of *Skolithos*, ?*Arenicolites*/*Diplocraterion* and *Thalassinoides* with associated pebble lag.
Upper Albian	WCSB Gilby A Field	Viking Fm (subsurface)	Intensely burrowed muddy siltstone deposits containing *Helminthopsis*, *Terebellina*, *Planolites* and rare *Chondrites*.	*Glossifungites* assemblage of *Skolithos* and ?*Arenicolites*/ *Diplocraterion* associated with sideritised surface and pebble lag.
Cretaceous (U. Albian)	WCSB Kaybob Field	Viking Fm (subsurface)	Thoroughly burrowed sandy shale: *Teichichnus*, *Helminthopsis*, *Asterosoma*, *Terebellina*, *Zoophycos*, *Chondrites*, rare *Rosselia* and *Rhizocorallium*.	*Glossifungites* assemblage consisting of *Thalassinoides* and *Skolithos* with associated rip-up clasts and pebbles.
Upper Albian	WCSB Kaybob S. Field	Viking Fm (subsurface)	Pebbly and sandy shales with *Planolites*, *Asterosoma*, *Terebellina*, rare *Chondrites*, *Helminthopsis* and *Zoophycos*.	*Glossifungites* assemblage consisting of robust *Arenicolites* shafts.
Upper Albian	WCSB Crystal Field	Viking Fm (subsurface)	Highly burrowed muddy sandstone with *Terebellina*, *Chondrites*, *Planolites*, *Helminthopsis*, *Asterosoma* & rare *Zoophycos*.	*Glossifungites* assemblage consisting of *Diplocraterion* shafts, *Thalassinoides* and *Gastrochaenolites*.
Upper Albian	WCSB Willesden Green	Viking Fm (subsurface)	Shales and silty shales with *Helminthopsis*, *Terebellina*, *Planolites*, *Chondrites* & *Zoophycos* (distal *Cruziana* ichnofacies).	*Glossifungites* assemblage consisting of *Rhizocorallium*, *Thalassinoides* and *Skolithos*.
Upper Albian	WCSB Sinclair Field	Peace River Fm Paddy Mbr (subsurface)	Pebbly shale, intensely burrowed, with *Chondrites*, *Helminthopsis*, *Terebellina*, *Asterosoma* and *Planolites*.	*Glossifungites* assemblage consisting of *Diplocraterion*, associated with dispersed pebbles.
Cenomanian	WCSB Jayar Field	Dunvegan Fm (subsurface)	Largely unburrowed and locally rooted mudstones in shallow water (lacustrine?) & deltaplain settings.	*Glossifungites* assemblage consisting of *Thalassinoides* systems.
Turonian	WCSB Pembina Field	Doe Creek Fm (subsurface)	Sandstones with *Ophiomorpha*, *Palaeophycus*, *Teichichnus*, *Terebellina*, *Planolites*, *Asterosoma* & *Zoophycos*.	*Glossifungites* ichnofacies consisting of *Thalassinoides*.
Turonian	WCSB Pembina Field	Cardium Fm (subsurface)	Silty shales containing *Planolites*, *Chondrites*, *Helminthopsis*, *Terebellina* & rare *Zoophycos*, (distal *Cruziana* ichnofacies).	*Glossifungites* ichnofacies consisting of *Thalassinoides*.
Maastrichtian	WCSB Drumheller Alberta	Horseshoe Canyon Fm (outcrop)	Unburrowed and rooted shales and coals formed within a back-barrier setting.	*Teredolites* assemblage consisting of abundant *Diplocraterion parallelum* subtending into a back- barrier coal.

Table III-1. Ichnologically-Demarcated Discontinuities within the Cretaceous of the Western Canada Sedimentary Basin (modified after Pemberton *et al.*, 1992a).

POST-EROSION TRACE SUITE	INTERPRETATION OF SURFACE
Bar margin: highly burrowed muddy sands with *Teichichnus, Helminthopsis, Palaeophycus, Rosselia, Asterosoma, Planolites, Terebellina.* Brackish pro-delta: sands & shales with *Teichichnus, Planolites & Palaeophycus.*	Subaerial exposure and progradation of coal-bearing delta plain sediments, followed by high energy flooding surface (FS/SB). Colonisation of erosion surface preceded main transgressive lag deposition. Overlying sediments consist of prograding bar margin or brackish water pro-delta of the next progradational cycle (Oppelt, 1988).
Silty shale with a distal *Cruziana* assemblage consisting of *Helminthopsis, Zoophycos, Terebellina, Planolites* and *Chondrites.*	Mannville Group surface was subaerially exposed (sequence boundary), subsequently transgressed, producing a high energy flooding surface (FS/SB) colonised by a firmground suite. The overlying shales reflect offshore to outer shelfal settings (Joli Fou Formation).
Intensely burrowed muddy sandstone with robust *Teichichnus, Asterosoma, Terebellina, Helminthopsis* , *Chondrites* and *Planolites,* reflecting the *Cruziana* ichnofacies.	Sequence boundary incised into offshore deposits, modified during transgression (FS/SB). FS/SB surface is buried by shoreface which prograded during sea level stillstand. Resumed transgression capped shoreface with flooding surface (Raychaudhuri *et al.*, 1992).
Sparsely burrowed, cross-bedded pebbly and coarse-grained sandstone with rip-up clasts. Mud drapes contain *Planolites.*	Subaerially exposure surface cut into offshore deposits during lowstand of relative sea level, modified by a high energy flooding surface reflecting erosive shoreface retreat (FS/SB). Surface overlain by shoreface sandstones during a relative stillstand of sea level (Downing and Walker, 1988; Pattison, 1991a).
Unburrowed, pebbly, medium-grained sandstones.	High energy flooding surface reflecting erosive shoreface retreat, amalgamated with subaerial exposure surface (FS/SB) incised into underlying offshore deposits. Relative stillstand of sea level permitted progradation of shoreface over FS/SB (Raddysh, 1988; Pattison, 1991a).
Trough and low angle parallel laminated sandstone: *Arenicolites, Skolithos, Ophiomorpha, Teichichnus, Palaeophycus, Helminthopsis, Chondrites, Rosselia, Planolites, Terebellina* and *Asterosoma.*	Surface corresponds to a sequence boundary (lowstand unconformity) incised into underlying offshore/inner shelf deposits as they are brought into zone of wave attack. Basinward displacement of the shoreline results in forced regression shoreface directly overlying sequence boundary (MacEachern *et al.*, 1992b).
Pebbly and sandy shales with *Teichichnus, Terebellina, Asterosoma, Planolites,* rare *Chondrites & Helminthopsis.*	The surfaces are high energy flooding surfaces generated during incremental transgression of the Colorado sea. The surfaces bound progradational wedges of sediment and constitute high energy parasequence boundaries (MacEachern *et al.*, 1992a).
Sandstones, interbedded sands and shales and shales with *Teichichnus, Ophiomorpha, Palaeophycus, Diplocraterion, Rosselia, Skolithos, Asterosoma, Terebellina,* & *Planolites.*	The surface reflects an FS/SB, interpreted as an incised valley, cut into underlying shelf to lower shoreface deposits during sea level lowstand. Sequence boundary is modified by high energy flooding surface during transgressive fill of the valley (Reinson *et al.*, 1988; Pattison, 1991a&b; Pemberton *et al.*, 1992c).
Cross-bedded pebbly sandstones & conglomerates; sands & shales contain a brackish suite of *Cylindrichnus, Teichichnus, Planolites, Terebellina, Palaeophycus* & *Asterosoma.*	Surface reflects an FS/SB. Sequence boundary cut as an incised valley, excavated into offshore to outer shelfal deposits. Surface is modified by a high energy flooding surface during ensuing transgression. Valley is filled with estuarine sediments of the transgressive systems tract (Boreen, 1989; Boreen and Walker, 1991).
Pebbly shale, intensely burrowed with *Helminthopsis, Zoophycos* and *Chondrites,* grading into less burrowed sandstone & shale with *Asterosoma, Planolites & Chondrites.*	The discontinuities are interpreted to reflect high energy flooding surfaces, associated with incremental transgression of the Shaftesbury/Colorado Sea. The surfaces bound thin progradational wedges of sediment and constitute high energy parasequence boundaries.
Medium-grained sandstones, intensely burrowed with *Ophiomorpha* (transgressive sheet sand), passing into marine shales with *Zoophycos, Planolites* and *Chondrites.*	Delta plain facies capped by subaerial exposure surface, reflecting a lowstand of relative sea level. High energy flooding surface modified this surface (FS/SB). Reworking of underlying facies produced a transgressive sheet sand (Bhattacharya, 1989; Bhattacharya and Walker, 1991).
Medium- to fine-grained sandstone containing *Zoophycos, Chondrites,* and *Planolites.* Passes into silty shales with *Helminthopsis, Planolites, Terebellina, Chondrites* and *Zoophycos.*	The surface overlies lower shoreface deposits, and reflects an FS/SB. Siderite cementation of underlying sandstones corresponds to subaerial exposure. Colonization of surface reflects initial transgression. Continued transgression produces a low energy flooding surface.
Largely unburrowed conglomerate, overlain by marine shale with dispersed pebbles; shales contain *Helminthopsis, Planolites, Chondrites, Terebellina* and *Zoophycos.*	The surface may be a sequence boundary with overlying conglomeratic forced regression shoreface, or an FS/SB reflecting transgressive modification of SB by erosive shoreface retreat. Overlying conglomeratic shorefaces may reflect stillstand of sea level (Walker and Plint, 1992).
Lower shoreface HCS and SCS sandstone with *Ophiomorpha, Rhizocorallium, Teichichnus, Conichnus, Skolithos & Rosselia.*	The erosion surface is interpreted as a high energy flooding surface separating back barrier deposits from overlying, prograding, storm-dominated shoreface deposits (Saunders and Pemberton, 1986).

correspond to distal sequence boundaries (Van Wagoner, pers. comm., 1993). Proximal sequence boundaries within the incised valley are typically overlain by freshwater deposits and are not demarcated by substrate-controlled assemblages.

In Cretaceous strata of the WCSB, the bulk of the preserved incised valley fill deposits are not associated with lowstand, but rather, subsequent transgressive conditions. Many of the valley systems appear to have dominantly been a zone of sediment bypass during falling sea level. Much of the sediment accumulation overlies either low energy (non-erosive) flooding surfaces or, more commonly, high energy (erosive) flooding surfaces. Erosive flooding surfaces are generated by tidal scour associated with transgressive invasion of the valley. These incised valley surfaces predominantly correspond to amalgamated FS/SB and are discussed below.

Forced Regression Shoreface Surfaces

The character of sequence boundaries generated during forced regression (*cf.* Posamentier and Vail, 1988; Plint, 1988) differs from many other sequence boundary expressions in that the surface is cut under submarine conditions. During falling sea level, sediments previously lying below fairweather wave base are brought into a zone of persistent wave attack. This produces an erosional sequence boundary which passes basinward into a correlative conformity and landward into a subaerial exposure surface. The rapid basinward shift of the shoreline "forces" a shoreface to prograde rapidly over the sequence boundary, with minimal, if any, record of its passage. The diminished accommodation space associated with the base level fall results in the abrupt establishment of shallow water deposits over deeper water sediments, typically occupying a wave-cut terrace at the most basinward position of the shoreline.

The forced regression shorefaces differ stratigraphically from the more typical regressive shoreface successions, which are associated with simple progradation. The forced regression shorefaces directly overlie the sequence boundary, are produced by conditions of lowstand, and are supplied with sediment derived from the cutting of the unconformity. As such, these successions are legitimate components of the lowstand systems tract. In contrast, sediment-induced progradational regressions directly overlie either marine flooding or FS/SB surfaces and correspond to parasequences, fitting within highstand or transgressive systems tracts, depending on the stacking pattern of the parasequence set.

The Albian Viking Formation of the Kaybob field (Figures III-5, III-6; see Chapter II; II-9), central Alberta, produces hydrocarbons from a sharp-based, coarsening upward, NW-SE trending sandstone body, interpreted as a forced regression shoreface (MacEachern *et al.*, 1992b; Pemberton *et al.*, 1992a). The sequence boundary is incised into thoroughly burrowed silty and sandy shales, containing a mixture of grazing and deposit feeding structures consistent with lower to upper offshore deposition. The sequence boundary is locally demarcated by a *Glossifungites* suite of *Skolithos, Thalassinoides* and rare *Diplocraterion,* passively filled with medium- to coarse-grained sand from the overlying forced regression shoreface (Chapter II; Figure II-9).

In proximal positions, upper shoreface sandstones, consisting of thin bedsets of trough cross-stratification with rare, intercalated swaley cross-stratified storm beds, directly overlie the sequence boundary. Softground trace fossils consist of *Arenicolites, Skolithos, Diplocraterion, Palaeophycus, Cylindrichnus,* rare *Conichnus* and escape traces. In intermediate positions, lower to middle shoreface sandstones (Figures III-5 and III-6) immediately overlie the sequence boundary. The sandstones consist of alternating storm beds, characterised by swaley cross-stratification and combined flow ripple lamination, and thoroughly burrowed muddy sandstone fairweather beds. The succession is typical of storm-dominated to storm-influenced settings (MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992b). The trace fossil suite consists of a mixture of deposit feeding, suspension feeding and passive carnivore structures, with less abundant grazing structures, typical of lower to middle shoreface deposits.

In more basinal positions, the sequence boundary is abruptly overlain by thoroughly burrowed lower shoreface muddy sandstones, which contain diverse trace fossil suites dominated by deposit feeding structures, with subordinate amounts of suspension feeding, passive carnivore and grazing structures. Further basinward, the sequence boundary passes into a correlative conformity and is difficult to recognise. The succession in this position demonstrates a gradual coarsening upward profile, which is difficult to differentiate from the highstand parasequences underlying the correlative conformity.

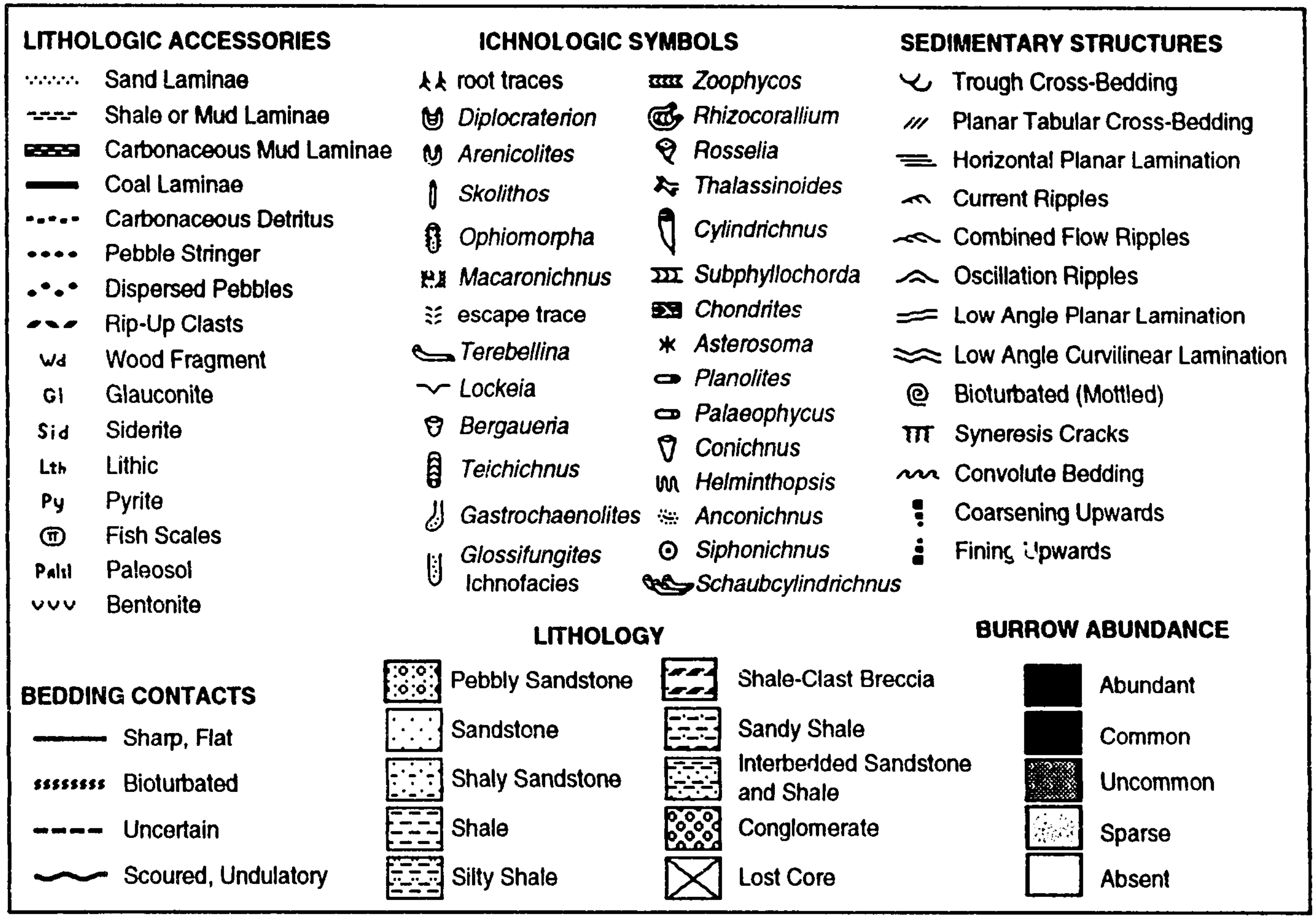


Figure III-5. Legend of Symbols used in Lithologs and Cross-section.

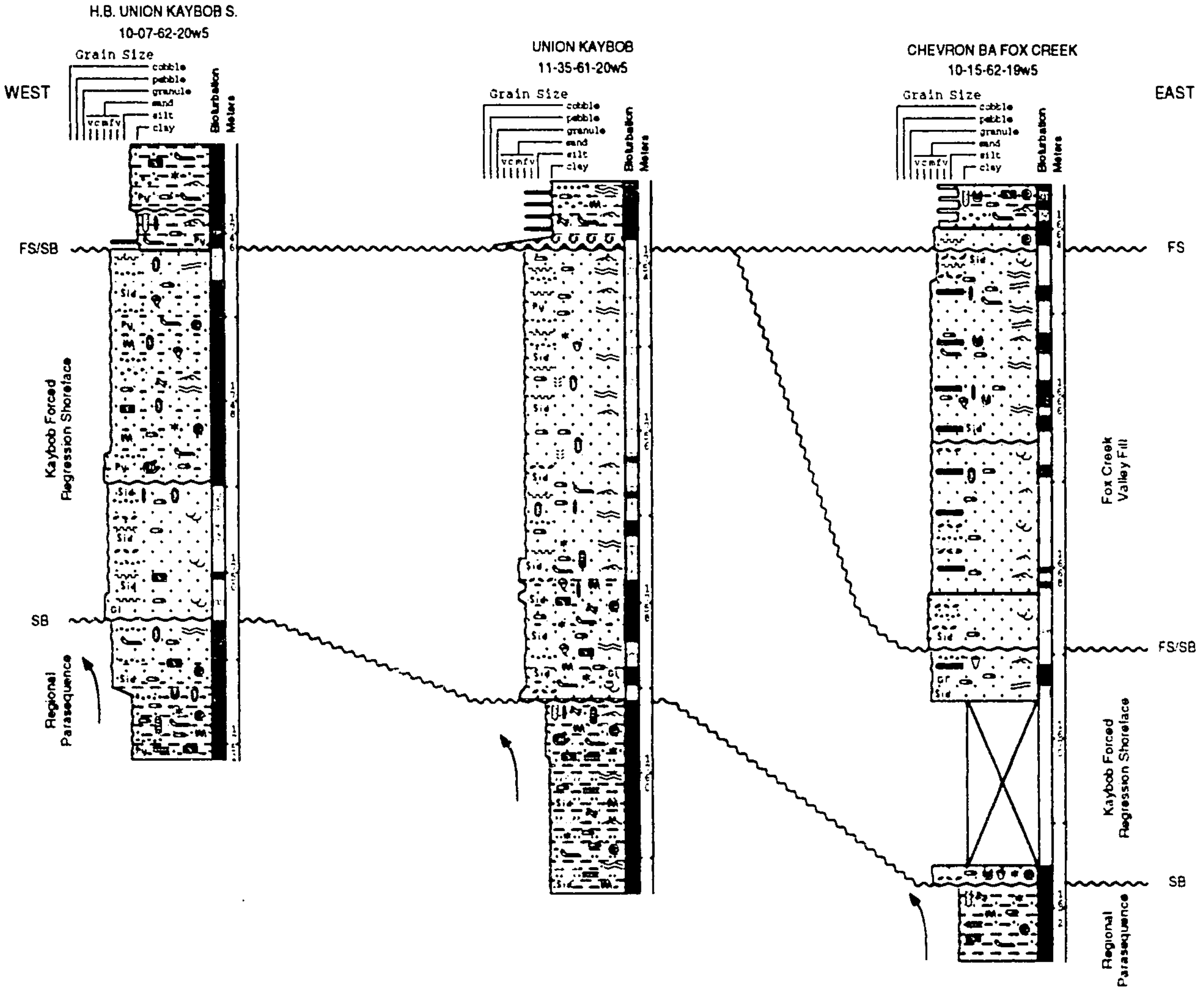


Figure III-6. West-east (proximal-distal) litholog cross-section of the Kaybob forced regression shoreface. The forced regression shoreface overlies a sequence boundary incised into regionally extensive parasequences of the lower Viking Fm. The shoreface is erosionally removed to the east by an FS/SB, defining the base of a proposed incised valley at Fox Creek. Legend of the symbols used in the lithologs occur in Figure III-5.

The upper portion of the Kaybob forced regression shoreface has been removed by a low relief, high energy (erosional) flooding surface. Any backshore or foreshore deposits that had accumulated have been subsequently removed. The sand body is relatively thin, typically less than 10 m, and shows rapid upward transition from lower to upper shoreface deposits. These features are consistent with the reduced accommodation space associated with a lowering of relative sea level.

A forced regression setting has also been proposed for the Viking Formation at the Joarcam field (Posamentier and Chamberlain, 1991, 1993; Posamentier *et al.*, 1992). In the few cored intervals from Joarcam studied by the authors, no substrate-controlled suites were observed to demarcate the sequence boundary. Nonetheless, the sharp, erosionally-based character of the shoreface sandstone attests to an abrupt basinward shift of facies, consistent with a relative fall of sea level. Other Viking successions interpreted to have been deposited during forced regression includes the Sunnybrook A and B sandstones (Pattison, 1991a) and the coarse-grained onlap markers in the Caroline and Garrington fields (Davies and Walker, 1993; *cf.* Chapter X). The conglomeratic shorefaces of the Turonian Cardium Formation (Walker and Plint, 1992) have been interpreted as forced regression deposits. More recently, this model has been applied to the "D2" cycle of the Albian Falher D member of the Spirit River Formation in the Elmworth area (Arnott, 1993).

Transgressive Surfaces

Transgressive surfaces are possibly the most abundantly represented stratigraphic break in Cretaceous strata of the Western Canada Sedimentary Basin. This is believed to be due to the additive effects of subsidence in the foreland basin (Stockmal and Beaumont, 1987; Cant and Stockmal, 1989) and conditions of overall (eustatic?) sea level rise during the Cretaceous (Haq *et al.*, 1987).

Transgressive surfaces are characterised by largely non-erosive low energy marine flooding surfaces and low relief, high energy (erosive) flooding surfaces. The low energy flooding surfaces (FS) correspond to the flooding surfaces or marine flooding surfaces of others (*e.g.* Bhattacharya and Walker, 1991; Beynon and Pemberton, 1992). The high energy flooding surfaces are analogous to the transgressive surfaces of erosion (TSE) of others (*e.g.* Bhattacharya and Walker, 1991; MacEachern *et al.*, 1992a) and the ravinement and marine erosion surfaces of Nummedal and Swift (1987).

Low Energy Marine Flooding Surfaces (LE FS)

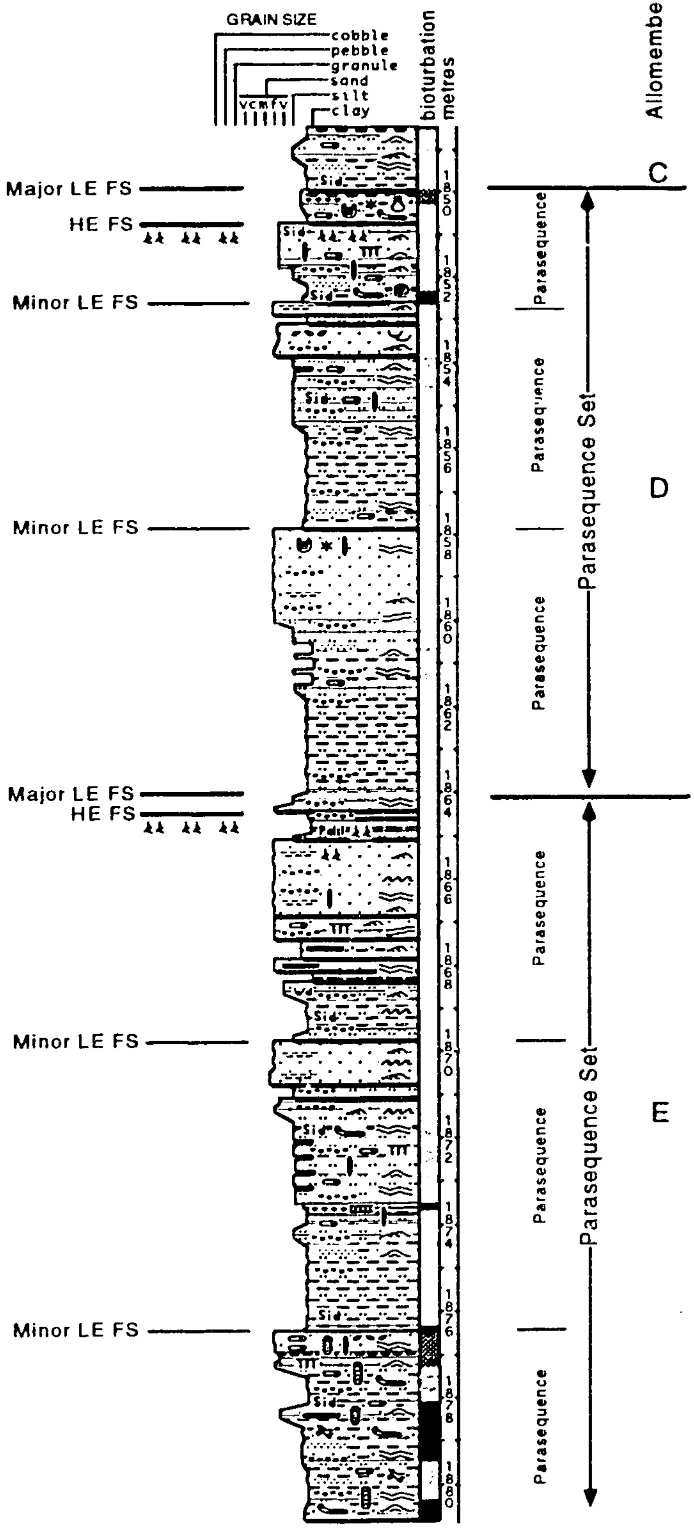
Low energy marine flooding surfaces (LE FS) are typically abrupt, sharp contacts across which there is evidence of an increase in water depth. Many such surfaces are mantled with dispersed sand, granules or intraformationally-derived rip-up clasts, indicating minor amounts of erosion. The preservation of underlying markers attests to the minimal degree of erosion.

FS are typically characterised by the abrupt juxtaposition of offshore, shelfal or prodelta shales on shallow marine sandstones (*e.g.* Figure III-7) and are easily picked on geophysical well logs. Consequently, FS have been utilised by several workers to subdivide stratigraphic intervals in the WCSB, such as the Cenomanian Dunvegan Formation (Bhattacharya, 1989; Bhattacharya and Walker, 1991) and the Albian Grand Rapids Formation (Beynon, 1991; Beynon and Pemberton, 1992).

Low energy flooding surfaces in the Cenomanian Dunvegan Formation have been differentiated into minor, major and maximum types, depending on their areal correlatability (Bhattacharya, 1990; Bhattacharya and Walker, 1991). The Dunvegan Formation is interpreted to represent a deltaic setting, ranging from river-dominated to wave-dominated over the history of its accumulation. The minor flooding surfaces appear to separate individual delta lobes, with a correlatable scale of 10's of kilometres, and may correspond to autocyclic abandonment of the lobes or to local tectonic events. Minor FS bound individual parasequences and correspond to low energy parasequence boundaries. Major marine flooding surfaces separate discrete, regionally extensive parasequence sets, have a correlatability on the scale of 100's of kilometres and are interpreted to represent eustatic rises in sea level. The maximum flooding surfaces are correlatable on a scale of 1000's of kilometres, and bound the base and top of the Dunvegan Formation itself, separating major over- and underlying transgressive systems tracts from the Dunvegan progradational wedge (Bhattacharya, 1989; Bhattacharya and Walker, 1991).

Figure III-7. Litholog of stacked parasequences, bound by low energy marine flooding surfaces and high energy flooding surfaces in the Dunvegan Formation of well 03-26-66-07W6. The succession records delta progradation and can be separated into parasequence sets bound by major flooding surfaces, locally with associated erosion, recording ravinement. These major surfaces commonly overlie rooted intervals. The parasequence sets can be further subdivided into individual parasequences bound by minor flooding surfaces. The parasequence sets have been mapped as regionally correlatable allomembers of the Dunvegan Formation (Bhattacharya, 1989; Bhattacharya and Walker, 1991). The legend for the litholog is given in Figure III-5.

Triad Pan Am Big Mtn. 03-26-66-07w6



The ichnology associated with the Dunvegan Formation marine flooding surfaces is sparse. The facies immediately overlying the flooding surfaces is related to prodelta progradation, and is characterised by tan coloured, largely unburrowed, highly silty shale, suggesting rapid sediment accumulation. In contrast, burrow intensity is moderate to common where minor associated erosion produces gritty and sandy shales above the flooding surface. In such shales, *Planolites* is the dominant element, with far less common *Terebellina, Thalassinoides,* and exceedingly rare *Teichichnus*. The suite consists of deposit feeding structures of trophic generalists, and may demonstrate stresses imparted on the infauna such as high sedimentation rates, water turbidity and salinity reductions, particularly in the river-dominated intervals. In general, the minor marine flooding surfaces bound thickening upward successions of storm-generated delta front sandstone beds (parasequences), characterised by wavy parallel lamination, combined flow ripple lamination and convolute bedding. These sandstones possess an impoverished suite of *Ophiomorpha, Skolithos, Arenicolites* and *Diplocraterion,* cross-cut by *Planolites, Terebellina, Teichichnus, Palaeophycus* and *Thalassinoides* (*cf.* tempestites; Pemberton *et al.*, 1992b). Major marine flooding surfaces cap progradational sets of delta lobes (parasequence sets) and commonly overlie rooted delta plain deposits or incipiently developing paleosols (Figure III-7).

In the Grand Rapids Formation, the most common facies consistently overlying marine flooding surfaces consists of interlaminated mudstones and sandstones. These intensely burrowed units contain a low diversity trace fossil suite, dominated by *Teichichnus, Planolites* and *Skolithos,* with rare *Asterosoma, Chondrites, Gyrolithes* and *Rhizocorallium*. Diversity is low but individual elements, particularly *Teichichnus,* are locally abundant. These facies are interpreted as brackish water deposits, suggesting that the transgressive events did not inundate the area with fully marine waters (Beynon, 1991; Beynon and Pemberton, 1992). Facies underlying the flooding surfaces record interdistributary bay, rooted delta plain and marsh deposits of bay-fill successions, and delta front sandstones within a salinity-stressed deltaic setting.

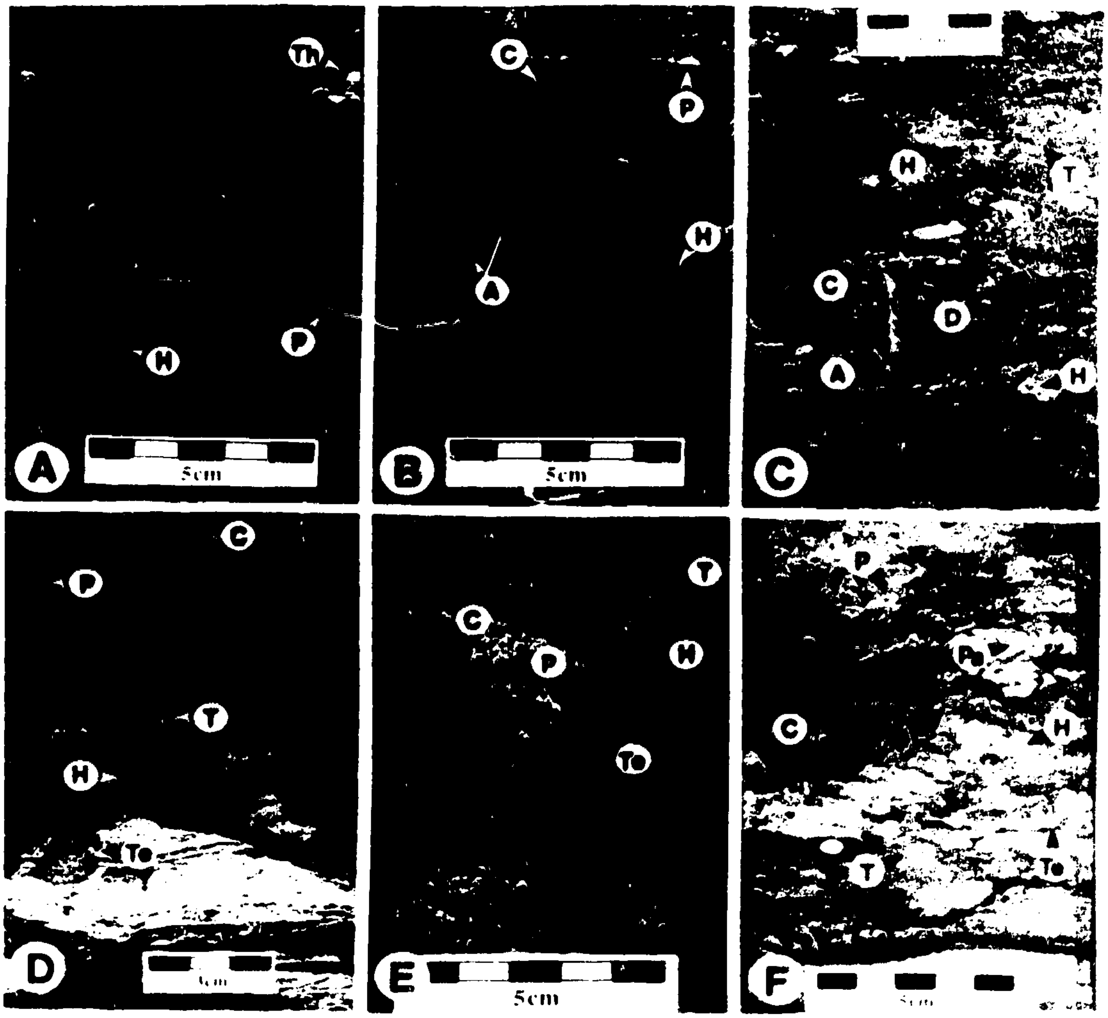
In contrast to these deltaic settings, the Viking Formation possesses numerous low energy flooding surfaces separating coarsening and sanding upward parasequences of regional extent, which correspond to shoreface progradation within fully marine conditions. These successions are informally referred to as the regional Viking cycles. These grade out of the marine shales of the Joli Fou Formation, which transgressively overlie a sequence boundary developed on the Mannville Group (*i.e.* FS/SB). Five main coarsening upward successions (fourth-order parasequences), the lower two of which contain numerous minor cycles (fifth-order parasequences) are interpreted to reflect changes in relative sea level, attributed to a combination of eustasy, local or regional tectonics and variations in sediment supply (Pattison, 1991a). The fourth-order parasequences are capped by more pronounced flooding surfaces. The parasequences reflect shoreface progradation from the NW to SE, with a NNE-SSW oriented strike. The parasequences occur as a regionally extensive progradational parasequence set, indicating accumulation within a highstand systems tract, downlapping onto the Joli Fou Formation marine shales of the underlying transgressive systems tract.

Three facies make up a complete coarsening cycle, although the minor cycles rarely comprise a complete cycle. The basal facies (Facies 1) consists of silty shale, typically showing intense bioturbation (Figure III-8 A,B). Silt is dispersed biogenically throughout the facies, and may locally be present as discontinuous remnants or stringers. Very rare, vfL-vfU grained sand interbeds (<2 cm thick) may be intercalated, and possess low angle wavy parallel lamination or combined flow ripple lamination.

The observed trace fossils of Facies 1 are relatively uniformly distributed and present in most intervals studied, with the exception of the accessory traces. *Helminthopsis, Chondrites, Planolites* and *Terebellina* comprise the dominant elements of the suite, occurring in moderate to abundant numbers in greater than 90% of the cored intervals. *Zoophycos* and *Thalassinoides* are present in 80-90% of the intervals in rare to moderate amounts, and constitute the secondary elements. *Asterosoma, Teichichnus, Rhizocorallium, Palaeophycus* and *Rosselia* occur in less than 30% of the examples and when present, occur in very rare to rare amounts.

Grading from the silty shale facies is the sandy shale facies (Facies 2; Figure III-8 C,D). Sand is typically vfL-fU in size and is present both as biogenically dispersed grains and as remnant wavy parallel laminated or combined flow ripple laminated beds. Burrowing is generally uniform and intense, although a few parasequences in the Cyn-Pem Field area (cycle 3 of Pattison, 1991a) show reduced degrees of burrowing.

Figure III- 8. Depositional Facies Comprising Regionally Extensive Parasequences of the Viking Formation. (A) Silty shales with moderate degrees of burrowing, containing thin, biogenically-mottled sandstone stringers. *Planolites* (P), *Helminthopsis* (H), *Thalassinoides* (Th) and *Chondrites* are present. The facies is interpreted to reflect lower offshore deposition. Sundance Field, 12-12-54-20W5, depth 2633.7 m. **(B)** Thoroughly burrowed silty shale, with a high proportion of interstitial silt and sand. *Helminthopsis* (H), *Planolites* (P), *Chondrites* (C) and small *Asterosoma* (A) are present. Sundance Field, 12-12-54-20W5, depth 2630.4 m. **(C)** Thoroughly burrowed sandy shale, interpreted to reflect upper offshore deposition. *Helminthopsis* (H), *Chondrites* (C), *Terebellina* (T), *Planolites*, *Asterosoma* (A) and *Diplocraterion* (D) are present. Sundance Field, 10-34-54-20W5, depth 2578.6 m **(D)** Thoroughly burrowed sandy shale facies with a remnant distal storm bed near the base. Trace fossils include *Chondrites* (C), *Planolites* (P), *Terebellina* (T), *Helminthopsis* (H) and *Teichichnus* (Te). The facies is interpreted to reflect upper offshore deposition. Sundance Field, 07-36-54-20W5, depth 2484.4 m. **(E)** Intensely burrowed muddy sandstone facies interpreted as distal lower shoreface deposits. *Helminthopsis* (H), *Chondrites* (C), *Planolites* (P), *Teichichnus* (Te) and *Terebellina* (T) are visible. Edson Field, 10-04-53-18W5, depth 2410.6 m. **(F)** Thoroughly burrowed muddy sandstone facies with *Terebellina* (T), *Teichichnus* (Te), *Palaeophycus* (Pa), *Planolites*, (P), small *Chondrites* (C) and *Helminthopsis* (H). The facies is interpreted to reflect distal lower shoreface deposition. Crystal Field, 13-05-46-03W5, depth 1754.0 m.



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The trace fossil suite of Facies 2 is more diverse than that of the silty shale underlying it, and is dominated by *Helminthopsis, Chondrites, Planolites, Terebellina, Teichichnus* and *Asterosoma*, occurring in moderate to abundant amounts in all intervals studied. Secondary elements are present in 40-80% of studied intervals and are rare to moderate in numbers. This component of the suite comprises *Zoophycos, Palaeophycus, Thalassinoides, Skolithos* and *Diplocraterion*. Accessory elements remain rare in numbers, occur in less than 30% of the intervals and are represented by *Rosselia, Arenicolites, Cylindrichnus, Rhizocorallium, Ophiomorpha, Siphonichnus, Lockeia* and fugichnia (escape traces).

Grading upward from the sandy shale facies is the muddy sandstone facies (Facies 3; Figure III-8 E,F). The sand remains vfL-fU in grain size, though typically fL; mud is generally dispersed throughout the facies and present as partings and discontinuous stringers. Discrete sandstone beds are rare, but show wavy parallel lamination where present. The general absence of discrete sandstone beds is a reflection of the high degree of bioturbation and the penetrative action of more robust infauna than in the previously described facies.

The dominant trace fossil elements of Facies 3 are *Planolites, Terebellina, Chondrites, Helminthopsis, Asterosoma, Palaeophycus, Skolithos, Teichichnus, Rosselia* and *Diplocraterion*, though individual ichnogenera are less abundant (moderate to common in numbers) and occur with less consistency (70-100%) than in the underlying facies. Secondary elements include *Ophiomorpha, Arenicolites, Zoophycos* and *Cylindrichnus* and occur in rare to moderate abundances within 40-60% of the studied intervals. Accessory elements occur in less than 40% of the examples, are rare in numbers, and include *Thalassinoides, Rhizocorallium, Schaubcylindrichnus, Lockeia, Siphonichnus* and fugichnia.

The cycles reflect both coarsening upward of facies and an increase in diversity of ichnogenera, under fully marine conditions. Each major cycle is interpreted as lower offshore to lower shoreface progradation (Figure III-3. The silty shale facies reflects a dominance of grazing and deposit feeding structures of the distal *Cruziana* ichnofacies and is interpreted as lower offshore deposition. Rare, thin sand beds reflect the distal deposits of exceptionally strong storms. The sandy shale facies shows a more diverse suite of trace fossils and a dominance of deposit feeding over grazing behaviour. The introduction of suspension feeding and passive carnivore structures is also distinctive. This facies is interpreted as upper offshore deposition at and above storm wave base. Thin sand beds record preservation of storm beds whose thicknesses exceeded the infauna's ability to completely obliterate it. The muddy sandstone facies shows an increase in diversity of behaviour, but less of a dominance by individual forms. Deposit feeding structures dominate, with diminishing influence of grazing behaviour and enhanced influence of suspension feeding, reflecting a proximal *Cruziana* suite. This facies is interpreted as distal lower shoreface deposition.

The marine flooding surfaces bounding the fourth-order parasequences are commonly marked by the return to lower offshore or shelfal shale deposition, and are typically abrupt (Figure III-9). The low energy flooding surface is unlikely to be disturbed by the diminutive tracemakers which characterise the lower offshore settings. Flooding surfaces bounding fifth-order parasequences tend to show much biogenic modification, particularly where lower shoreface deposits are overlain by upper offshore sandy shales. Such contacts locally appear gradational, owing to the biogenic homogenization of the surface by the more robust tracemakers. Elsewhere, the upward transition from shallow to deeper water deposits may occur over intervals of several decimetres or more. Such transitions must reflect gradual relative sea level rise, possibly due to enhanced sedimentation rates contemporaneous with transgression.

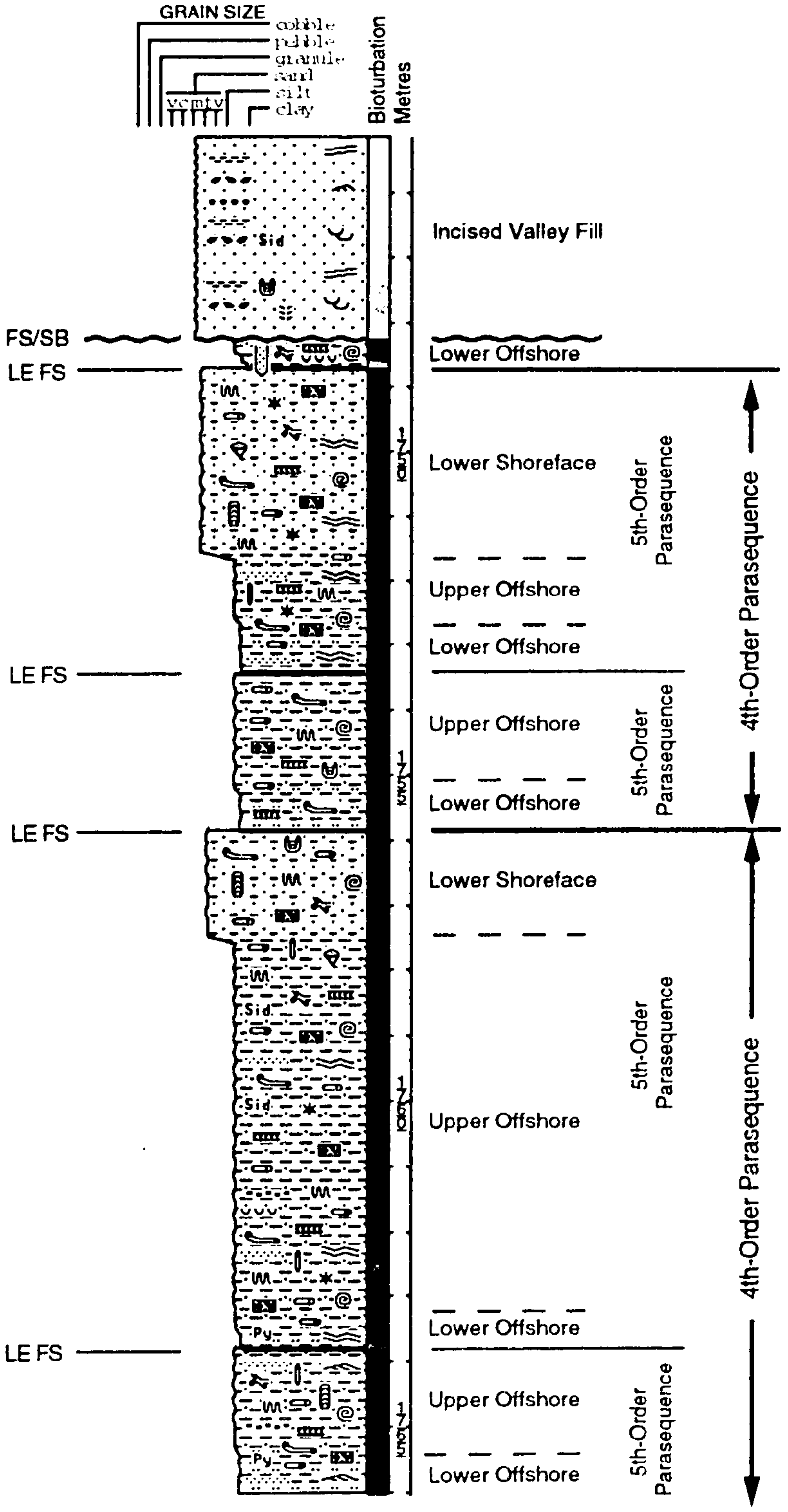
The stacked fourth- and fifth-order parasequences comprise a progradational parasequence set, reflecting a highstand systems tract, downlapping onto the Joli Fou marine shales of the underlying transgressive systems tract (Figure III-10). The trace fossil suites show abundant burrowing, characterised by a high diversity of forms, a lack of dominance by a few forms, presence of significant numbers of specialised feeding/grazing structures, and uniform distribution of individual elements, supportive of an equilibrium (K-selected), unstressed community (*cf.* Pianka, 1970) within fully marine environments. Sedimentation is interpreted to have been relatively slow and generally continuous.

High Energy Flooding Surfaces

High energy flooding surfaces (HE FS) are manifest as low relief, erosion surfaces cut by wave and current processes, associated with erosional

Figure III-9. Litholog of stacked fourth- and fifth-order parasequences bound by low energy flooding surfaces. These parasequences are erosionally truncated at the top by an amalgamated FS/SB, demarcating the base of an incised valley system in the Viking Formation of well 10-06-46-03W5 in the Crystal Field. The stacked parasequences can be grouped into a parasequence set, constituting a highstand systems tract. Incision of the valley reflects lowstand erosion, but eventual fill of the valley did not occur until the ensuing transgression, and constitutes the transgressive systems tract. The legend for the litholog is given in Figure III-5. Modified after Pemberton *et al.* (1992c).

Westcoast Et Al. Crystal 10-06-46-03w5



FOURTH- AND FIFTH-ORDER PARASEQUENCES IN THE REGIONAL VIKING FORMATION

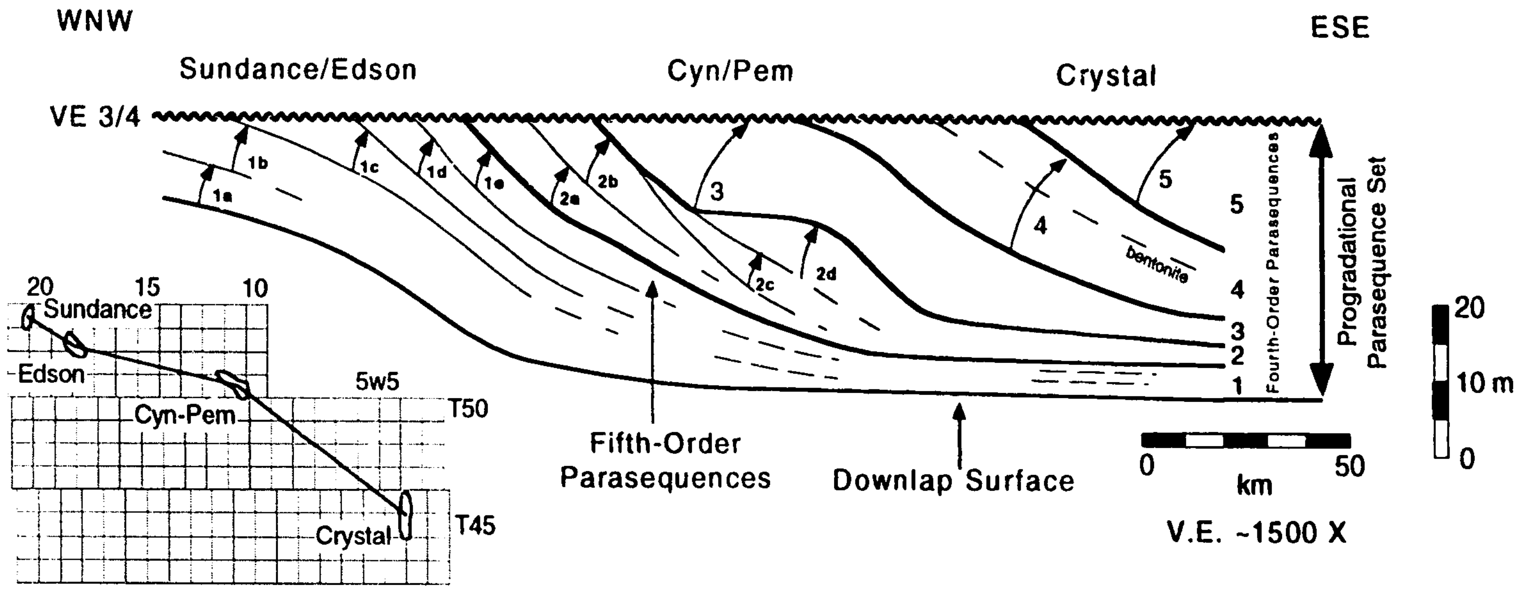


Figure III-10. Regionally Extensive Parasequences of the Viking Formation. This schematic cross-section shows the character of a number of coarsening upward successions in the basal portion of the Viking Formation. The main successions (1-5) correspond to fourth-order parasequences, consisting of shelfal/lower offshore to lower shoreface deposition. The lower two fourth-order parasequences consist of a number of fifth-order parasequences. All parasequences are generally bounded by low energy flooding surfaces. The overall stacking pattern corresponds to a progradational parasequence set, reflecting a highstand systems tract. The succession is truncated by a high energy flooding surface (VE3/4). The map to the lower left indicates the approximate line of section. Figure modified after Pattison (1991a).

shoreface retreat during transgression. Nummedal and Swift (1987) identified two subcategories of transgressive erosion surfaces: the higher energy ravinement surfaces (*cf.* Stamp, 1921) and the lower energy (distal) offshore marine erosion surfaces. Basinward, high energy flooding surfaces pass into low energy, non-erosional flooding surfaces.

These high energy flooding surfaces afford an elegant means of generating substrate-controlled trace fossil suites, because the surfaces are erosionally exhumed within a marine or marginal marine environment. This favours colonisation by firmground-dwelling organisms after the surface is cut, and prior to deposition of significant thicknesses of overlying sediment.

Many of these surfaces are of limited spatial extent and may be discontinuous, limiting their effectiveness in regional correlations. In addition, high energy flooding surfaces commonly produce pronounced stratigraphic breaks in the rock record, which may be easily mistaken for sequence boundaries (Nummedal and Swift, 1987) or amalgamated FS/SB surfaces, unless carefully placed into stratigraphic context.

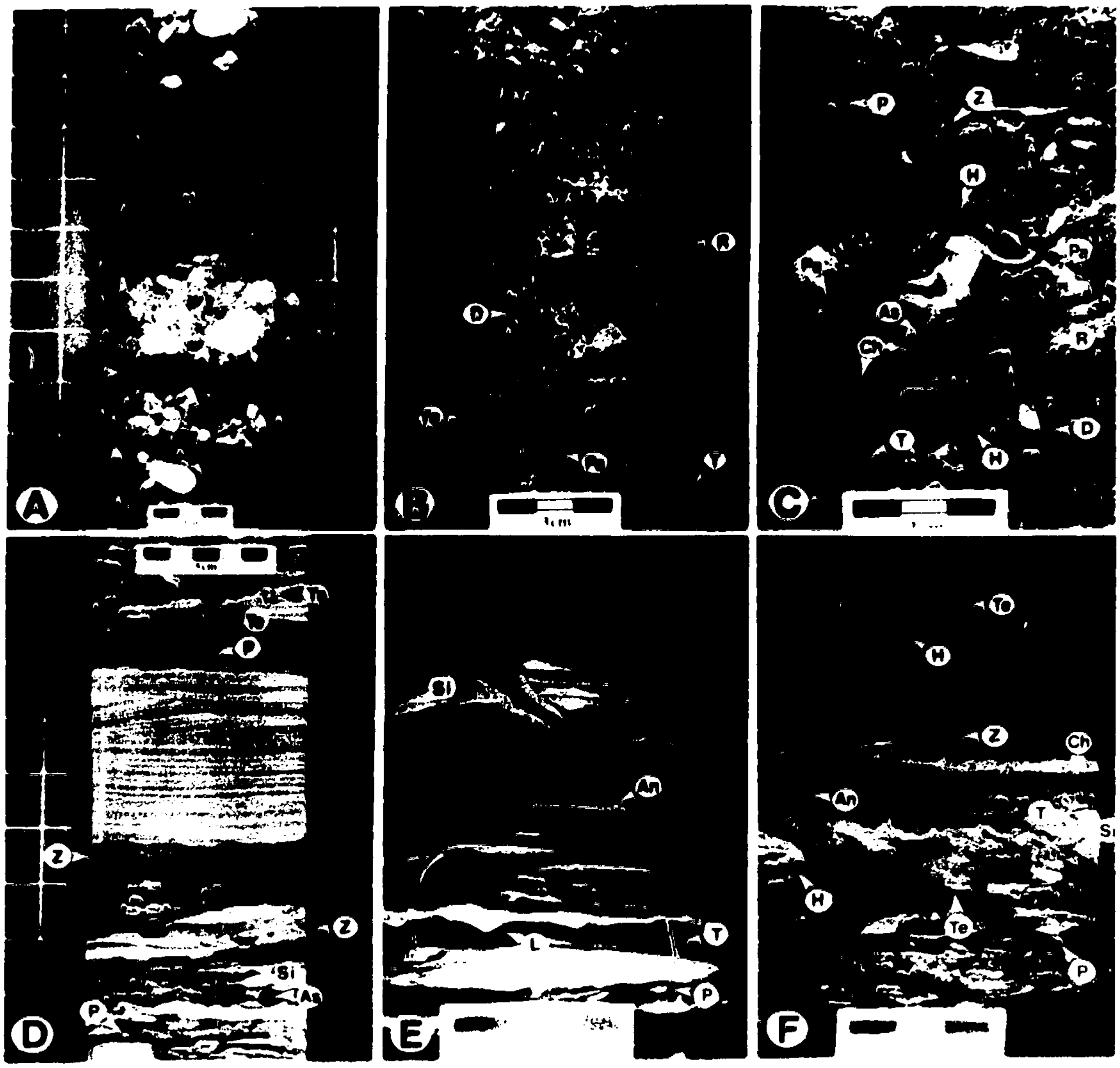
The upper portion of the Albian Viking Formation in the subsurface of central Alberta contains numerous high energy flooding surfaces, recording a complex history of transgression which culminated in maximum flooding of the North American Interior Seaway and deposition of the widespread Colorado shales and equivalents. Detailed stratigraphic correlations across the south central portion of Alberta by Pattison (1991a) have demonstrated the complexity of this transgression, where minor falls in relative sea level, stillstand periods and enhanced rates of relative sea level rise have produced at least seven discrete discontinuities of sequence stratigraphic significance.

The recognition of discrete high energy flooding surfaces is difficult on the basis of sedimentology alone, particularly when dealing with the upper Viking Formation, where there exist abundant sharp-based pebble stringers and thin, trough cross-stratified, coarse-grained sandstones within interbedded sandstones, siltstones and shales. Many of these coarse stringers could reflect veneers on transgressive surfaces, but due to their abundance, picking which ones have stratigraphic significance is highly problematic. However, virtually every high energy flooding surface incised into, or cut across shaly sediments, shows a *Glossifungites* suite. Several intervals contain up to seven such ichnologically-demarcated flooding surfaces within 6 meters of section. Many firmgrounds also appear to have been developed on siderite-cemented intervals within the shales. Whether the siderite is a function of the transgressive erosion, a chemical response related to deep penetration by the tracemakers of the *Glossifungites* suite, or that preexisting siderite-cemented bands formed resistant layers which the high energy flooding surface could not incise through, is uncertain, although in the latter case, soft-bodied fauna would find it difficult to penetrate such a layer.

Glossifungites assemblages are characterised by the ichnogenera *Diplocraterion* (dominantly *D. habichi*), *Skolithos*, *Arenicolites*, and firmground *Thalassinoides* (see Chapter II, Figure II-10; MacEachern *et al.*, 1992a,b). In many cases, the nature of the contact is cryptic, due to biogenic reworking by deeply penetrating structures. The presence of the firmground suite and dispersed pebbles are employed to interpret the existence of these hidden bed junctions (*i.e.* concealed bed junction; *cf.* Simpson, 1957). The *Glossifungites* assemblages record suspension-feeding behaviour associated with the period of higher energy during active marine erosion. Colonisation of the exhumed surface post-dates erosive shoreface retreat, but presumably occurs prior to significant deepening. Although these higher energy suites clearly cross-cut the lower energy softground suites, most authors have routinely regarded them as part of the softground assemblage, obscuring the true, original depositional conditions of the facies.

These high energy flooding surfaces are commonly overlain by conglomeratic lags, or erosionally-based, highly burrowed, pebbly muddy sandstones and sandy shales. The transgressive lags (Figure III-11A) locally contain shale interbeds containing an impoverished suite of *Planolites*, *Terebellina* and rare *Skolithos*, demonstrating marine conditions of deposition (refer to Facies A, MacEachern *et al.*, 1992a). These lags are interpreted as the proximal facies of the transgressive erosion (ravinement) process, and corresponds to the erosional remnants of a backstepping shoreface during erosional shoreface retreat. The pebbly muddy sandstones and sandy shales may grade out of the lags, or sharply overlie the high energy flooding surfaces themselves. They typically contain an abundant softground suite of *Terebellina*, *Planolites*, *Chondrites*, *Asterosoma*, *Teichichnus*, *Cylindrichnus*, *Rosselia*, *Siphonichnus*, *Helminthopsis*, *Zoophycos*, rare *Diplocraterion* and *Palaeophycus* (refer to Facies B, MacEachern *et al.* 1992a; Figure III-11 B,C). This facies is interpreted as the distal deposits of the continuing ravinement process; the presence of coarse-grained sand and

Figure III-11. Facies of the Transgressive Systems Tract, Viking Formation. **(A)** Facies A: Transgressive Lag. Conglomerate with sandy matrix at base passing into muddy matrix upwards, suggesting progressive deepening. Joffre Field, 02-21-38-26W4, depth 1582.6 m. **(B)** Facies B: Distal Ravinement Deposits. Pebbly, muddy sandstone with abundant *Diplocraterion* (D), *Teichichnus* (Te), *Palaeophycus* (Pa), *Terebellina* (T) and *Rosselia* (R). Joffre Field, 12-26-38-26W4, depth 1541.0 m. **(C)** Facies B: Distal Ravinement Deposits. Thoroughly burrowed sandy shale with dispersed pebbles. *Planolites* (P), *Helminthopsis* (H), *Zoophycos* (Z), *Terebellina* (T), *Chondrites* (Ch), *Rosselia* (R), *Diplocraterion* (D), *Asterosoma* (As) and *Palaeophycus* (Pa) are present. Kaybob South Field, 07-19-62-19W5, depth 1652.8 m. **(D)** Facies C: Stillstand Deposits. Wavy parallel laminated and combined flow ripple laminated sandstone beds, interstratified with thoroughly burrowed sandy shale, containing *Siphonichnus* (Si), *Planolites* (P), *Zoophycos* (Z), *Asterosoma* (As) and *Teichichnus* (Te). The facies is interpreted as a moderately storm-dominated, distal lower shoreface to proximal upper offshore deposit. Joarcam Field, 10-04-48-20W4, depth 974.3 m. **(E)** Facies C: Stillstand Deposits. Weakly-burrowed, wavy parallel laminated and oscillation ripple laminated sandstones and silty shales. *Lockeia* (L), *Anconichnus* (An), *Terebellina* (T), *Planolites* (P) and *Siphonichnus* (Si) are present. The facies is interpreted as a moderately storm-dominated, upper offshore deposit. Kaybob Field, 02-28-63-20W5, depth 1552.5 m. **(F)** Facies C: Stillstand Deposits. Intensely-burrowed sandy shale with a distal, normally graded storm bed. Traces include *Zoophycos* (Z), *Teichichnus* (Te), *Planolites* (P), *Chondrites* (Ch), *Anconichnus* (An), *Siphonichnus* (Si), *Terebellina* (T) and *Helminthopsis* (H). The facies is interpreted as a lower offshore deposit. Kaybob South Field, 07-19-62-19W5, depth 1651.5 m.

A
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dispersed pebbles record ongoing transgressive erosion in shallower water settings, with the coarser material reworked seaward by storm-initiated or storm-enhanced currents. The associated softground suite supports sediment accumulation in upper to lower offshore settings associated with continuing deepening.

Commonly grading out of the pebbly shales are interstratified sandstones, siltstones and shales, which possess moderate to low degrees of burrowing, and preserve remnant low angle parallel laminae, combined flow ripple laminae and less common oscillation ripple and current ripple laminae. The softground suite consists of *Planolites, Teichichnus, Asterosoma, Chondrites, Terebellina, Cylindrichnus, Rhizocorallium, Siphonichnus, Thalassinoides, Helminthopsis, Zoophycos, Anconichnus horizontalis,* rare *Diplocraterion, Skolithos, Arenicolites, Lockeia,* and *Palaeophycus* (refer to Facies C, MacEachern *et al.*, 1992a; Figure III-11 D,E,F). This facies is interpreted as upper offshore to distal lower shoreface deposits in a moderately to highly storm-dominated setting, records shallower water conditions than the underlying pebbly shales, and is attributable to progradation during a relative stillstand of sea level.

The stacking of *Glossifungites*-demarcated, erosionally-based, pebbly muddy sandstones and sandy shales, with interlaminated sandstones, siltstones and shales, supports the interpretation of transgressive erosion followed by short-lived periods of progradation. These successions reflect parasequences with high energy parasequence boundaries, and appear to be arranged in a retrogradational parasequence set. Many of these parasequences are probably the distal equivalents of more substantial shorefaces developed in landward positions.

The regional significance of these ichnologically-demarcated transgressive surfaces requires careful mapping and correlation. High energy flooding surfaces appear localised or amalgamated (co-planar) in several localities, making delineation difficult. The character of the overlying transgressive deposits also tends to vary considerably, even across short distances, complicating the process of determining surface equivalence. In addition, some *Glossifungites* ichnofacies-demarcated surfaces may be autocyclically-generated as well. Regardless, the presence of a substrate-controlled ichnofacies overlain by transgressive deposits provides a more distinctive and reliable means of identifying a surface of **more likely** sequence stratigraphic significance than merely choosing the base of any one of a number of pebble stringers or gritty shales. Ichnologically-demarcated high energy flooding surfaces occur in the Viking Formation over much of central Alberta, as well as in the roughly equivalent Paddy Member (Peace River Formation) of the Sinclair Field in north-central Alberta.

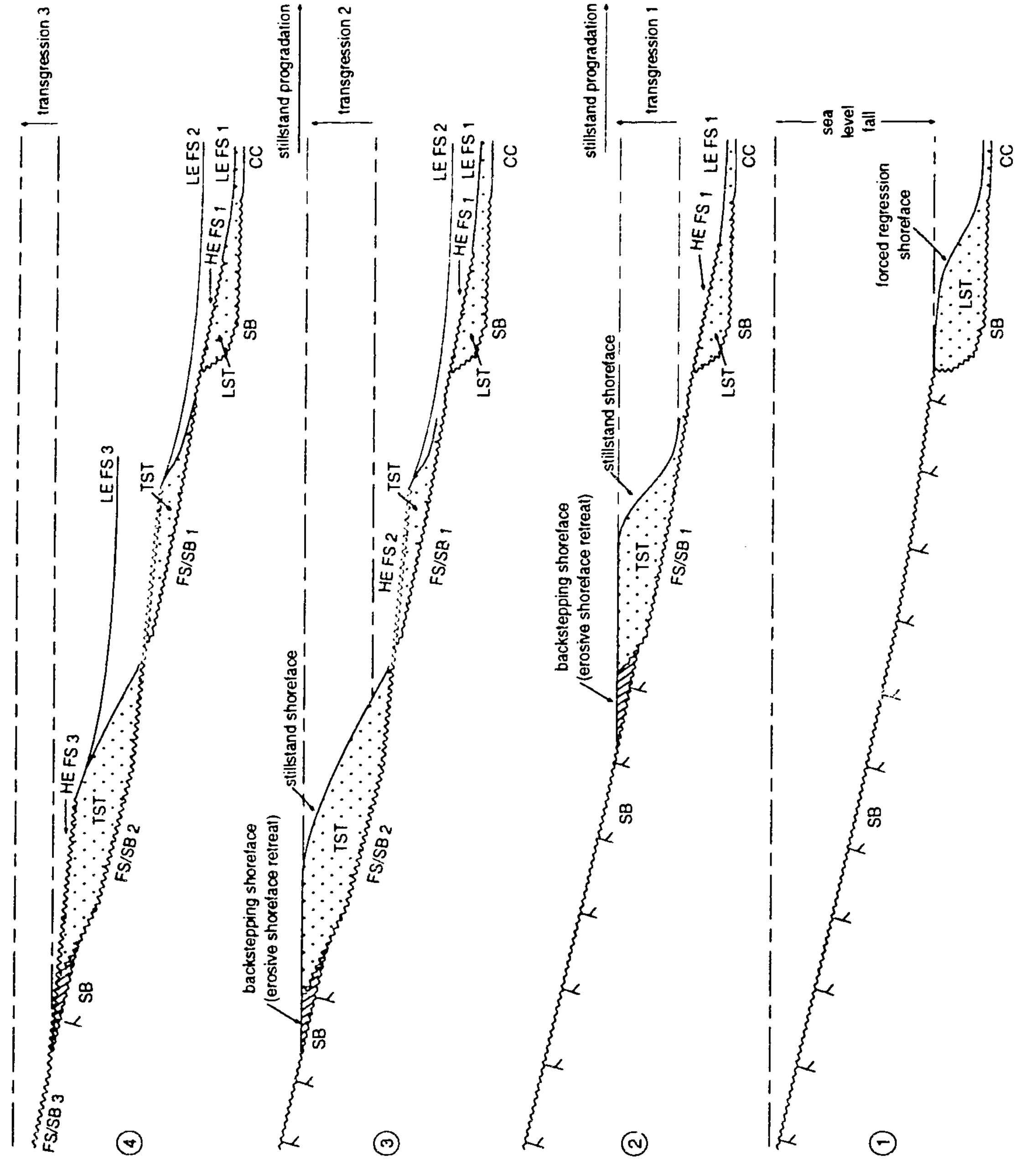
High Energy Parasequences: Stillstand Shorefaces

Several Viking Formation oil and gas fields in central Alberta produce hydrocarbons from NW-SE trending shoreface successions. Many of these shoreface deposits are areally restricted parasequences, bound above and below by high energy flooding surfaces (high energy parasequence boundaries). The progradational packages of strata overlying high energy marine flooding surfaces are herein termed "high energy parasequences". These parasequence boundaries may pass basinward into low energy flooding surfaces discussed above, and landward into FS/SB with abundant evidence of subaerial exposure preserved.

Figure III-12 schematically illustrates the development of these areally restricted parasequences and their relationship to forced regression shorefaces. The lower parasequence boundary corresponds to an FS/SB, generated by erosive shoreface retreat across a subaerial exposure surface. The high energy flooding surface removes all evidence of subaerial exposure in the Viking examples studied. A decrease in the rate of sea level rise or an increase in sedimentation rate permits the progradation of a shoreface over the FS/SB, seaward of the backstepping shoreface. The progradational shoreface constitutes the parasequence, marking a basinward shift of facies during a period of relative stillstand of sea level (*i.e.* a stillstand shoreface). An increase in the rate of transgression (resumed transgression) produces a low energy flooding surface below fairweather wave base and a high energy flooding surface at and above fairweather wave base. The high energy flooding surface truncates the upper portion of the stillstand shoreface and cuts a new FS/SB landward of the previous one. It is clear that what initially appears to be a single FS/SB is actually a composite surface, generated by multiple, discrete periods of transgressive modification of the sequence boundary. Since each successive stillstand shoreface lies progressively landward of the previous one, these high energy parasequences stack as a

Figure III-12. Schematic Model of Forced Regression and Stillstand Shoreface Development in the Viking Formation. **(1)** Relative sea level fall shifts the shoreline basinward, creating a widespread subaerial exposure surface. At the new shoreline position, a wave-cut notch is generated to a depth corresponding to fairweather wave base (FWWB). Below this, a non-erosional correlative conformity (CC) is developed. The subaerial exposure surface, wave-cut notch and CC are manifestations of the same sequence boundary (SB). The new shoreface, termed a forced regression shoreface, progrades over the SB and is an element of the lowstand systems tract (LST). **(2)** Ensuing transgression (transgression 1) generates a low energy flooding surface (LE FS) below FWWB, and a high energy flooding surface (HE FS), generated by erosive shoreface retreat, at and above FWWB. Continued transgression truncates the top of the forced regression shoreface, and cuts an amalgamated flooding surface and SB (FS/SB). The backstepping shoreface sits on the SB. No evidence of subaerial exposure is preserved on the FS/SB. During a relative stillstand of sea level, a shoreface progrades over the FS/SB. Note that since the FS/SB is cut during rising sea level, initial deposits on the surface may correspond to facies lying basinward of FWWB, in contrast to the forced regression shoreface. **(3)** Resumed transgression (transgression 2) generates an LE FS below, and an HE FS at and above the initial FWWB. Here, the HE FS removes the backstepping shoreface. Erosive shoreface retreat creates a new FS/SB landward of the first stillstand shoreface. The remnant of this shoreface constitutes a parasequence. During a pause in transgression, a new stillstand shoreface is produced seaward of the backstepping shoreface, and progrades over the FS/SB. **(4)** Resumed transgression (transgression 3) generates an LE FS below, and HE FS at and above initial FWWB. In this example, a remnant of the backstepping shoreface and, hence the SB, is preserved. Evidence of subaerial exposure is removed landward of this remnant, as a new FS/SB is cut. The progressive landward-stepping stillstand shorefaces produce a retrogradational parasequence set, reflecting the transgressive systems tract (TST).

The only localities where the initial SB is preserved are underlying the forced regression shoreface, small remnants veneered by backstepping shorefaces, and the CC. Erosive shoreface retreat has removed virtually all other evidence of subaerial exposure. The FS/SB is actually a composite surface, made up of segments of FS/SB (*i.e.* FS/SB1 - FS/SB 3) which are genetically related to specific transgressive events. Each FS/SB therefore correlates to its equivalent HE FS and LE FS, not to the previous FS/SB.


④
FS/SB 3
SB
HE FS 3
TST
FS/SB 2
LE FS 3
TST
FS/SB 1
LE FS 2
HE FS 1
LE FS 1
LST
SB
CC
transgression 3
③
SB
backstepping shoreface
(erosive shoreface retreat)
TST
FS/SB 2
stillstand shoreface
HE FS 2
TST
FS/SB 1
LE FS 2
HE FS 1
LE FS 1
LST
SB
CC
stillstand progradation
transgression 2
②
SB
backstepping shoreface
(erosive shoreface retreat)
TST
stillstand shoreface
FS/SB 1
HE FS 1
LE FS 1
LST
SB
CC
stillstand progradation
transgression 1
①
SB
forced regression
shoreface
LST
SB
CC
sea
level
fall

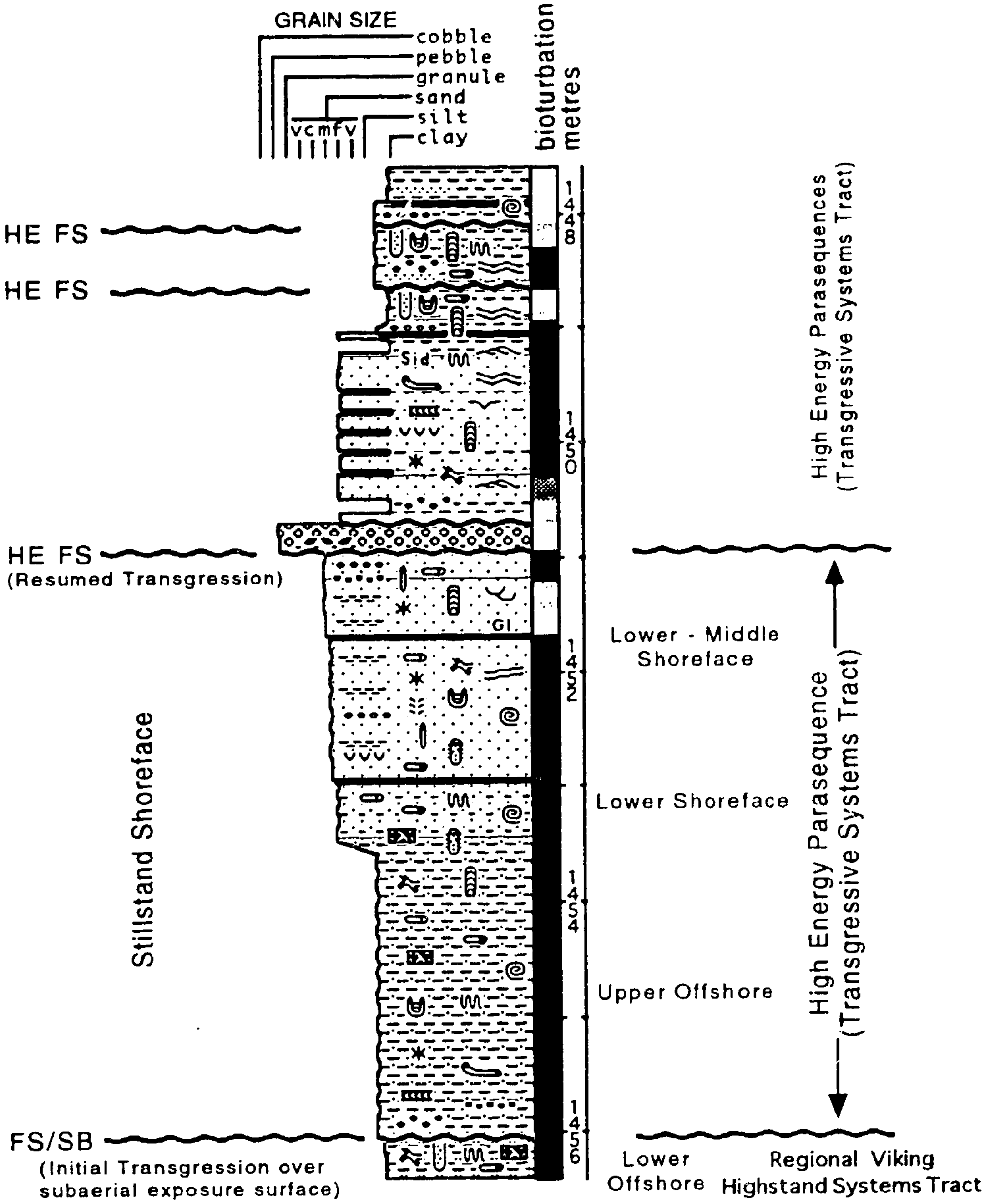
retrogradational parasequence set and thus, constitute elements of the transgressive systems tract.

The Viking interval of the Chigwell field is interpreted to reflect this depositional scenario (Figure III-13). The principal sand body overlies highly burrowed silty shales and sandy shales equivalent to those of the regionally extensive Viking Formation parasequences (*cf.* Figure III-8; Raychaudhuri *et al.*, 1992). The high energy flooding surface is rarely preserved as a discrete surface; intense burrowing has largely obliterated it. Instead, dispersed pebbles and *Glossifungites* assemblages consisting of *Thalassinoides* highlight the presence of the stratigraphic break. In a basinward direction, evidence of a break is largely lacking and the discontinuity may have graded into a low energy flooding surface overlying a correlative conformity, which has been biogenically homogenized.

The facies overlying the FS/SB are similar to those of the regionally extensive Viking Formation parasequences, both sedimentologically and ichnologically, although their distribution is restricted to a transgressively-cut notch (*cf.* Figure III-12). A fully marine, diverse assemblage of *Ophiomorpha, Skolithos, Arenicolites, Diplocraterion, Conichnus, Bergaueria, Helminthopsis, Chondrites, Terebellina, Schaubcylindrichnus, Planolites, Asterosoma, Cylindrichnus, Rosselia, Rhizocorallium, Teichichnus, Thalassinoides, Palaeophycus, Subphyllochorda, Siphonichnus,* and fugichnia, is recognised from the intensely burrowed muddy sandstone facies (Raychaudhuri, 1989; Raychaudhuri *et al.*, 1992). Interbedded with this facies is a trough cross-bedded to structureless, medium-grained sandstone facies, with *Ophiomorpha, Skolithos, Siphonichnus, Asterosoma, Palaeophycus* and *Planolites*. These two facies are interpreted to reflect weakly storm-influenced, low energy lower shoreface and middle to upper shoreface deposits, respectively. The lower shoreface trace fossil assemblage is diverse, and both intensely and uniformly burrowed, consistent with fully marine, equilibrium (K-selected) communities in unstressed environments (Pianka, 1970). The predominance of deposit feeding structures, with associated grazing and suspension feeding structures supports a lower shoreface setting (Figure III-3; MacEachern and Pemberton, 1992). The cross-bedded facies possesses a reduced diversity, a reduced abundance of burrowing and a greater dominance of vertical structures, reflecting the shallower water, higher energy and greater dynamic conditions of deposition in the middle to upper

Figure III-13. Litholog of a stillstand shoreface deposited on a high energy FS/SB, incised into lower offshore silty shales of an underlying parasequence. A *Glossifungites* suite of *Thalassinoides*, with associated chert pebbles demarcates the FS/SB. The overlying shoreface, manifest by upper offshore sandy shales passing into muddy sandstones of the lower shoreface, reflects progradation during a relative stillstand of sea level. Resumed transgression generated a high energy flooding surface (HE FS) which truncates the succession. The succession reflects a parasequence bound by high energy flooding surfaces. The overlying facies correspond to those of Figure III-16, reflecting later transgressive/stillstand cycles. Litholog is from the Viking Formation of the Chigwell Field (well 06-34-41-25W4), and is based on the interpretation of Raychaudhuri *et al.* (1992). The legend for the litholog is given in Figure III-5.

Resman Jorex Chigwell 06-34-41-25w4



shoreface setting. Basinward, thoroughly burrowed upper offshore sandy shales, containing a *Cruziana* suite similar to Facies 2 of the regionally extensive Viking Formation highstand parasequences, constitutes the initial deposition on the FS/SB (Figure III-13). These grade upward into lower and middle shoreface sandstones. The sand body overlying the FS/SB is interpreted to reflect progradation of a shoreface during a short-lived stillstand of relative sea level, which punctuated an overall transgression (Raychaudhuri *et al.*, 1992). The top of the main sand body has been truncated by erosion associated with resumed transgression, and is capped by a transgressive lag; features consistent with other high energy flooding surfaces (*cf.* MacEachern *et al.*, 1992a). A similar stratigraphic scenario has been proposed for other Viking Formation fields, such as Joffre and Gilby (Downing and Walker, 1988; Raddysh, 1988) as well as the Giroux Lake field (Chapter VIII).

The Turonian Cardium Formation in central Alberta also contains a series of stillstand shorefaces (parasequences) overlying FS/SB surfaces and capped by marine flooding surfaces (*cf.* Walker and Eyles, 1991; Walker and Plint, 1992). In the Pembina field, silty shales lying below the FS/SB contain a diverse trace fossil assemblage, including *Planolites, Chondrites, Helminthopsis, Terebellina, Asterosoma,* and rare *Zoophycos.* This suite reflects a distal *Cruziana* ichnofacies, suggesting offshore to shelfal accumulation (Figure III-3). This facies was subaerially exposed, probably with associated erosional exhumation, during a fall in sea level. The surface was subsequently transgressed and a high energy marine flooding surface substantially modified the sequence boundary, removing the evidence of subaerial exposure. This FS/SB surface is demarcated by a *Glossifungites* assemblage locally consisting of robust *Thalassinoides* (see Chapter II, Figure II-12) and more rarely, *Skolithos*, subtending into the underlying silty shales. The *Thalassinoides* systems are passively filled with pebbles and sand from the overlying structureless conglomerates (Vossler and Pemberton, 1988). The conglomerate body sharply overlies the FS/SB and corresponds to a gravelly shoreface which prograded basinward during a relative stillstand of sea level. The conglomerate largely appears structureless and shows no burrowing except within thin mud interbeds. The gravelly shoreface passes upward into a ?low energy flooding surface overlain by shelfal shales that contain *Helminthopsis, Planolites, Chondrites, Terebellina,* and *Zoophycos.*

As in the Viking Formation at Chigwell, these successions correspond to parasequences. The FS/SB, as is characteristic of these stratigraphic scenarios, shows a step-like morphology, which is steeper along the landward margin and flattens out in a basinward direction. Where the overlying flooding surface (related to resumed transgression) becomes erosional, it truncates the top of the conglomerate body and landward, cuts down to become co-planar with the FS/SB.

Colonisation of the FS/SB surface by the omission suite tracemakers corresponds to a hiatus in deposition after the initial transgressive modification of the sequence boundary, and progradation of the shoreface conglomerates during a stillstand in relative sea level. The stillstand shoreface was ultimately drowned and locally removed during resumed transgression, marked by the capping marine shelfal shales.

Differentiation from Forced Regression Successions:

It is imperative to differentiate between lowstand-generated forced regression shorefaces and high energy parasequences produced during periods of incremental transgression; the two successions reflect markedly different sequence stratigraphic settings. The forced regression shoreface is an element of the lowstand systems tract and lies directly on the sequence boundary. In contrast, the high energy parasequences are elements of the transgressive systems tract and are separated from the sequence boundary by a marine flooding surface.

Insofar as the ichnology of the sediment is concerned, there is little difference between the two stratigraphic settings. The parasequences and the forced regression shorefaces are shorefaces and are therefore subject to the same physical conditions. Animal behaviours, and hence their biogenic structures, are not significantly affected by either depositional scenario; trace fossil distributions in both settings largely obey existing models (Figures III-1 and III-3). Further, both the sequence boundary and the FS/SB are erosionally developed under marine conditions and favour colonisation by tracemakers of the substrate-controlled ichnofacies. In the Viking Formation, both shoreface successions are typically truncated by high energy flooding surfaces during initial or resumed transgression, respectively. In many cases, therefore, it may be difficult to discriminate between the deposits of these fundamentally different stratigraphic scenarios, except on the basis of regional stratigraphic context. Forced regression shorefaces, for example, occupy the most basinward position of a particular sea level lowstand, with the high energy parasequences stacking progressively landward along the depositional profile (Figure III-12).

There are, however, a few subtle differences in the character of the two successions that may be employed to separate them. In positions lying basinward of the erosional expressions of both the sequence boundary and the FS/SB (*i.e.* the correlative conformity and the LE FS, respectively), the successions are virtually identical. Both intervals are characterised by gradual coarsening upward successions, overlying a generally cryptic surface. Some differences do occur in basinal positions, however, where the surfaces are erosional.

Since the erosional sequence boundary extends seaward only to a depth of fairweather wave base, forced regression deposits directly overlying the surface should reflect conditions no deeper than lower shoreface (*cf.* Figure III-6). Continued sea level fall produces even shallower water facies overlying the sequence boundary. The FS/SB is also erosionally generated at initial fairweather wave base, but in contrast, is followed by increasing accommodation space. Thus, stillstand deposits immediately overlying the FS/SB may reflect deeper water conditions than fairweather wave base (*i.e.* offshore or shelfal shales; *cf.* Figure III-13).

In proximal positions, forced regression shorefaces tend to pass from lower to upper shoreface deposits over relatively short intervals, due to the reduced accommodation space. Further, since the shoreface is rapidly displaced basinward during falling sea level, lower, upper and even foreshore deposits may lie directly on the sequence boundary. It is this sharp-based character of the shoreface that is commonly employed to interpret an interval as a lowstand shoreface (*e.g.* Posamentier and Chamberlain, 1991, 1993; Posamentier *et al.*, 1992). In contrast, parasequences are associated with enhanced accommodation and therefore typically show more gradual coarsening upward successions. Even in proximal positions, initial deposition on the FS/SB will probably be no shallower than lower shoreface, because the parasequence must prograde basinward to fill the accommodation space.

The difficulties in discriminating between the two successions are further compounded by the necessity of detecting the erosional character of the stratigraphic break. Many of these surfaces are cryptic due to bioturbation and may easily be missed when logging core, particularly when the facies over- and underlying the surface are not fundamentally different. In the Viking Formation, for example, the discontinuity locally lies between upper offshore sandy shales of the regional highstand parasequences and lower shoreface sandstones of these anomalous successions. Intense burrowing in both facies obscures or destroys the contact, and the succession initially appears to be one of conformable progradation from offshore to lower shoreface environments. Locally, the presence of biogenically disturbed and displaced chert and lithic pebbles constitutes the only evidence of the erosion surface's existence. Elsewhere, a substrate-controlled trace fossil suite demarcates it. Only the full integration of sedimentology, ichnology and stratigraphy permits the reliable recognition and genetic interpretation of the sequence stratigraphic surface.

This difficulty in discriminating between lowstand and stillstand shorefaces is readily apparent in the Viking Formation of central Alberta. The main sandstones of the Joffre, Gilby and Chigwell fields were initially interpreted as lowstand shorefaces (Downing and Walker, 1988; Raddysh, 1988; Raychaudhuri, 1989), but have been subsequently re-interpreted as high energy parasequences produced during a relative stillstand of sea level, which punctuated an overall transgression (Pattison, 1991a; Raychaudhuri *et al.*, 1992). The re-interpretations arose principally as a result of placing these sand bodies into regional stratigraphic context.

The Cardium Formation poses an even greater problem, since the principal clastic material is conglomerate rather than sand. These gravelly shorefaces lack a diverse suite of trace fossils and possess few useful physical structures necessary to subdivide the interval into facies. Without these critical data, there is very little on which to base an interpretation of the shoreface's genesis, despite the well-preserved character of the underlying stratigraphic break; both stratigraphic scenarios are regarded as probable (Walker and Plint, 1992). Purely from a stratigraphic point of view, the most basinward shoreface on each sequence boundary probably reflects the forced regression shoreface, while each shoreface landward of it corresponds to later high energy parasequences of the transgressive systems tract.

Condensed Sections

Condensed sections are deposited over a long span of time, but remain thin due to slow rates of hemipelagic or pelagic sedimentation. Such intervals are most extensive during periods of maximum transgression (Loutit *et al.*, 1988), when the basin is starved of terrigenous material (Van Wagoner *et al.*, 1990). Several condensed sections have been described from the rock record (*e.g.*, Legget, 1980; Jenkyns, 1980; Leckie *et al.*, 1990), and Loutit *et al.* (1988) summarised most of their common characteristics (Table III-2). Leckie *et al.* (1990) studied a condensed section in the Shaftesbury Formation of the Peace River area, Alberta, which overlies a high energy flooding surface. Numerous differences exist between those condensed sections summarised by Loutit *et al.* (1988) and the Shaftesbury example (Table III-2), which Leckie *et al.* (1990) attributed to the shallower water setting of the latter. This type of shallow water condensed section may be more typical of basins such as the epicontinental Cretaceous Interior Seaway.

Leckie *et al.* (1990) did not recognise trace fossils in the Shaftesbury Formation condensed section, mainly due to the poor preservation of the shales in outcrop. In subsurface cores of the Shaftesbury Formation, south of the Peace River Arch area, the same high energy flooding surface and overlying transgressive succession described by Leckie *et al.* (1990) can be recognised, but the ichnology is more readily observed due to the unweathered character of the rock. The transgressive erosion surface is commonly overlain by a 25-50 cm thick pebble lag, locally grading into an intensely burrowed pebbly or sandy shale. A fully marine suite of *Planolites, Terebellina, Thalassinoides, Teichichnus, Helminthopsis, Chondrites, Asterosoma* and *Diplocraterion* is present within the transgressive deposits. These pass abruptly into laminated shales with rare thin silt stringers. The shale is virtually unburrowed, though it contains a sporadic and impoverished distribution of rare *Planolites, Teichichnus,* and very rare *Chondrites, Zoophycos* and *Lockeia*. This may correspond to the shallow water condensed section of Leckie *et al.* (1990). There does not appear to be a significant difference, however, between the abundance, diversity, and distribution of ichnogenera in intervals corresponding to high radioactivity on the gamma-ray well log signature (*i.e.* the condensed section) and intervals lying above it. It is unclear whether the impoverished nature of the

COMMON CHARACTERISTICS OF CONDENSED SECTIONS

Legend
- ● feature present
- O feature not present
- ? presence or absence not addressed

	Cambro-Ordovician, Baltic Shield	Jet Rock Shales	Shaftesbury Fm	Mowry Shale	Awgu Shale	Eocene-Oligocene Boundary, Alabama
1. Slow sedimentation rates	●	●	●	●	●	●
2. Reduced oxygen values	●	●	●	●	●	●
3. High organic matter content (TOC)	●	●	●	●	●	●
4. High concentration of Platinum elements (iridium)	?	?	O	?	?	?
5. Presence of authigenic minerals (e.g. glauconite, phosphate, siderite)	●	●	O	?	●	●
6. High Gamma-ray counts	?	?	●	●	?	●
7. Abundant and diverse plankton	●	O	O	●	●	●
8. Abundant and diverse microfauna	●	O	O	●	●	●
9. Abundant open-ocean planktonic foraminifera	?	O	O	?	●	●
10. Low concentrations of benthic foraminifera	●	●	●	●	●	●
11. Abruptly overlies nonmarine or shallow marine sediments	●	O	●	●	O	●
12. Section overlain by downlap surface	?	?	O	●	O	●
13. Associated with burrowed, bored or slightly lithified tops	●	?	O	●	?	?
14. Generally unburrowed or sparsely burrowed interval	●	●	●	●	●	?

Table III-2. Six condensed sections selected from epeiric settings are summarised. Data were collected as follows: Cambro-Ordovician (Baltic Shield) - Lindström (1963) and Jenkyns (1986); Jet Rock Shales (Toarcian; U.K.) - Morris (1979, 1980); Shaftesbury Formation (Albian; Alberta, Canada) - Leckie *et al.* (1990); Mowry Shale (Late Albian; Wyoming, U.S.A.) - Byers and Larson (1979) and Jenkyns (1980); Awgu Shale (Turonian; Benue Trough, Nigeria) - Petters (1978) and Jenkyns (1980); Eocene-Oligocene Boundary (Alabama, U.S.A.) - Loutit *et al.* (1988). Modified after Pemberton *et al.* (1992a).

suite corresponds to reduced oxygenation or is purely a taphonomic phenomenon (*cf.* Facies E, MacEachern *et al.*, 1992a).

The ichnological signatures of condensed sections per se have yet to be documented adequately. In general, the units tend to be unburrowed, which is commonly attributed to low oxygen content and overall stressful conditions for benthic organisms. Six selected condensed sections from epeiric settings show a general adherence to conditions of higher total organic carbon (TOC), reduced oxygen values, low concentrations of benthic foraminifera, and minimal or absent burrowing (Table III-2). The interrelationships of low oxygen, preservation of organic carbon, and biologically lethal seafloor conditions have been discussed by numerous authors (*e.g.*, Byers and Larson, 1979; Legget, 1980; Jenkyns, 1980; Savrda and Bottjer, 1987). Savrda and Bottjer (1987) noted that ichnofaunas are generally more indicative of both magnitudes of, and rates of change in, oxygen levels than are macrobenthic body fossil suites. Bromley and Ekdale (1984) found that with decreasing oxygenation at the sea floor, *Planolites, Thalassinoides,* and *Zoophycos* progressively disappear before *Chondrites* does, suggesting that the *Chondrites* tracemaker may have been capable of surviving conditions of anoxia. Savrda and Bottjer (1987) also found that burrow sizes decrease with increasing depth and decreasing oxygen levels. In their study of the Monterey Formation (Miocene) of California and the Niobrara Formation (Cretaceous) of Colorado, Savrda and Bottjer (1987) proposed oxygen-related ichnocoenoses to distinguish units of more or less uniform bottom-water oxygenation. One possible means of recognising condensed sections characterised by dysaerobic or anaerobic conditions may be by the presence of a suspiciously unburrowed or slightly burrowed dark carbonaceous shale lying between more intensely burrowed marine deposits. Bhattacharya (1989), in his work on the Dunvegan Formation, differentiated shallow water shales from those attributed to maximum flooding by the transition from weakly burrowed shales to well-laminated, unburrowed shales. The laminated shales may represent condensed sections separating transgressive systems tract deposits from highstand systems tract deposits.

Amalgamated Sequence Boundaries And Flooding Surfaces (FS/SB)

Amalgamated sequence boundaries and high energy flooding surfaces (FS/SB) are commonly colonised by substrate-controlled tracemakers. The lowstand erosion event typically produces widespread firmground, hardground, and woodground surfaces. The ensuing transgressive event tends to remove much of the lowstand deposits by erosive shoreface retreat and exposes the discontinuity to marine or marginal marine conditions, permitting organisms to colonise the re-exhumed substrate. The sequence boundary component may correspond to subaerially exposed areas, such as delta plains, fluvial floodplains, interfluves, or incised valleys.

Transgressive Erosion Across Subaerially Exposed Surfaces

The Dunvegan Formation in the subsurface of the Jayar Field, central Alberta, contains a high energy flooding surface cut into rooted and subaerially exposed delta plain deposits (Bhattacharya and Walker, 1991). The erosional discontinuity is demarcated by a *Glossifungites* suite of *Thalassinoides*, passively filled with coarse-grained sands infiltrated from an overlying transgressive sand sheet (see Chapter II, Figure II-14 C). The FS/SB constitutes the boundary between Allomember B and C of the Dunvegan Alloformation (Bhattacharya, 1989; Bhattacharya and Walker, 1991). Oppelt (1988) noted a similar type of FS/SB at the ?Aptian/Albian Gething/Bluesky contact in northeastern British Columbia (Table III-1). An excellent example of this also occurs at the Lower Albian Mannville Group-Joli Fou Formation contact in the Kaybob Field of central Alberta, where rooted, incipient paleosols are cross-cut by robust firmground *Thalassinoides*, passively filled with muddy sand and large siderite-cemented clasts (see Chapter II, Figure II-14 A,B). The overlying silty shales record deposition in proximal shelf to lower offshore conditions, with *Planolites, Helminthopsis, Terebellina,* rare *Chondrites* and very rare *Zoophycos.*

Areas marginal to incised valley systems correspond to interfluves which are subaerially exposed during lowstand excavation of the valley and late lowstand valley infill. In the Viking Formation, these interfluves are generated on original fully marine regional Viking offshore to lower shoreface deposits. When the valley becomes filled and is transgressively overrun, a high energy flooding surface is commonly generated on the interfluve, which removes any evidence of exposure. Differentiating this from pure transgressive erosion is impossible, until placed into regional context. In other localities, the FS/SB may not even appear to reflect deepening, such as where the interfluve is cut into lower offshore or shelfal deposits of a regional Viking parasequence and is overlain by lower or upper offshore shales. In such settings, recognition of the nature of the surface may hinge on the delineation of the associated incised valley fill deposits.

Incised Valley Fill Deposits

Five Viking Formation fields, namely Crystal, Willesden Green, Sundance, Edson, and Cyn-Pem, contain facies associations interpreted to reflect estuarine incised valley deposition. The observed facies types and their distributions indicate that they accumulated in a barrier estuary or wave-dominated embayed estuary setting, in the sense of Roy *et al.* (1980) and Dalrymple *et al.* (1992) (Figure III-14; see Chapter IX).

The valley fill deposits demonstrate a tripartite zonation of facies and facies associations, defining three major depositional zones within the estuary. The bay head delta complex is sand-dominated and formed at the head of the estuary, where much of the sediment is fluvially-derived, though commonly wave-reworked. The central basin complex grades seaward out of the bay head delta complex and into the estuary mouth complex, and is a zone of interference between marine and fluvial processes. The central basin corresponds to the lowest energy zone of the estuary. The estuary mouth complex occurs seaward of the central basin and is sand-dominated. Marine processes (waves and tides) are responsible for transport and deposition of the sediment. A fourth depositional complex reflects channel deposition, largely corresponding to periods of re-incision and fill.

Ichnology of Viking Formation Incised Valley Surfaces:

In most of the incised valley systems of the Viking Formation, the valley base and walls are demarcated by a *Glossifungites* assemblage, indicating that the valley probably did not fill until the ensuing transgression. Either the valley served as a zone of sediment bypass and possessed no fluvial deposits, or any lowstand deposits were subsequently eroded and reworked during the transgression, producing a high energy FS/SB. The high energy flooding surface most likely reflects initial transgression or tidal scour ravinement,

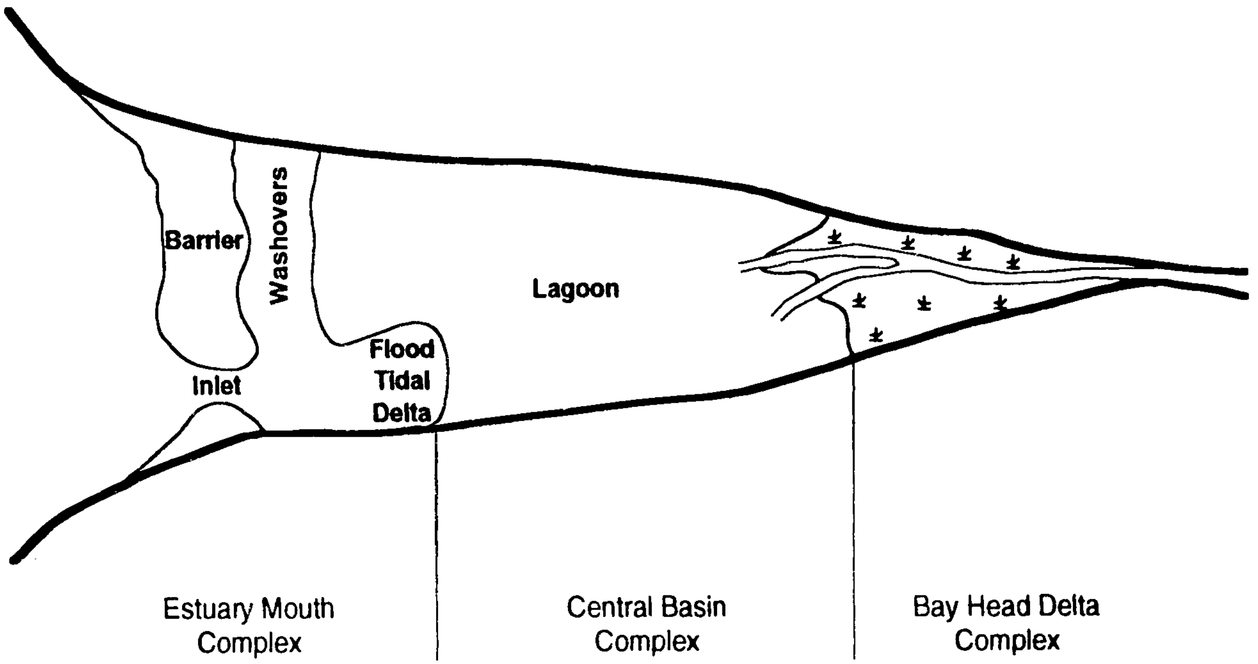


Figure III-14. Conceptual Model for Wave-Dominated, Embayed Estuarine Depositional Systems. The model best explains the distribution of observed facies and facies associations in the Viking Formation incised valley fills. The system demonstrates a tripartite zonation of facies, corresponding to three main depositional complexes: the bay head delta, the central basin and the estuary mouth. The model is based on observations of embayed estuary systems along the New South Wales coast of Australia, by Roy *et al.* (1980). Figure is modified after Dalrymple *et al.* (1992).

associated with rapid rise of sea level. As such, the base of the valley serves both as a sequence boundary and as the base of the transgressive systems tract.

More recently, Allen and Posamentier (1993) and Zaitlin *et al.* (in press) have designated a number of transgressive surface types within valley fill successions. They discriminate between the transgressive surface (corresponding to the initial flooding surface), the wave ravinement surface, the tidal scour ravinement surface and the maximum flooding surface (Figure III-15). All surfaces may be demarcated by a *Glossifungites* assemblage, although the zones of colonisation are clearly restricted to the limits of marine influence within the valley.

Widespread *Glossifungites* suites may be developed within the valley where the initial flooding surface is directly amalgamated with the sequence boundary (FS/SB). Where initial fluvial lowstand deposits separate the two surfaces, a substrate-controlled suite is absent. In situations where the initial flooding surface is highly erosive, lowstand fluvial deposits may be completely reworked, permitting the sequence boundary to become colonised. Such *Glossifungites* assemblages may be overlain by relatively thick, transgressively reworked lags. Most of the basal valley surfaces in the Viking Formation probably reflect this type of high energy initial FS/SB.

During continued transgressive fill of the valley, erosive shoreface retreat of the barrier complex generates a relatively widespread wave ravinement surface, which may become amalgamated with the initial flooding surface and/or the sequence boundary. This type of FS/SB is largely restricted to the mouth of the estuary complex and, with continued transgressive fill, rises stratigraphically as the wave ravinement surface incises into previously deposited estuarine valley fill. Consequently, the wave ravinement surface may facilitate firmground colonisation along its entire extent, but corresponds to an FS/SB near the valley mouth, passing landward into an inter-valley transgressive surface of erosion (TSE).

The development and migration of tidal inlets also favours the generation of firmgrounds, which may become colonised by the *Glossifungites* ichnofacies. These tidal scour ravinement surfaces may locally erode through all previous valley fill deposits and incise into the sequence boundary, generating a relatively localised FS/SB. With continued erosive shoreface retreat during transgressive fill of the valley system, these tidal scour ravinement surfaces may rise stratigraphically and incise into previously

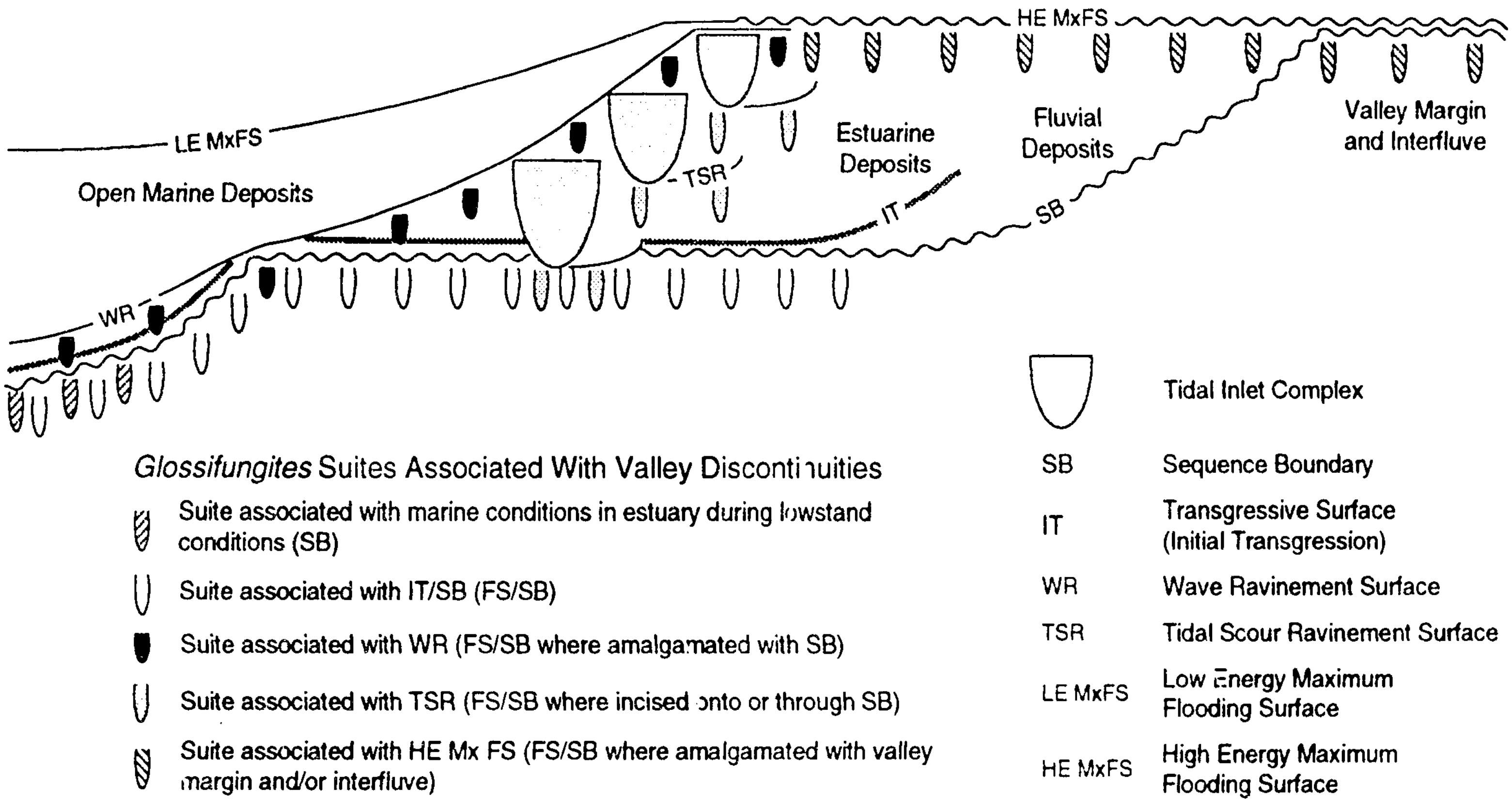


Figure III-15. Schematic representation of erosional discontinuities within a simple (single stage) incised valley system. The diagram also shows the zones which may contain *Glossifungites* assemblages. The surfaces locally amalgamate with one another, affording the possibility of *Glossifungites* suites of differing stage of valley infill to overprint one another. The diagram is adapted from Zaitlin *et al.* (in press).

deposited estuarine deposits, producing areally restricted *Glossifungites*-demarcated TSE. Fluvial channel diastems, which may appear sedimentologically similar, are not colonised, because the surfaces are generated landward of the marine limit in the valley.

If the valley is ultimately filled and transgression overruns the entire system, the potential exists to generate a widespread *Glossifungites*-demarcated TSE corresponding to the maximum flooding surface. A high energy (erosive) maximum flooding surface favours truncation of the upper portion of the valley and generation of widespread firmgrounds across both the valley fill and the adjacent valley margins and interfluves, which may become colonised by a substrate-controlled trace fossil suite. In contrast, low energy (non-erosive) maximum flooding surfaces may not permit firmground colonisation except along the valley margins and interfluves, where subaerial exposure has permitted the substrates to dewater and become firm.

In situations where the valley is subjected to re-incision events during subsequent periods of lowstand conditions, new sets of FS/SB and inter-estuarine TSE may be cut, and colonised. The compound fills of such valley systems typically display numerous dissected and locally amalgamated segments of *Glossifungites*-demarcated surfaces, and require careful stratigraphic analysis in order to discriminate one from another, delineate their extents in the valley, and place them into a sequence stratigraphic framework.

The FS/SB are excavated into the coarsening upward, regionally extensive Viking silty shales, sandy shales and muddy sandstones of the underlying highstand parasequence set. These intervals contain fully marine, high diversity and abundant distal to proximal *Cruziana* softground suites (Figures III-3 and III-8), in marked contrast to that of the valley-fill successions. In the Crystal Field, the FS/SB is marked by the *Glossifungites* ichnofacies, manifest by numerous sharp-walled, unlined *Diplocraterion* shafts (see Chapter II, Figure II-17 A,B,C), firmground *Thalassinoides, Diplocraterion habichi*, and firmground *Gastrochaenolites*. In the Willesden Green field, the valley base is locally marked by a *Glossifungites* assemblage consisting of spectacular *Rhizocorallium saxicava* (see Chapter II, Figure II-17 D,E,F), *Thalassinoides, Arenicolites, Skolithos* and *Diplocraterion habichi*. The valley surface in the Sundance and Edson fields is only rarely demarcated by firmground

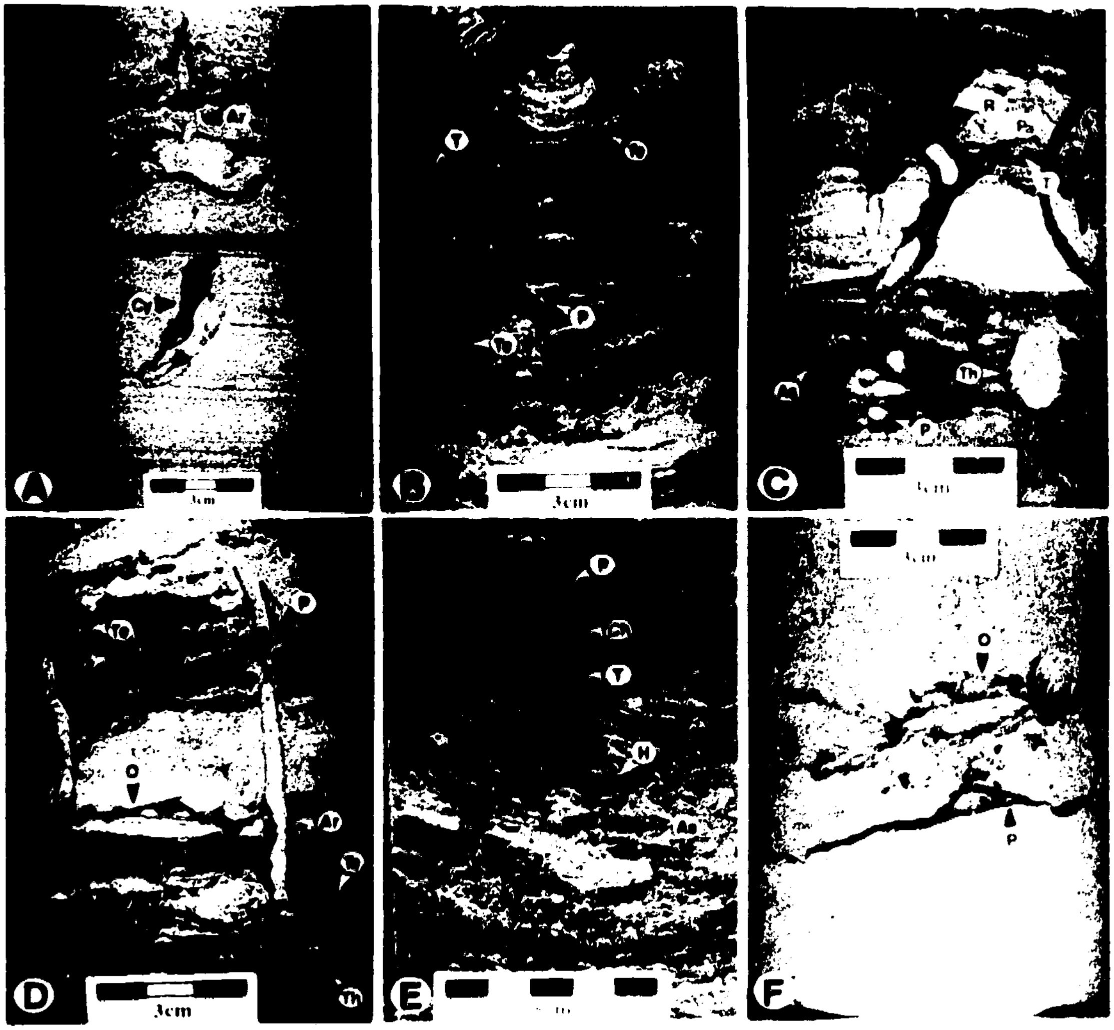
Thalassinoides, while the valley at the Cyn-Pem field is marked by abundant firmground *Arenicolites* and *Skolithos*.

Ichnology of Incised Valley Fills:

The bay head delta complex (Figure III-16 A) is generally characterised by weakly and sporadically burrowed, wavy and parallel laminated sandstones reflecting delta front storm beds, horizontal laminated to current rippled delta slope sediment-gravity flows, and trough cross-beds reflecting distal portions of distributary channels. All shallow water facies of the bay head delta have been removed by subsequent transgressive erosion. The overall trace fossil diversity is high with 16 ichnogenera noted (Figure III-17), though the burrow distribution is sporadic and numbers of individual forms are low. Any one cored interval may possess as little as 3 or 4 ichnogenera. The stresses imposed on the organisms and their resulting behaviour are due largely to the episodic nature of deposition and the variable sedimentation rates, rather than to fluctuating salinity, although brackish water conditions may have exerted an influence.

The central basin complex (Figure III-16 B, C) consists of two interbedded facies. The most distinctive facies comprises delicately interstratified, moderately to intensely burrowed sandy mudstones, weakly burrowed sand- and silt-poor, dark mudstones, and thin (millimeter to centimeter scale) sandstone stringers. Syneresis cracks are sporadically distributed, though typically uncommon. Burrowing is variable on a small scale, but relatively uniform throughout the facies interval. The facies is interpreted as fairweather deposition of sands and muds within the lagoon or bay environment of the central basin. Most biogenic structures associated with this facies indicate deposit feeding to grazing behaviour, consistent with sediment deposition predominantly from suspension. The other main facies consists of storm-generated wavy parallel to combined flow and oscillation ripple laminated sandstone beds. Thin conglomerate beds and dispersed pebbles are locally common. The trace fossil suite demonstrates opportunistic colonisation of the tempestite, subsequently replaced by the fairweather suite. The trace fossil assemblage for the central basin complex reflects a high diversity, (19 ichnogenera; Figure III-17), with intense and reasonably uniform burrowing. Close inspection, however, demonstrates that the ichnological suite of the central basin complex is quite complicated and

Figure III-16. Facies of Estuarine Incised Valley Fills in the Viking Formation. **(A)** Bay Head Delta Complex: Wavy parallel laminated, fine-grained sandstone passing into burrowed sandstone, reflecting storm bed deposition on the delta front. *Cylindrichnus* (Cy) and *Arenicolites* (Ar) correspond to opportunistic colonisation of the storm bed. The mottled top of the bed reflects the replacement of this suite by the resident fairweather community. Crystal Field, 16-24-45-04W5, depth, 1807.1 m. **(B)** Central Basin Complex: Highly burrowed sandy shales. Remnant storm beds are present, but largely destroyed by infaunal burrowing. *Teichichnus* (Te), *Terebellina* (T), and *Planolites* (P) dominate. Crystal Field, 08-31-46-03W5, depth 1673.1 m. **(C)** Central Basin Complex: Sand-dominated, interbedded sandstones and sandy shales. Note the combined flow ripple laminated sandstone, penetrated by *Rosselia* (R). *Planolites* (P), *Thalassinoides* (Th), *Asterosoma* (A), *Palaeophycus* (Pa) and *Terebellina* (T) are also present. Willesden Green Field, 06-36-40-07W5, depth 2322.7 m. **(D)** Estuary Mouth Complex: Storm-generated, wavy parallel laminated sandstones with mud interlaminae, reflecting deposition on the landward side of the estuary mouth barrier system. Note the *Ophiomorpha* (O), *Arenicolites* (Ar), *Planolites* (P), *Teichichnus* (Te) and *Thalassinoides* (Th). Crystal Field, 08-16-48-03W5, depth 1529.1 m. **(E)** Estuary Mouth Complex: Thoroughly burrowed, sandy shale reflecting upper offshore deposits of the barrier system, on the seaward side of the estuary mouth complex. *Chondrites* (Ch), *Helminthopsis* (H), *Planolites* (P), *Asterosoma* (A) and *Terebellina* (T) are present. Sundance Field, 01-06-55-20W5, depth 2676.5 m. **(F)** Channel-Fill Complex: Moderately well-sorted, medium-grained, trough cross-stratified sandstone. The presence of *Ophiomorpha* (O) and *Planolites* (P) attests to a marine influence on the channel fill. Edson Field, 12-34-52-19W5, depth 2586.5 m.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records highly variable depositional conditions. Salinity fluctuations, episodic deposition and variable substrate consistency appear to be the dominant stresses imparted on the trace-making organisms.

The estuary mouth complex (Figure III-16 D, E), like the bay head delta, is preserved as an erosional remnant, consistent with the model of Roy *et al.* (1980). The dominant facies association reflects the landward side of the estuary mouth adjacent to the central basin, and shows a genetic affinity with sandy central basin facies associations. Fairweather conditions are characterised by moderately to abundantly burrowed, ripple laminated sandstones, with minor intercalated mud beds. As in virtually all the other valley fill facies associations, tempestites are common. Washover deposits record the breaching of the barrier by storms acting on the seaward side of the estuary mouth. Like the central basin complex, the trace fossil suite shows a high diversity of forms (19 ichnogenera; Figure III-17), but the distribution of individual elements reflects the presence of various environmental stresses. The higher energy nature of fairweather deposition is reflected by the general decrease in importance of grazing and deposit feeding behaviours. Episodic deposition appears to be the main environmental stress indicated by the trace fossil suite, mainly in the form of opportunistic colonisation of the tempestites by simple vertical dwelling and suspension feeding structures.

The facies association from the seaward side of the estuary mouth (Figure III-16 E) is erosionally-bound and interpreted as the basal portion of the estuary mouth barrier bar itself. It rests on an amalgamated FS/SB surface and is overlain by a high energy flooding surface. The facies association shows fully marine conditions, consistent with a position on the seaward side of the estuary. Although there may be some transgressive reworking of the top of the succession due to erosive shoreface retreat, the coarsening upward interval of sandy shales and muddy sandstones is interpreted to reflect the upper offshore to distal lower shoreface component of the erosionally removed estuary mouth barrier complex (Figure III-14). The trace fossil suite shows a uniform distribution of individual forms, a high degree of burrowing, a reasonable diversity of elements (15 ichnogenera), a lack of overwhelming dominance by a few forms, and the presence of moderate numbers of specialised grazing and feeding/dwelling structures; features that contrast markedly with the ichnology of facies associations deposited in the valley. The assemblage associated with the remnant barrier complex is consistent with a fully marine, largely unstressed, equilibrium (K-selected) community and shows a closer genetic affinity with facies associations of the regionally extensive Viking Formation highstand parasequences (Figure III-8) than to the incised valley fill assemblages.

Channel fill facies associations (Figure III-16 F) predominantly reflect relatively small, migrating subaqueous dunes. The amalgamation of the trough cross-beds into thick intervals supports a high aggradation rate. Interstratified low angle planar laminated sandstones with associated current ripple lamination are interpreted as sheet-flow transport of sand capped by waning flow deposits, possibly reflecting higher flow velocities during flood stage discharge in the channel, or proximity to the channel margins. The trace fossil suite (Figure III-17) demonstrates that most channel complexes accumulated in marine or marginal marine conditions, although the degree of salinity stress is difficult to determine. The main stresses imposed on the trace fossil suite appear to be related to migration of subaqueous dunes and to high energy sheet-flow conditions followed by rapid deposition.

Facies associations within the incised valley fills *sensu stricto* show a remarkably high trace fossil diversity (Figure III-17), particularly when compared to other estuarine settings (*e.g.* Wightman *et al.*, 1987; Ranger and Pemberton, 1992). On close inspection, however, the degree of burrowing, its uniformity, and the distribution of individual elements is highly variable. Overall, *Teichichnus*, *Terebellina* and *Planolites* dominate in the shaly substrates, while *Ophiomorpha*, *Skolithos* and *Arenicolites* are dominant in the sandy substrates. Both groups are ubiquitous in the valley fill facies associations and correspond to simple structures produced by trophic generalists. Such r-selected (opportunistic) behaviours are characteristic of stressed environmental settings (Pianka, 1970), particularly those subject to salinity fluctuations. The regular alternation between these two groups of trace fossils reflects the episodic nature of tempestite deposition and the variability in substrate consistency, and constitutes the mixed *Skolithos-Cruziana* ichnofacies (Pemberton and Frey, 1984; Pemberton *et al.*, 1992b).

Many of the secondary and accessory elements of the trace fossil assemblage are not opportunistic and record more specialised and elaborate feeding behaviours which are uncommon in stressful environmental settings. Their sporadic distribution and variable abundances in the facies associations are interpreted to reflect fluctuations in salinity within the

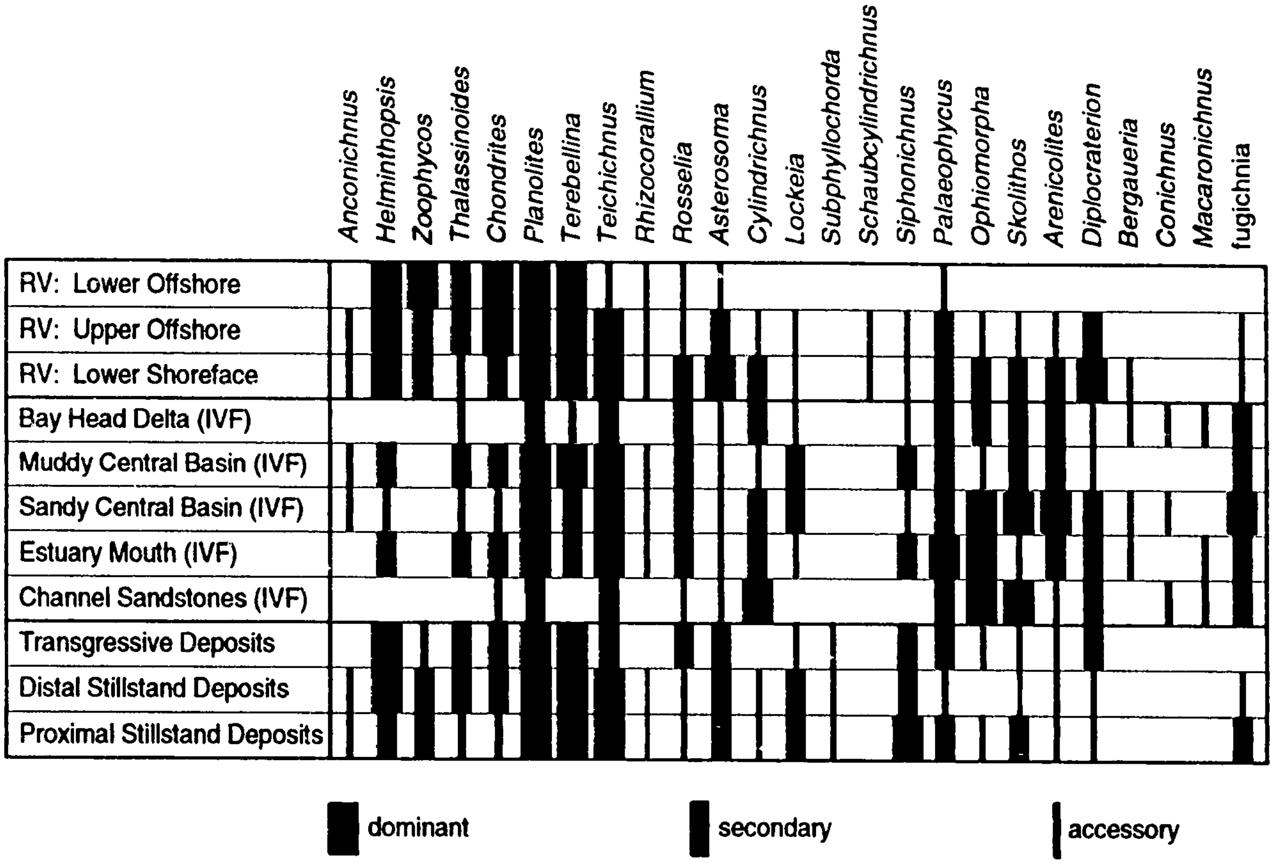

Figure III-17. Trace Fossil Distributions in Viking Formation Depositional Complexes. The chart is separated into three main zones; those associated with facies in the regionally extensive Viking parasequences (see Figure III-8), those related to the various depositional complexes within estuarine incised valley fills (see Figure III-16), and those associated with facies of the high energy flooding surface-bounded parasequences (see Figure III-11).

estuary, which may have repeatedly ranged from brackish to fully marine. *Helminthopsis, Chondrites, Asterosoma, Conichnus, Rhizocorallium* and *Macaronichnus* probably only occurred in the valley fill deposits when conditions approached fully marine. Their absence is most pronounced in the bay head delta complex, which probably experienced the lowest overall salinities. *Lockeia, Rosselia, Diplocraterion, Cylindrichnus* and *Siphonichnus* seem to possess greater tolerance for the observed stresses in the environment and, consequently, are more commonly present in valley fill deposits. In addition, *Asterosoma, Rosselia,* and *Cylindrichnus* are typically smaller than their fully marine counterparts, a feature also regarded as characteristic of brackish water conditions (Remane and Schlieper, 1971).

The bay head delta complex possesses one of the weakest degrees of burrowing, most sporadic distribution of burrowing and, almost exclusively, structures generated by trophic generalists. This supports high aggradation rates, episodic deposition and reduced salinity as the main controls on the trace fossil suite. The central basin complex demonstrates a dominance of simple structures by opportunistic organisms, with generally high degrees of burrowing. The sporadic distribution of traces reflecting specialised or elaborate feeding behaviours demonstrates that this zone of the basin probably experienced the greatest salinity fluctuations, ranging from brackish to nearly fully marine. Episodic storm bed deposition is well represented by alternations between opportunistic assemblages of vertical dwelling structures and fairweather deposit feeding or grazing structures. Vertical structures dominate where storm beds comprise the bulk of the facies association. The landward side of the estuary mouth complex shows high degrees of burrowing, characterised by stresses similar to those of the central basin. The estuary mouth appears less affected by salinity fluctuations than the central basin, although this is difficult to determine with any certainty. The channel fill complex shows a dominance by *Skolithos, Cylindrichnus* and *Ophiomorpha*. Migrating subaqueous dunes pose a severe difficulty to infaunal organisms, since progressive avalanching of sand down the slip face of the bedform tends to bury the entrance to the dwelling structures, and the non-cohesive shifting nature of the substrate precludes effective deposit feeding or grazing behaviour. Only elongate shafts and deeply penetrating, branching networks of dwelling structures are suited to these dynamic settings. The remainder of the suite corresponds to the muddy interlaminae, recording pauses in the migration of the bedforms. These assemblages contrast markedly with those of the regional highstand parasequences and those of the seaward side of the estuary mouth (Figure III-17), which are characterised by fully marine, equilibrium (K-selected) suites. The fully marine suites are typically uniformly burrowed, with intense degrees of burrowing and uniform distribution of individual elements.

CONCLUSIONS

The main applications of ichnology to sequence stratigraphic analysis are two-fold. The most obvious use is in the demarcation of erosional discontinuities having a significant temporal break between the eroding event and the successive depositional event. To date, substrate-controlled ichnofacies have been under-utilised as a means of recognising and mapping stratigraphically important surfaces in outcrop and subsurface. Locally, many surfaces are obvious on the basis of sedimentology alone. However, the character of such surfaces can change markedly with geography, making correlation difficult. The *Glossifungites* ichnofacies is proving to be exceedingly important in the recognition and genetic interpretation of erosional discontinuities in marine-influenced siliciclastic intervals, corresponding to sequence boundaries, high energy flooding surfaces and FS/SB surfaces. Many of the examples cited in this paper deal with their applications to the Cretaceous of the Western Canada Sedimentary Basin, but clearly, the ichnological applications transcend geography and, to a lesser degree, age.

In many cases, the interpretation as to the genesis of the sequence stratigraphic surface has come principally from the ichnofossil assemblage associated with the underlying deposits, the discontinuity itself, and the overlying units. In other cases, stratigraphically significant surfaces have required re-interpretation as to their genesis; however, the recognition of the surface as a major break in the rock record has not changed. Ultimately, this remains the essential element in any genetic stratigraphic analysis. The continued integration of substrate-controlled ichnofacies with detailed stratigraphic and sedimentologic analysis will undoubtedly enhance and refine developing sequence stratigraphic paradigms.

The second use is more subtle and is concerned with the environmental implications of the trace fossil suites in general. Many of the genetic interpretations of stratigraphic surfaces hinge on the paleoenvironmental interpretation of facies over- and underlying the discontinuity. Ichnology is ideally suited to impart valuable data about the depositional environment not readily obtainable from lithofacies analysis. Ichnofossils, when used in conjunction with sedimentary structures, are unequalled in the delineation and interpretation of facies and facies associations. When this two-fold ichnological procedure is integrated with other sedimentologic and stratigraphic analyses, the result is a powerful new approach to the recognition and genetic interpretation of sequence stratigraphic surfaces and their associated systems tracts.

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CHAPTER IV

AN INTEGRATED ICHNOLOGICAL - SEDIMENTOLOGICAL MODEL FOR THE RECOGNITION OF TEMPESTITES[3]

INTRODUCTION

Stratigraphy, once considered to be a somewhat routine and mundane discipline, consisting mainly of the dry cataloguing of lithostratigraphic units, has recently undergone a dramatic renaissance. During the last decade, stratigraphers have radically altered how we perceive and therefore interpret the rock record, using approaches such as seismic stratigraphy, allostratigraphy, tephrastratigraphy, magnetostratigraphy, sequence stratigraphy, eco-stratigraphy and event stratigraphy.

The stratigraphic utility of trace fossils can take on many guises and their significance varies depending on what stratigraphic paradigm one is employing. In the past, trace fossils were considered to be almost useless in stratigraphy because their long temporal ranges, made their biostratigraphic value negligible. On the other hand, trace fossils are proving to be one of the most important groups of fossils in delineating stratigraphically important boundaries related to sequence stratigraphy (MacEachern *et al.*, 1990, 1992; Savrda, 1991a,b) and allostratigraphy (Pemberton *et al.*, 1992a). Likewise, event stratigraphy is another area where trace fossils are proving to be a powerful tool for the recognition and interpretation of event beds (Seilacher, 1981, 1982a,b; Pemberton and Frey, 1984; Aigner, 1985; Wheatcroft, 1990; Seilacher and Aigner, 1991; Pemberton, in press).

Sedimentary event layers represent beds that were deposited during short periods of time and differ in some significant way from the ambient sediment (Wheatcroft, 1990). Event beds include such diverse entities as: volcanic ash

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beds or tephra deposits (*i.e.* Pedersen and Surlyk, 1983), beds resulting from seismic shocks, or seismites (Seilacher, 1969); and episodic sedimentation events such as turbidites (Seilacher, 1962; Föllmi and Grimm, 1990); phytodetrital pulses (Rice *et al.*, 1986); flood deposits or inundites (Leithold, 1989) and storm deposits or tempestites (Aigner and Reineck, 1982; Pemberton and Frey, 1984; Aigner, 1985; Pemberton *et al.*, 1992b; Pemberton, in press).

EPISODIC DEPOSITIONAL EVENTS

During the last two decades, geologists have begun to recognise the extent and significance of relatively rapid influxes of sediment (episodic depositional events) in the rock record. In fact, Dott (1983, 1988) has successfully argued that most of the sedimentary record, rather than reflecting day-to-day, steady-state conditions, typically represents episodic or discontinuous depositional events. Initial research was confined almost exclusively to deep water, outer continental shelf and slope environments, where gravity-induced turbidity currents constitute the main operating mechanism of episodic deposition. More recently, however, sedimentologists have focused their attention upon episodic depositional events in shallow, coastal areas. Such events, generally the result of major storms or hurricanes, are well-documented in recent environments (*e.g.* Hayes, 1967; Kumar and Sanders, 1976; Owens, 1977; Fox and Davis, 1978; Howard and Reineck, 1981; Hunter and Clifton, 1982; Niedoroda *et al.*, 1984; Morton and Paine, 1985; Morton, 1988), and are being recognised with greater frequency in the rock record (*e.g.* Bourgeois, 1980; Kreisa, 1981; Aigner and Reineck, 1982; Dott and Bourgeois, 1982; Leckie and Walker, 1982; Pemberton and Frey, 1984; Walker, 1984; Duke, 1985; Rosenthal and Walker, 1987; Frey, 1990; Duke *et al.*, 1991; Seilacher and Aigner, 1991; MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992b; Arnott, 1993; Walker and Bergman, 1993).

In a seminal paper, Seilacher (1982a) succinctly pointed out that episodic sedimentation events (turbidites, tempestites, inundites, and phytodetritus pulses) have a number of common characteristics. They reflect the onset, culmination, and waning of water turbulence during the event, by distinctive erosional and depositional structures. They redistribute the organic and inorganic sediment material along a vertical (bottom to top) and horizontal (shallow to deep) gradient. Finally, they change the ecological situation for benthic organisms by altering the consistency and/or the food content of the local sea floor for a biologically relevant period of time after the event. This latter effect has a profound influence on the nature of infaunal behaviour and hence, on the ichnological record they leave behind.

Sedimentological Aspects of Tempestites

Much of the difficulty surrounding the recognition and interpretation of tempestites is associated with our limited understanding of the mechanics of their deposition and the primary physical stratification ultimately produced. Hummocky cross-stratification (HCS; *cf.* Dott and Bourgeois, 1982), is probably the best known bedding type believed to be exclusively generated under storm-induced conditions (*cf.* Walker, 1984; Duke, 1985, 1990; Leckie and Krystinik, 1989; Duke *et al.*, 1991).

Duke *et al.* (1991) indicated that the main points of contention involved: (1) the class of flow that generates HCS; (2) the bed configuration(s) which produce(s) HCS; and (3) the nature of the storm-induced currents. To further complicate matters, considerable uncertainty persists regarding possible depth restrictions that may be associated with this bedding style. Although Walker (1984) suggested that HCS can form only below fairweather wave base, Harms (1979) estimated that it can form in water depths ranging from 5 to 30 meters, and Hunter and Clifton (1982) indicated a depth as shallow as 2 meters. Recently, Cotter and Graham (1991) recognised HCS in what they interpreted as late Devonian fluvial deposits from Ireland. Similar interpretation problems surround swaley cross-stratification (SCS; *cf.* Leckie and Walker, 1982; Rosenthal and Walker, 1987) and quasi-planar lamination (QPL; *cf.* Arnott, 1993).

Traditional paleontological control is rarely useful in resolving the above problems because most sandy clastic units are commonly devoid of body fossils. These same units, however, locally display diverse and well-preserved trace fossil associations (Pemberton and Frey, 1984; Vossler and Pemberton, 1988; Dam, 1990; Frey, 1990; MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992a,b,c). Integrating physical sedimentary structures with these distinctive trace fossil suites greatly improves the recognition and interpretation of tempestites in the rock record.

HCS is characterised by low angle (<15°), undulatory truncation surfaces, overlain by parallel to subparallel lamination. Laminae are continuous across the entire bedding structure, thinning over the highs (hummocks) and thickening into the lows (swales). A distinctive characteristic of HCS is the convex-upward orientation of the laminae which drape the hummocks. Waning flow deposits, consisting mainly of oscillation ripple laminated sandstones, are locally preserved.

SCS is characterised by truncation surfaces similar to HCS, though generally more steeply inclined, overlain by parallel to subparallel lamination which shows an upward decrease in inclination, as the relief is progressively draped. In contrast to HCS, convex-upward laminae are lacking and the stratification consists exclusively of stratification filling the swales between the hummocks (Leckie and Walker, 1982). SCS appears to represent the enhanced erosional amalgamation of HCS-type beds, where the hummocks have been preferentially scoured away by each successive storm event. Consequently, waning flow structures are rarer than in HCS.

QPL is a newly described bedding type (Arnott, 1993), based on outcrop studies from the Late Albian-Early Cenomanian Bootlegger Member of the Blackleaf Formation, Montana. The basic stratification type is similar to both HCS and SCS, particularly in the predominance of low angle (<15°) to horizontal parallel stratification.

In contrast, the scale of QPL is considerably greater than for HCS/SCS, manifest by extensive low angle to horizontal, gently undulating erosional truncation surfaces. Undulations display spacings of 2.1 m and heights of 1.8 cm, giving spacing to height ratios in excess of 100. Waning flow deposits consist of combined flow or current ripple laminated sandstones, and paleocurrent analyses show offshore-oriented sediment transport. This contrasts markedly with the largely isotropic fabrics delineated from HCS beds by Cheel (1991) and Duke *et al.* (1991), although Leckie and Krystinik (1989) described beds that they interpreted as HCS which also possessed offshore-oriented paleocurrent fabrics, based on sole marks, combined flow ripples and current ripples. Controversy continues to surround the mechanism of HCS generation, as well as its recognition in the rock record.

The most recent studies seem to indicate that both HCS and SCS appear to correspond to high energy deposition under purely oscillatory conditions during storms (Cheel, 1991; Duke *et al.*, 1991; Arnott, 1993). SCS corresponds to higher energy conditions than HCS, characterised by the enhanced erosional amalgamation of beds (Leckie and Walker, 1982; Rosenthal and Walker, 1987). This higher energy condition may correspond to more energetic storms, higher frequency of storms (minimising the thickness of cohesive, mucous-bound fairweather deposits needed to be removed), or shallowing. The common upward transition of HCS beds into SCS beds of storm-dominated shoreface successions suggests that the latter scenario is more prevalent.

QPL, on the other hand, appears to correspond to high energy deposition under combined flow processes during storms (Duke *et al.*, 1991; Arnott, 1993) and hence, reflects a fundamentally different mechanism of deposition. Although at present QPL has only been described from the Bootlegger Member, it is likely a common bedding type in the rock record which has been misidentified as HCS or SCS. The HCS-type beds containing offshore-oriented paleocurrents, described by Leckie and Krystinik (1989), may correspond to thinly bedded QPL. Alternatively, these observations may demonstrate that the basinal expression of some HCS beds may not reflect purely oscillatory conditions but rather, with decreasing oscillation strength, weak currents may combine with the flow to generate offshore sediment transport. In general, however, it is unlikely that QPL can be differentiated from HCS/SCS in core, and for the present, all three bedding types are best considered a single stratification type for the purposes of paleoenvironmental interpretations.

Storm units, whether HCS, SCS or QPL, represent individual sandstone beds that were deposited rapidly (over a few hours to several days) from single waning flow events, which commonly possessed a strong oscillatory flow component (Dott, 1983). They can superficially resemble turbidites but are generally distinguished from them by the presence of oscillatory and/or combined flow sedimentary structures, and by shallow marine faunas preserved in any intercalated shale deposits (Johnston and Baldwin, 1986).

Conceptual physical sedimentary models of storm-derived units have been constructed (*e.g.* Dott and Bourgeois, 1982; Dott, 1983) and interpreted. These idealised successions generally show the following characteristics: (1) storm erosion, manifest by an undulatory basal erosion surface, locally with sole marks, intraclasts of pebbles, shells or mudstone rip-up clasts (locally siderite-cemented); (2) main storm deposition, characterised by an HCS, SCS or QPL sandstone interval; (3) waning storm deposition consisting of oscillation and/or combined flow ripple laminated sandstone, indicating a progressive return to lower flow regime conditions; and (4) post-storm (fairweather) mud deposition, reflecting either the final suspension fall-out of storm-derived sediment (*i.e.* post-storm mud) or the return to normal background sedimentation (*i.e.* fairweather mud) (Johnston and Baldwin, 1986). This post-storm mud deposit may not accumulate or be preserved if the tempestite has been deposited above fairweather wave base. Under shallower water conditions, this capping layer may be reflected by burrowed sandstone of variable argillaceous content.

OPPORTUNISM *VS.* EQUILIBRIUM BEHAVIOURS: THE MODERN BIOLOGICAL BASIS FOR THE ICHNOLOGICAL TEMPESTITE MODEL

Opportunistic Strategies

In recent ecological studies of benthic organisms, equilibrium (or K-selected) species have been distinguished from opportunistic (or r-selected) species (Jumars, 1993; *cf.* Table IV-1). In general, opportunistic species can respond rapidly to an open or unexploited niche and are characterised by: (1) a lack of equilibrium population size; (2) a density independent mortality; (3) an ability to reproduce rapidly; (4) a relatively poor competitive ability; (5) a high dispersal ability; and (6) having a high proportion of resources devoted to reproduction (Grassle and Grassle, 1974). Opportunistic organisms display an r-strategy in population dynamics, emphasising rapid growth rate (r), whereas equilibrium species adopt a K-strategy, based on the carrying capacity of the environment (K) (Boesch and Rosenberg, 1981). Short generation span is the most important mechanism for increasing population size in an r-strategy, therefore, life spans of opportunistic species are shorter, and sexual maturity is reached earlier (Rees *et al.*, 1977). Broad environmental tolerances and generalised feeding habits facilitate rapid colonisation of open niches (Levinton, 1970; Pianka, 1970; Jumars, 1993).

Opportunistic organisms are tolerant of conditions that are physiologically stressful. As such, their lifestyles and feeding strategies can be extremely variable (Grassle and Grassle, 1974). In most cases, opportunistic

Table IV-1. Characteristics of r-selected and K-selected populations (modified after Pemberton *et al.*, 1992b).

r-selected (Opportunistic)	K-selected (Equilibrium)
1. responds rapidly to open niche	1. slow to colonise
2. lacks equilibrium population size	2. reach population size equilibrium
3. density-independent mortality	3. density-dependent mortality
4. relatively poor competition ability	4. excellent competitors
5. high dispersal ability	
6. efficient reproductive system	

colonists tend to be either suspension feeding or surface deposit-feeding polychaetes (Table IV-2). However, Cadée (1984) stressed that opportunistic organisms have a great capacity to vary their feeding habits depending on food availability. Thus, if suspension-feeding is the most viable strategy, opportunistic organisms will utilise it.

Rhoads *et al.* (1978) found that opportunistic colonists tend to live in dense clusters, because gregarious colonisation can inhibit competitors from settling. Whitlatch and Zajac (1985) stated that among opportunistic species, individuals tend to settle near others of the same species, indicating that gregarious settling behaviour is based primarily on the presence of others, rather than on the availability of a preferred substrate. They went on to conclude that since these organisms tend to brood their larvae, they can settle immediately upon release from the adult, permitting rapid crowding in a given space. These initial colonists thus preempt space, inhibiting the settlement of other species.

Recolonisation Following Disruption

The mechanics of initial larvae settlement are presently undergoing intense scrutiny. In the past, the most favourable hypothesis involved active habitat selection by the organism. In this hypothesis, the larvae actively select the habitat by employing a variety of strategies such as swimming, substrate selection and inhibiting metamorphosis until a suitable area is found (Butman, 1987). Currently, however, benthic ecologists are realising the importance of hydrodynamics in larval settlement and a new hypothesis, termed "Passive Deposition", is gaining wide acceptance. Butman (1987) summarised the two main points of view regarding passive deposition as either: (1) larvae are deposited over broad areas, but only survive in favourable (hospitable) habitats; or (2) species-specific "larval fall velocities" correspond with particular sediment fall velocities, such that hydrodynamically similar sediment particles and larvae are deposited in the same environment. Recent work on larvae in sediment flumes (Jumars and Newell, 1984) has confirmed that larvae respond to prevailing hydrodynamic conditions. Episodic depositional events, like storms, therefore, can have a powerful effect on the redistribution of the larvae of benthic organisms (Rees *et al.*, 1977; Hagerman and Rieger, 1981; Dobbs and Vozarik, 1983).

Table IV-2. Modern Examples of Recolonisation Following Defaunation (modified after Vossler and Pemberton, 1988).

Author	Setting	Stress	First Colonist	Second Colonist	Others
Grassle & Grassle, 1974	estuary-nearshore	oil spill	1st month: *Capitella capitata*	8 months: *Polydora ligni*	*Microphthalmus aberrans*, *Syllides verilli*, *Streblospio benedicti*
Dauer & Simon, 1976	intertidal	red tide	1st month: *Polydora ligni*	2-3 months: *Eteone* heteropod *Nereis succinea*	year 2: *Capitata ambiseta*, *Minuspio cirrifera*, *Trovisia* sp.
Boesch *et al.*, 1976	embayment	storm	2 months: *Melita nitida*, *Streblospio benedicti*, *Scoloplo fragilis*, *Glyeinde solitaria*		
Pearson & Rosenberg, 1978	micro-tidal fiord	pollution	3 years: *Capitella capitata*	*Scolepsis fulignosa*	
Grassle, 1977	deep sea (1760m)	experimental defaunation	2 months: *Priapulis atlantsi*	28 months: *Capitella* sp.	
McCall, 1977	embayment	experimental defaunation	10 days: *Streblospio benedicti*, *Capitella capitata*, *Ampelisca abdita*	50 days: *Nucula proxima*	
Rees *et al.*, 1977	shallow marine	storms			mobile predators with short life cycles
Rhoads *et al.*, 1978	estuary	dredging	10 days: *Streblospio benedicti*	29-50 days: *Capitella capitatta* *Ampelisca abdita*	50 days: *Nucula annulata* 86 days: *Tellina agilis* 175 days: *Nephthys incisa*
Sanders *et al.*, 1980	marine-estuary	oil spill	1st 11 months: *Capitella*	2nd year *Mediomastus*	
Desbryers *et al.*, 1980 (*in* Thistle, 1981)	offshore (2160m)	experimental defaunation	6 months: *Prionspio* sp. *Ophryaboche puerilis*		
Bonsdorff, 1983	shallow, brackish	dredging	*Nereis diversicolor* *Corophium volutator* *Macoma balthica*		
Bonvicini Paglial *et al.*, 1985	Shallow marine	dredging	6 months: *Corbula gibba*, *Lumbrineresis gracilis* *Nephthys sphaerocirrata* *Prionospio malmgreni* *Scolelepsis fuliginosa*		
Whitlatch & Zajac, 1985	estuary	experimental defaunation	20 days: *Streblospio benedicti*, *Hobsonia florida*, *Polydora ligni* *Capitella capitata*	30 days: *Microdeutopus gryllotalpa*, *Corophium insidiosum*, *Nemetostella vectensis*	
Berry, 1989	shallow marine	storms	2 months: *Phragmatopema lapidosa*, *californica*		

At present, most benthic biologists believe that larval settlement involves a complex interaction between active and passive processes. Competent planktonic larvae initially reach the sea floor at sites where sediment with similar fall velocities first settle (Hannan, 1984). Other biological or physical processes may then subsequently redistribute them. In this way, larvae are passively deposited and accumulate at the large spatial scales that apply to sediment transport and deposition (*i.e.* tens of meters or kilometers). Active habitat selection then occurs over much smaller scales (centimeters or meters) within these broad depositional areas (Butman, 1987).

In most event deposits, therefore, initial larval settlement may be a function of the hydrodynamic conditions of the event which brings both larvae and sediment into the area (Table IV-3). After initial settlement, exploitation of the open niche becomes largely a function of the reproductive characteristics of the individual species. In most cases, because of their efficient reproduction cycles, opportunistic species quickly dominate the initial stages of recolonisation. Table IV-4 summarises the life-history characteristics of the seven most common modern opportunistic colonisers. Zajac (1986) documented that adults of opportunistic species become sexually active immediately following a physical disturbance or seasonal depopulation, facilitating a rapid increase in the size of the larval pool. Gray (1974) noted that opportunistic organisms can have both planktonic and benthic larvae, thereby giving them flexible reproductive capabilities.

Adult recruitment from surrounding areas into naturally depopulated zones can also be appreciable (Santos and Simon, 1980). This is facilitated by the transport and subsequent relocation of adults by storm currents. Rees *et al.* (1977) noted that following storm abatement there was a large mass-stranding and redistribution of many species. Both adult organisms and their larval forms were displaced to open ocean areas, thus facilitating rapid recolonisation. Dobbs and Vozarik (1983) concluded that disturbances by storms may also be a mechanism for wide post-larval dispersal, relied upon by some infauna.

Studies concerning recolonisation rates of stable and unstable (*e.g.* fluctuating ecological parameters such as salinity, sedimentation rate, temperature, *etc.*) modern environments show that organisms in stable environments are more adversely affected by physiological stress. Species present in unpredictable environments (such as estuaries and river-

Table IV-3. Major parameters affecting the rate and pattern of colonisation following a disturbance (adapted from Sousa, 1984).

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1. The morphological and reproductive traits of species that are present on the site when the disturbance occurs. Such traits determine, in part, the likelihood that these species will survive the event and rapidly reoccupy the site.

2. The reproductive biology of species that were not present on the site when it is disturbed, but have occupied it previously or live within dispersal distance of it.

3. Characteristics of the disturbed patch, including:

    a. the intensity and severity of the disturbance that created it.
    b. its size and shape.
    c. its location and degree of isolation from sources of colonists.
    d. the heterogeneity of its internal environment.
    e. the time of year it was created (reflecting seasonal controls on recolonisation).

Table IV-4. Life-history characteristics of the 7 most common macrofaunal taxa found after defaunation of an estuary (modified after Whitlatch and Zajac, 1985).

Taxon	Feeding/mortality type	Reproductive features
Polychaetes		
Streblospio benedicti	Bi-palpate; surface deposit feeder; tube-dwelling	Larviparous; *planktonic phase: 1-14 days. * generation time: 30-50 days.
Hobsonia florida	Multi-tentaculate; surface deposit feeder; tube-dwelling	Tube brooding; planktonic phase (?); generation time: 25-35 days.
Polydora ligni	Bi-palpate; surface deposit feeder; tube-dwelling	Tube brooding; plankton phase: 2-10 days; generation time: 30-40 days.
Capitella capitata	sub-surface deposit feeder	Tube brooding; plankton phase: several hours; generation time: 30-40 days.
Amphipod crustaceans		
Corophium insidiosum	Surface deposit feeder; tube-dwelling	Brooding; generation time: 30-90 days.
Microdeutopus gryllotalpa	Surface deposit/suspension feeder; tube-dwelling	Brooding generation time: 30-50 days.
Anthozoan		
Nematostella vectensis	Infaunal; zooplanktivore (?)	?

* Approximate times based upon summer water temperatures

dominated deltas), generally have broad environmental tolerances and can recover from disturbances quickly (Jernëlou and Rosenberg, 1976). For instance, the benthic population of relatively stable deep sea environments may take longer than two years to recover completely, while the benthic population of relatively unstable estuarine environments may require less than 11 months (Dauer and Simon 1976; Grassle, 1977). Marginal marine organisms are subject to relatively high physiological stress on a more or less continual basis, and therefore, the resident population is likely to exhibit some degree of r-selected strategy (Ekdale *et al.*, 1984; Ekdale, 1985; Beynon *et al.*, 1988).

After initial post-disturbance recolonisation, only those organisms suited to the prevailing or modal (fairweather) conditions of the depositional environment will continue to survive. Persistent fairweather conditions result in a return of a benthic community similar to that preceding the disturbance. Many of the opportunists, which originally colonised the defaunated area die off, due to a combination of unsuitability for the environment and an inability to compete with the organisms of the re-establishing equilibrium community (Grassle and Grassle, 1974; Boesch and Rosenberg, 1981; Föllmi and Grimm, 1990).

This juxtaposition of opportunistic "storm" and equilibrium "fairweather" benthic communities is primarily reflected in the style of organism behaviours and hence, their biogenic structures (Figure IV-1). The trace fossil record of each community is relatively distinctive, and forms the main paleontologic basis for recognising tempestites in the otherwise unfossiliferous siliciclastic intervals dominating the Cretaceous record of the Western Interior Seaway of North America.

ICHNOLOGY OF STORM DEPOSITS

The activities of soft-bodied infauna, which have low preservational potential as body fossils, represent a significant component of any biological succession (McCall and Tevesz, 1983). It has already been shown that most opportunistic species that initially recolonise defaunated environments, are tube-dwelling polychaetes (Table IV-2). Thus, the ichnofossil record (Figure IV-1) may be the best place to find evidence of opportunistic colonists in an

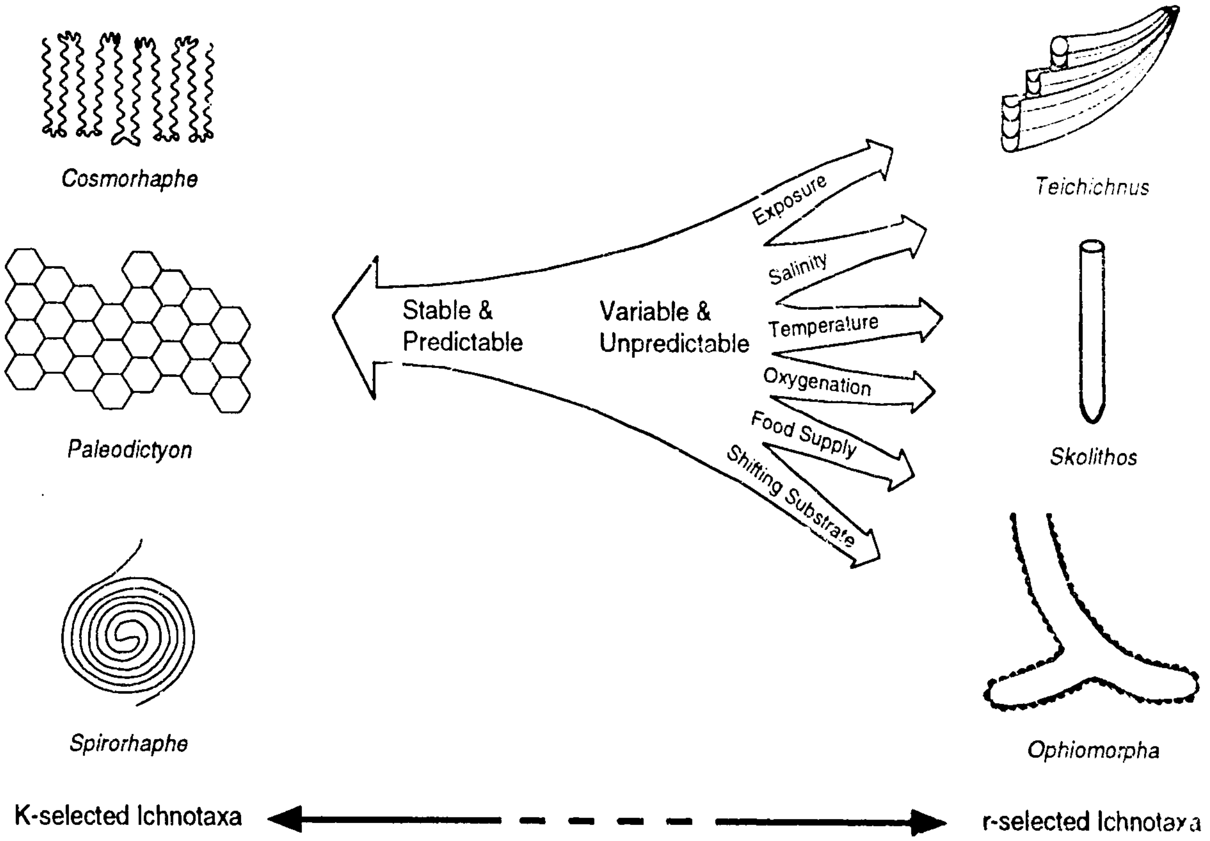


Figure IV-1. Gradients in the stability and predictability of physical environmental conditions will control population strategies among burrowing organisms. Equilibrium (K-selected) trace fossils flourish in high-diversity assemblages under very stable and predictable conditions. Opportunistic (r-selected) trace fossils rise to prominence in low-diversity assemblages under extremely variable and unpredictable conditions (modified after Ekdale, 1985).

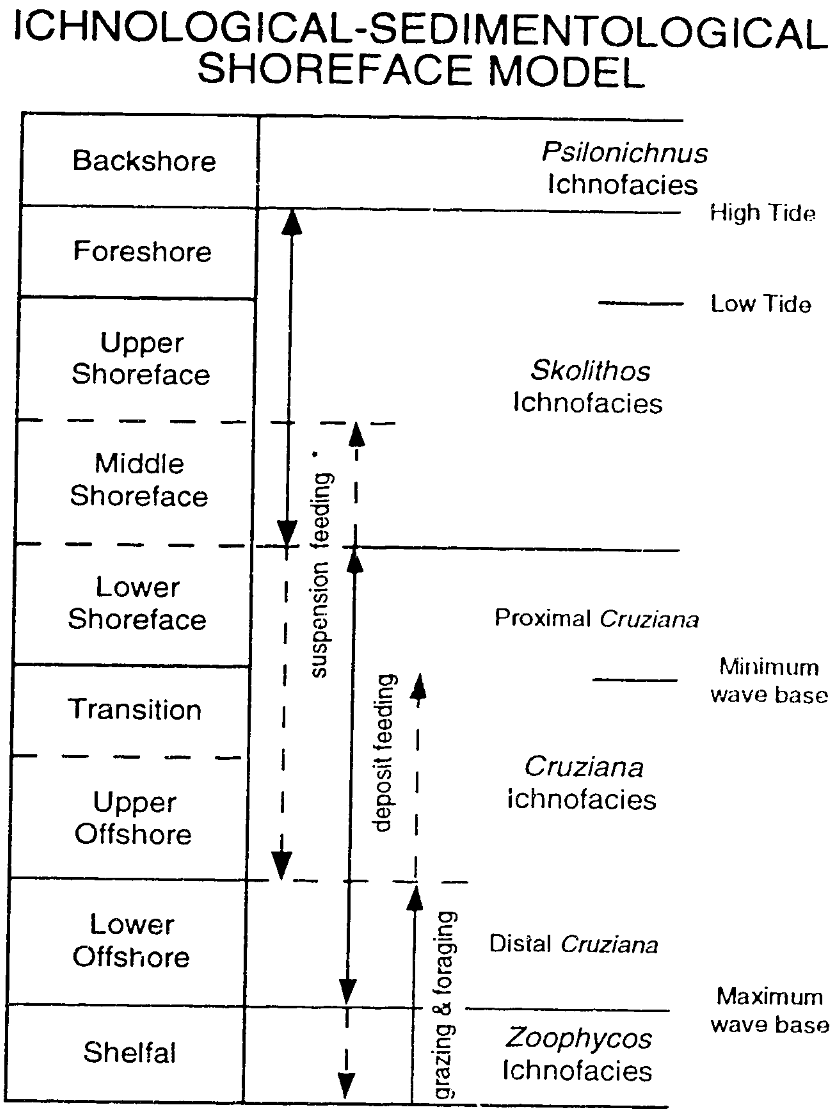
ecological succession (Vossler and Pemberton, 1988). Ekdale (1985) summarised a number of possible examples resulting from (1) turbidite deposition (*i.e.* Seilacher, 1962; Föllmi and Grimm, 1990); (2) salinity variations (*i.e.* Wightman *et al.*, 1987; Beynon *et al.*, 1988; Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; Ranger and Pemberton, 1992); (3) oxygen deficiencies (Bromley and Ekdale, 1984); and (4) storm deposition (*i.e.* Pemberton and Frey, 1984; Vossler and Pemberton, 1988, 1989; MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992a,b,c; Pemberton, in press). In all of these cases, some sort of physical and/or chemical stress was applied to the benthic population.

In order to illustrate the characteristic trace fossil suites reflecting storm-influenced settings, careful study was made of 15 Cretaceous siliciclastic wave-dominated shoreface intervals in the Western Interior Seaway of North America (Table IV-5). The successions range from Upper Aptian to Campanian, and from the Western Canada Sedimentary Basin of Alberta, to the Book Cliffs of Utah. Table IV-5 summarises the observed opportunistic trace fossil suites associated with initial colonisation of the tempestites, as well as the assemblages characterising the intervening fairweather deposits. Where possible, these equilibrium fairweather suites have been further subdivided into proximal and distal assemblages, based on the physical sedimentology and the organism behaviours indicated by the ichnogenera present (Figure IV-2).

Proximal to distal trends in tempestites are manifest by a number of physical and biological elements. Distal tempestites (Figure IV-3) tend to display thinner beds, finer grain sizes and overall, less marked penetration by fairweather assemblages. Trace fossils of the intervening burrowed zones tend be less robust and dominated by grazing and deposit feeding structures. With progressively less distal conditions, greater disruption of the thin tempestites occurs (Figure IV-3 H, I). Proximal tempestites (Figure IV-4) show thick sandstone beds with greater penetration by biogenic structures. However, erosional amalgamation also tends to be enhanced, commonly removing all (Figure IV-4 A) or much (Figure IV-4 F) of the intervening burrowed zones. Biogenic structures of the intervening burrowed zones tend to reflect a wide diversity of infaunal behaviours, including grazing, surface deposit feeding, stationary deposit feeding, mobile carnivore, passive carnivore and suspension feeding. In general, whether proximal or distal,

AGE	UNIT	LOCATION	TRACE FOSSIL SUITE	
			STORM	FAIRWEATHER
U. Aptian - L. Albian	Bluesky Fm	WCSB W-C Alberta	*O. nodosa, Ar, Sk, D, Co, fu*	Distal: *H, An, Ch, P, Th, Te.* Proximal: *Ch, T, P, As, Ro, Te, Rh, Cy, Pa, D, M. simplicatus.*
Albian	Cadotte Mbr	WCSB W-C Alberta	*O. nodosa, Ar, Sk, D, Co, fu*	Proximal: *T, P, Ro, Te, Pa, M. simplicatus, O. irregulaire.*
U. Albian	Viking Fm	WCSB Alberta	*O. nodosa, Ar, Sk, D, Co, fu.*	Distal: *An, Z, Ch, P, H, T, Te, Th.* Proximal: *H, Ch, T, Ro, As, P, Te, Sk, Rh, Pa, Ar, Cy, Si, Sch, O. irregulaire.*
U. Albian	Newcastle Sst	Montana	*O. nodosa, Co,* fu.	Proximal: *Ch, T, P, Te, O. irregulaire.*
Turonian	Cardium Fm	WCSB Alberta	*O. nodosa, D, Sk,* fu.	Distal: *H, An, Z, Ch, P, T, Ro, Te, Gy, Cy, Th.* Proximal: *H, An, Z, Ch, P, T, As, Ro, Te, Rh, Cy, Pa, Sch, Gy, Sk,* D, *Ar, Si, O. irregulaire.*
Campanian	Spring Canyon Mbr	Book Cliffs Utah	*O. nodosa, D, Ar, Sk, Pa,* fu.	Distal: *H, An, P, T, Te, Th.* Proximal: *H, An, Ch, P, T, Th, As, Ro, Rh, Pa, Sk, Ar, D, O. irregulaire*
Campanian	Aberdeen Mbr	Book Cliffs Utah	*O. nodosa, Ar, Sk,* fu	Distal: *H, Z, Ch, P, As, T, Te, Th.* Proximal: *P, Ta, Lo, Pa, Sch, Te, Anc, Gy, Fus, O. irregulaire.*
Campanian	Kenilworth Mbr	Book Cliffs Utah	*O. nodosa, Sk, Pa, Be,* fu.	Proximal: *H, Ch, P, As, Ro, Te, Ta, Cy, Pa, Sch, Gy, Sc, Be, Al, Ma, Cosm, Th, Aul, O. irregulaire.*
Campanian	Sunnyside Mbr	Book Cliffs Utah	*O. nodosa, Sk,* fu.	Proximal: *H, Ch, P, Pa, Sch, Te, O. irregulaire.*
Campanian	Eagle Sst	Montana	*O. nodosa, Co,* fu.	Proximal: *Pa, Cy, Sch, Te, Anc, O. irregulaire.*
Campanian	Virgelle Mbr	Writing-On-Stone Alberta	*O. nodosa, Sk, Be,* fu.	Proximal: *P, T, Ro, Be, Cy, Pa.*
Campanian	Shannon Sst	Wyoming	*O. nodosa, Sk, Pa, Be, Co, D,* fu.	Proximal: *H, Cosm, P, Ro, T, Te, Gy, Pa, Sch, Anc, Cy, M. simplicatus.*
Campanian	Sussex Sst	Wyoming	*O. nodosa, Sk, Pa, Co,* fu.	Proximal: *H, P, T, Sc, Lo, Cy, Pa, Sch, Gy.*
Campanian	Blood Reserve	Jenson Reservoir Alberta	*O. nodosa, Sk, Co, Be,* fu.	Proximal: *H, Ch, P, Lo, Be, Ro, O. irregulaire.*
Campanian	Appaloosa Sst	Drumheller Alberta	*O. borneensis, Sk, Co,* fu.	Proximal: *H, P, Te, Rh, Pa, As, Ro, O. irregulaire, M. simplicatus.*

Table IV-5: Storm (Opportunistic) and Fairweather Trace Fossil Suites From Cretaceous Strata of the Western Interior Seaway of North America. *Al: Altichnus, An: Anconichnus, Anc: Ancorichnus, Ar: Arenicolites, As: Asterosoma, Au: Aulichnites, Be: Bergaueria, Ch: Chondrites, Co: Conichnus, Coc: Cochlichnus, Cosm: Cosmorhaphe, Cy: Cylindrichnus, D: Diplocraterion, fu: fugichnia, Fus: Fustiglyphus, Gy: Gyrochorte, H: Helminthopsis, Lo: Lockeia, M. simplicatus: Macaronichnus simplicatus, Ma: Mammilichnus, O. borneensis: Ophiomorpha borneensis, O. irregulaire: Ophiomorpha irregulaire, O. nodosa: Ophiomorpha nodosa, P: Planolites, Pa: Palaeophycus, Pho: Phoebichnus, Rh: Rhizocorallium, Ro: Rosselia, Sc: Scolicia, Sch: Schaubcylindrichnus, Si: Siphonichnus, Sk: Skolithos, T: Terebellina, Ta: Taenidium, Te: Teichichnus, Th: Thalassinoides, Z: Zoophycos.*



* Many tube dwellers are passive carnivores rather than suspension feeders.

Figure IV-2. Idealised shoreface model of ichnofacies successions, based on observation of Cretaceous strata of the Western Interior Seaway of North America (modified after Pemberton *et al.*, 1992a).

Figure IV-3. Distal Tempestites. **(A)** Normally graded tempestites, interstratified with shelfal shales containing *Zoophycos* (Z), *Helminthopsis* (H), *Anconichnus* (An), *Thalassinoides* (Th), *Chondrites* (Ch) and *Planolites* (P). Bluesky Fm., 13-09-74-12W6, 1858.2 m. **(B)** Lower offshore silty and sandy shales contain *Palaeophycus* (Pa), *Helminthopsis* (H), *Zoophycos* (Z), *Terebellina* (T), *Chondrites* (Ch), *Diplocraterion* (D), *Siphonichnus* (Si), *Asterosoma* (As) and *Planolites* (P). A thin tempestite is cross-cut by *Zoophycos* and *Asterosoma*. Cardium Fm., 10-01-35-08W5, 2571.4 m. **(C)** Lower offshore silty shales contain robust *Chondrites* (Ch), *Anconichnus* (An), *Zoophycos* (Z), *Teichichnus* (Te), *Thalassinoides* (Th), *Planolites* (P) and *Asterosoma* (As). A thin tempestite erosionally truncates the facies and becomes burrowed towards the top. Cardium Fm., 10-01-35-08W5, 2570.3 m. **(D)** Offshore silty and sandy shales contain *Helminthopsis* (H), *Chondrites* (Ch), *Planolites* (P) and *Anconichnus* (An). A tempestite near the top of the interval is disrupted by fugichnia (fu) and contains *Ophiomorpha* (O) and *Diplocraterion* (D). A virtually obliterated tempestite occurs near the base of the interval. Viking Fm., 10-36-64-13W5, 1431.3 m. **(E)** A tempestite truncates lower offshore silty shales containing *Helminthopsis* (H), *Anconichnus* (An), *Chondrites* (Ch), *Planolites* (P) and *Asterosoma* (As). The tempestite is disrupted by fugichnia (fu) and *Diplocraterion* (D), but shows little other biogenic disturbance. Viking Fm., 02/12-04-64-11W5, 1458.8 m. **(F)** Sharp-based tempestite truncates upper offshore silty to sandy shales containing *Helminthopsis* (H), *Asterosoma* (As), *Rosselia* (Ro), *Palaeophycus* (Pa), *Teichichnus* (Te) and *Planolites* (P). The top of the tempestite is disrupted by *Ophiomorpha* (O), reburrowed with *Helminthopsis* and *Planolites*. Overlying traces show little penetration into the event bed. Viking Fm., 11-27-62-20W5, 1660.2 m. **(G)** A tempestite passes abruptly into thoroughly burrowed offshore silty to sandy shales containing *Helminthopsis* (H), *Anconichnus* (An), *Palaeophycus* (Pa), *Asterosoma* (As), *Chondrites* (Ch), *Planolites* (P) and robust *Rosselia* (Ro). The tempestite contains fugichnia (fu) and diminutive *Skolithos* (S) shafts, with little other biogenic disruption from tracemakers of the overlying facies. Viking Fm., 11-03-63-19W5, 1557.2 m. **(H)** Upper offshore sandy shales containing *Asterosoma* (As), *Helminthopsis* (H), *Anconichnus* (An), *Chondrites* (Ch), *Planolites* (P), *Palaeophycus* (Pa) and *Thalassinoides* (Th). Biogenically disrupted tempestites occur at the top and the base of the photo. Viking Fm., 10-34-54-20W5, 2577.0 m. **(I)** Upper offshore sandy shales containing *Helminthopsis* (H), *Teichichnus* (Te), *Terebellina* (T), *Chondrites* (Ch), *Diplocraterion* (D) and *Palaeophycus* (Pa). A biogenically-disrupted tempestite occurs near the base of the photo. Viking Fm., 11-27-62-20W5, 1660.3 m.

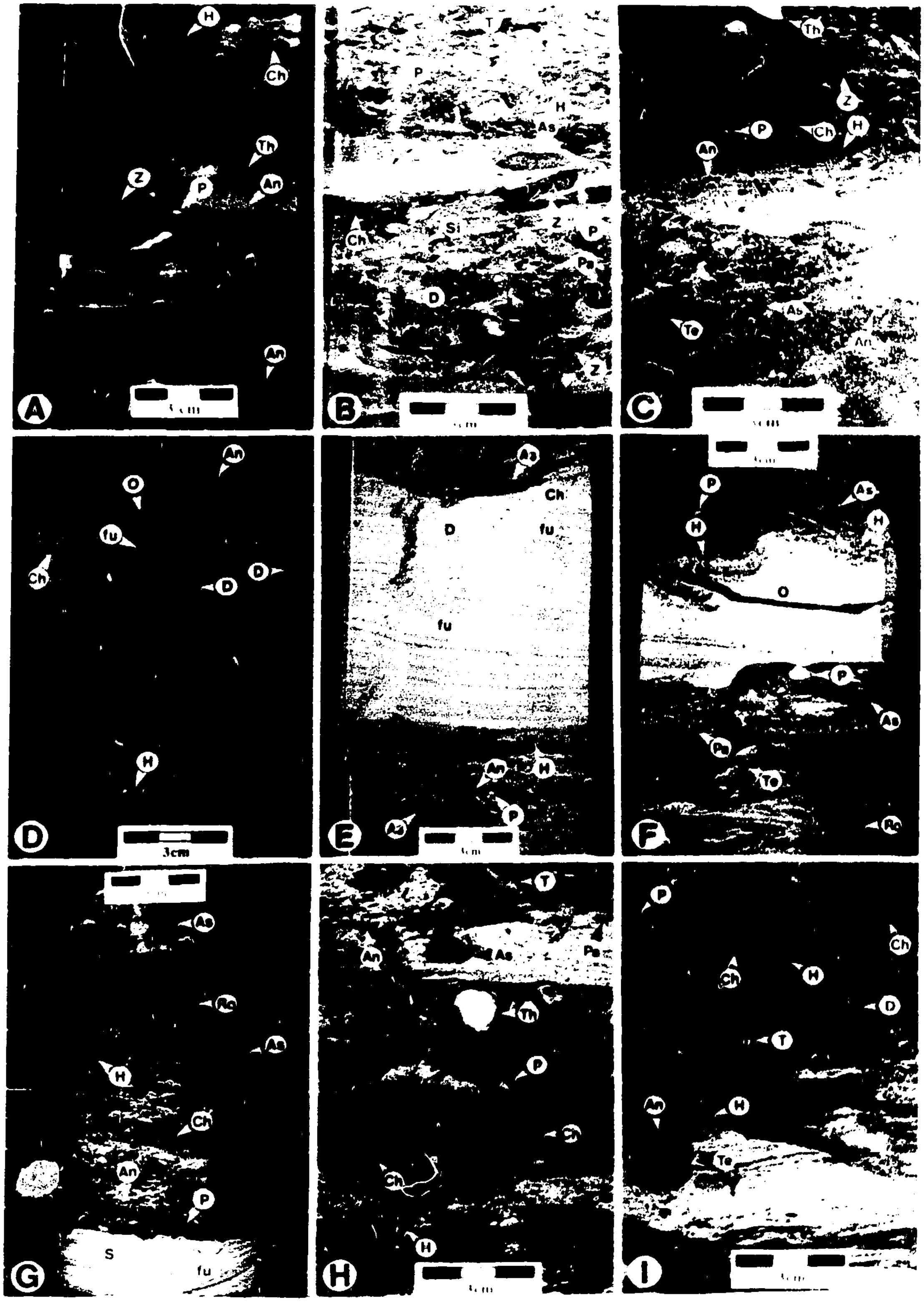

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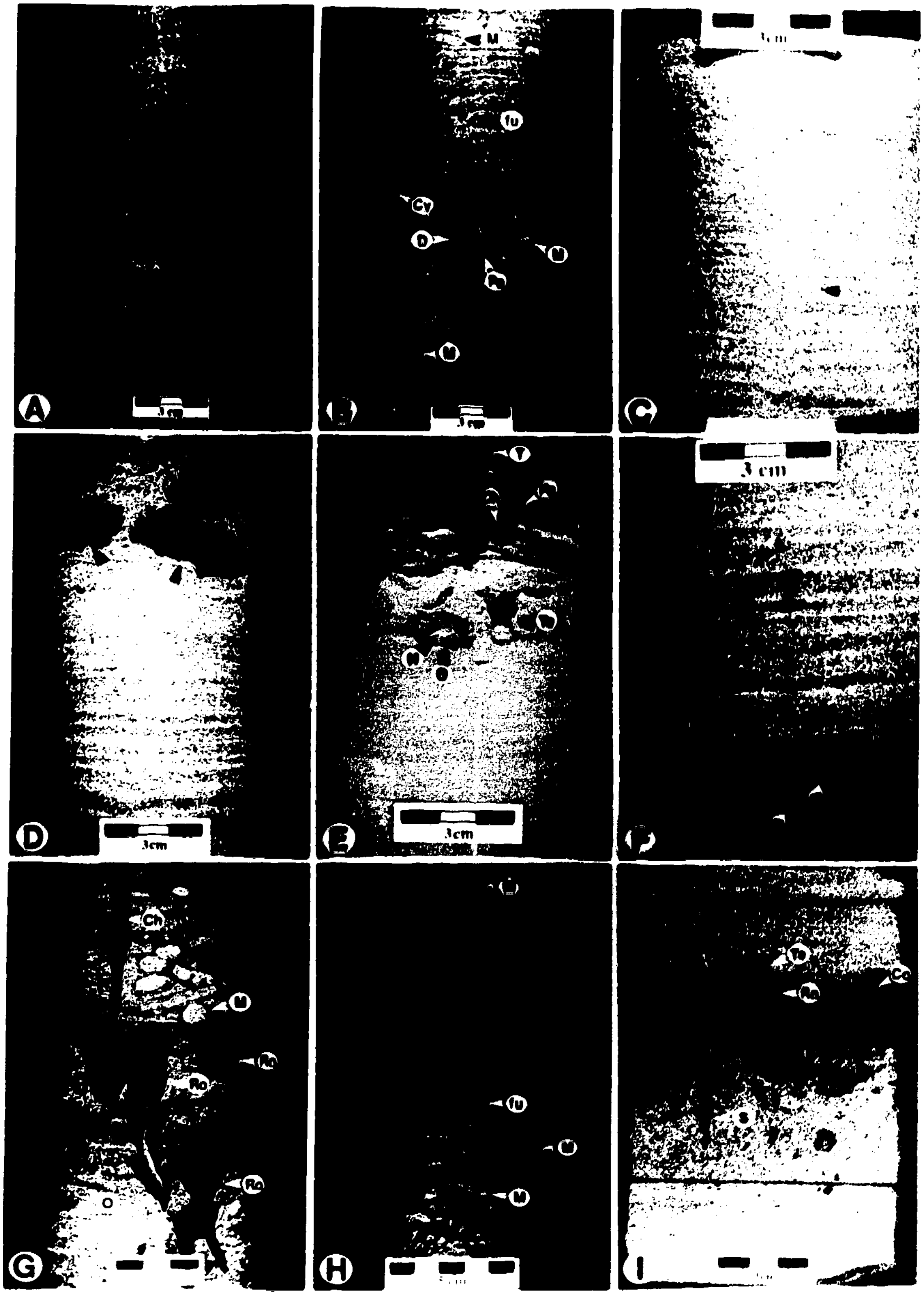
Figure IV-4. Proximal Tempestites. (A) Stacked, low angle parallel laminated, erosionally amalgamated, lower to middle shoreface tempestites. The relatively steep inclination to the truncation surface, overlain by subparallel laminae displaying an upward decrease in inclination is typical of HCS and SCS. Cadotte Mbr., Peace River Fm., 10-30-68-06W6, 1703.8 m. **(B)** Sharp-based, parallel laminated sandstone bed, interpreted as a lower shoreface tempestite, truncates a burrowed sandstone containing *Macaronichnus* (M), *Palaeophycus* (Pa), *Cylindrichnus* (Cy) and *Diplocraterion* (D). The fugichnia (fu) directly above the *Diplocraterion,* demonstrates the attempted escape of the tracemaker following storm bed emplacement. Bluesky Fm., 03-28-74-11W6, 1793.2 m. **(C)** Thick, well-laminated sandstone, interpreted as a lower to middle shoreface tempestite, containing well-developed fugichnia (arrow). Cadotte Mbr., Peace River Fm., 10-29-73-10W6, 1387.3 m. **(D)** Lower to middle shoreface tempestite, containing an opportunistic assemblage of heavily-lined, siderite-cemented *Ophiomorpha nodosa* (arrows). Cadotte Mbr., Peace River Fm., 10-11-69-09W6, 1800.0 m. **(E)** Upper portion of a lower shoreface tempestite, showing an opportunistic assemblage of *Ophiomorpha irregulaire* (O) and *Teichichnus* (Te). The fill of the *Ophiomorpha* has been reburrowed with *Helminthopsis* (H). The overlying muddy facies may reflect post-storm mud deposition or fairweather deposition, and contains *Helminthopsis, Chondrites* (Ch), *Terebellina* (T) and *Palaeophycus* (Pa). Viking Fm., 10-14-66-22W5, 1375.6 m. **(F)** Base of a tempestite, containing small mudstone rip-up clasts. The tempestite has truncated an underlying burrowed zone, leaving only the deeply penetrating, mud-lined, central shafts of *Rosselia* (arrows). Cadotte Mbr., Peace River Fm., 10-01-68-09W6, 2150.5 m. **(G)** Four, stacked, thin tempestites, showing re-equilibration of *Rosselia* (Ro) (particularly evident near the upper right side of the core). *Ophiomorpha* (O), *Macaronichnus* (M), and *Chondrites* (Ch)(reburrowing the *Rosselia*) comprise the remainder of the biogenic structures. Bluesky Fm., 07-27-72-13W6, 2144.5 m. **(H)** Multiple, stacked, thin tempestites in the middle shoreface, with fugichnia (fu) and *Macaronichnus* (M). Bluesky Fm., 10-34-70-13W6, 2371.0 m. **(I)** Tempestite near the base of the core displays preserved laminae, grading upwards into a burrowed top containing *Rosselia* (Ro), *Skolithos* (S), *Conichnus* (Co) and *Teichichnus* (Te). This tempestite is truncated by an overlying storm bed. Viking Fm., 11-24-65-18W5, 1362.0 m.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there is a marked difference between the trace fossil suite marking initial opportunistic colonisation of the tempestite and the fairweather suite reflecting the return of the resident, equilibrium population.

Opportunistic Trace Fossil Suites of Tempestites

In virtually all tempestites encountered, the initial trace fossil assemblage consists of simple, vertical to subvertical dwelling structures. All intervals contain escape traces (fugichnia), reflecting the disturbances made by animals entrained in the flow or buried by the bed, as they attempt to reach the sediment-water interface (*e.g.* Figure IV-4 B, C). Their abundance demonstrates the incremental nature of the depositional events. Most intervals contain *Ophiomorpha* and *Skolithos*, with lesser *Conichnus*, *Diplocraterion*, *Arenicolites*, *Bergaueria* and *Palaeophycus*, respectively (Table IV-5). Many distal tempestites may display minimal opportunistic colonisation (*e.g.* Farrow, 1975; Figure IV-3 D).

Most *Ophiomorpha* encountered consists of heavily-lined *O. nodosa*, or more rarely, *O. borneensis*. Burrows range from near vertical to steeply inclined in the upper parts of the beds, but may become horizontal at depth. Intensities of burrowing are highly variable and depend upon the suitability of the opportunistic colonists to the setting, as well as to the time available between storm events for colonisation. The observed suites correspond to a *Skolithos* ichnofacies, primarily dominated by trophic generalists mainly engaging in surface deposit feeding or suspension feeding. In general, individual densities of traces are high, but overall, ichnotaxonomic diversity is low.

Recently, Bromley and Asgaard (1991) introduced a new ichnofacies, the *Arenicolites* ichnofacies, to account for short-term, opportunistic occurrences of trace fossils in incongruous settings, such as tempestites. Such a designation is confusing because it can not be clearly separated from the present *Skolithos* ichnofacies concept. This is particularly evident in the Spring Canyon Member of the Price River area of Utah, where middle shoreface tempestite deposits contain an opportunistic *Skolithos* ichnofacies which cannot be differentiated from the fairweather *Skolithos* ichnofacies (Pemberton *et al.*, 1992c). In both situations, the same behaviours are demonstrated by the infauna, and the similarity of the suites corresponds to the general similarity of substrate consistency, whether storm-generated or fairweather-generated. Consequently, to designate the initial suite as a different ichnofacies does not appear practical. In general, the present array of ichnofacies is adequate to explain such occurrences.

Equilibrium Trace Fossils of Fairweather Deposits

Most examples in Table IV-5 show fairweather assemblages dominated by deposit feeding and mobile carnivore structures, with lesser grazing/foraging structures and suspension feeding or passive carnivore structures. Such suites are characteristic of the *Cruziana* ichnofacies (Figure IV-2). This depositional paradigm permits the separation of the fairweather deposits into distal and proximal suites.

Distal suites (distal *Cruziana* ichnofacies), although dominated by deposit feeding structures, contain a significant proportion of grazing/foraging structures (Figure IV-3 B-E). Suspension feeding structures are generally absent. Distal fairweather deposits typically consist of silty to sandy shales.

Grazing/foraging structures are dominated by *Helminthopsis, Anconichnus horizontalis* and *Zoophycos*. Deposit feeding structures are mainly *Chondrites, Planolites, Terebellina, Teichichnus,* and *Thalassinoides,* with much rarer *Rosselia, Asterosoma, Cylindrichnus, Gyrochorte, Cochlichnus* and *Phoebichnus*. Such suites are consistent with shelf to lower offshore deposition (Figure IV-2).

Proximal *Cruziana* fairweather suites contain large numbers of deposit feeding and mobile carnivore structures, with a much reduced grazing/foraging component and a significant proportion of suspension feeding and passive carnivore structures (Figure IV-4 F-I). The proximal fairweather deposits consist mainly of sandy shales and muddy sandstones. The grazing/foraging structures typically consist of *Helminthopsis, Anconichnus horizontalis* and much rarer *Zoophycos* and *Cosmorhaphe*. Deposit feeding/mobile carnivore structures consist of *Chondrites, Planolites, Terebellina, Teichichnus, Rosselia, Asterosoma, Rhizocorallium, Macaronichnus simplicatus,* with rarer *Ancorichnus, Taenidium, Schaubcylindrichnus, Siphonichnus* and *Altichnus*. Less commonly encountered structures include *Scolicia, Lockeia, Fustiglyphus, Mammilichnus, Gyrochorte,* and *Aulichnites*. Suspension feeding and passive carnivore structures include *Skolithos, Diplocraterion, Ophiomorpha irregulaire, O, nodosa, O. borneensis, Bergaueria, Palaeophycus* and rarer *Arenicolites*. Such suites typically occur in upper offshore to distal lower shoreface settings.

In both proximal and distal *Cruziana* fairweather suites, the assemblage is characterised by high diversity of ichnogenera, high intensity of burrowing, presence of specialised structures and an absence of dominance by individual ichnogenera, supporting a fully marine, unstressed, equilibrium benthic community, exploiting a nutrient-rich, low energy offshore to distal lower shoreface setting.

Where tempestites accumulate in shallower water settings such as the lower and middle shoreface, the resident community is less easily distinguished from the initial opportunistic suite (*cf.* Figure IV-2). Some opportunists may continue to persist as part of the fairweather community (*e.g.* Pemberton *et al.*, 1992c). Further, greater erosional amalgamation of tempestites limits the preservation of the fairweather structures while higher frequency storm events tends to limit the time available for colonisation. These factors also serve to inhibit the discrimination between the two suites. Under middle shoreface conditions, the fairweather assemblage, where preserved, may be indistinguishable from the opportunistic assemblage (Pemberton, *et al.*, 1992c).

The Ichnological Tempestite Model

The most common scenario, where the tempestite suites can be differentiated from the fairweather suites, shows a regular alternation between opportunistic *Skolithos* ichnofacies and an equilibrium *Cruziana* ichnofacies (Figure IV-5). Collectively, therefore, most storm-bedded successions contain a mixed trace fossil assemblage within a single depositional cycle. This alternation of two typically depth-related ichnocoenoses has commonly been attributed to repeated rises and falls of sea level, but a more likely interpretation involves the alternation of sand deposition with silt and mud sedimentation, caused by *in loco* hydrodynamic energy fluctuations. The two different ichnocoenoses reflect varying behavioural response of the animals colonising two successive, individually distinct habitats. The resident "fairweather" ichnocoenose (*e.g.* elements of

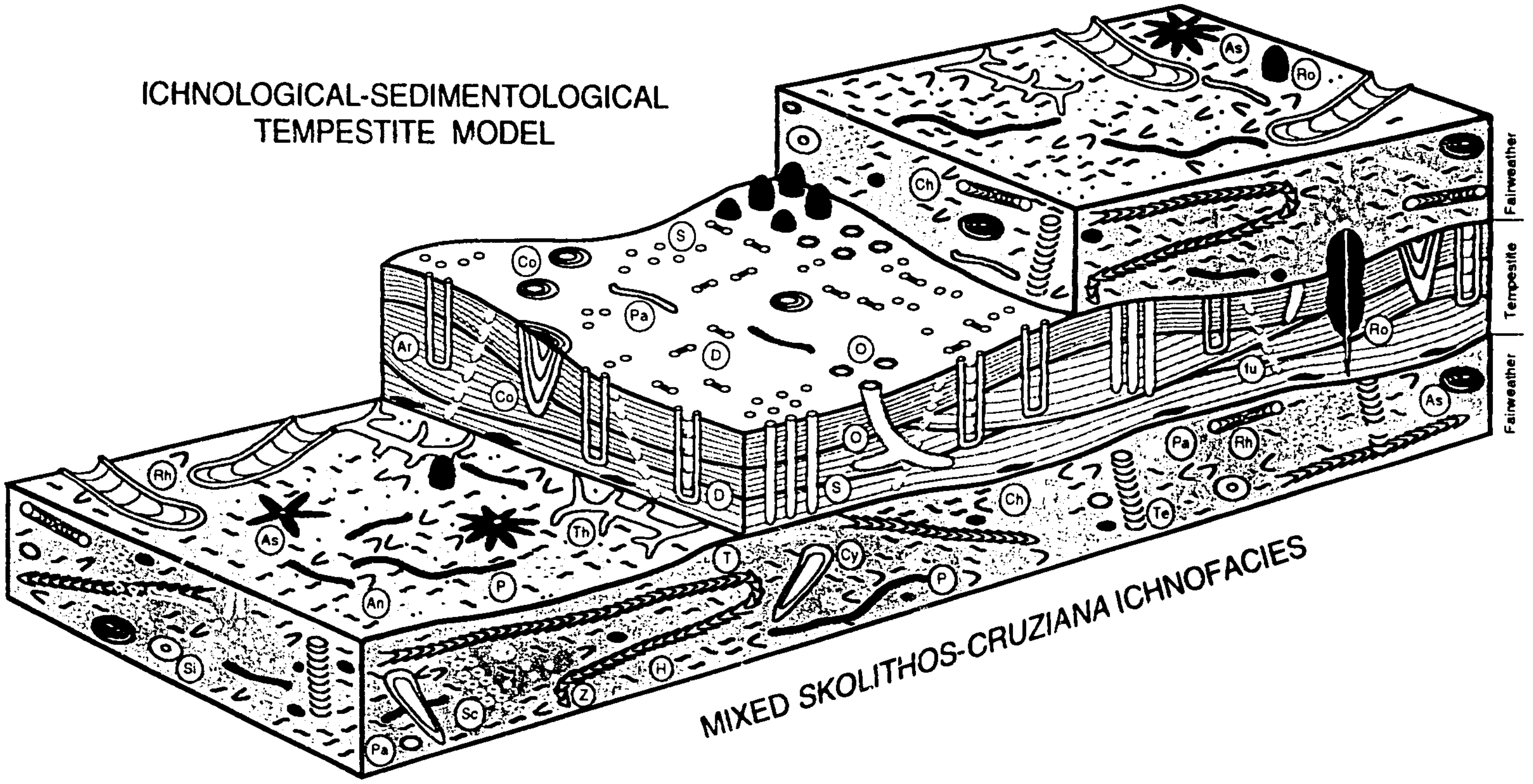


Figure IV-5. Idealised ichnological-sedimentological model of a high diversity mixed *Skolithos-Cruziana* ichnofacies, based on observations of Cretaceous strata of the Western Interior Seaway of North America. Fairweather deposits are characterised by thorough bioturbation with a high diversity of deposit feeding and grazing structures. The tempestite is burrowed with a lower diversity suite of mainly suspension feeding and dwelling structures. An: *Anconichnus*, Ar: *Arenicolites*, As: *Asterosoma*, Ch: *Chondrites*, Co: *Conichnus*, Cy: *Cylindrichnus*, D: *Diplocraterion*, fu: fugichnia, H: *Helminthopsis*, O: *Ophiomorpha*, P: *Planolites*, Pa: *Palaeophycus*, Rh: *Rhizocorallium*, Ro: *Rosselia*, Sc: *Schaubcylindrichnus*, Si: *Siphonichnus*, Sk: *Skolithos*, T: *Terebellina*, Te: *Teichichnus*, Th: *Thalassinoides*, Z: *Zoophycos*.

the *Cruziana* ichnofacies) can be considered representative of a stable benthic community, within which individual populations are at, or near their carrying capacity (*i.e.* equilibrium suites). Such associations, which typically are regarded to be resource-limited (Levinton, 1970), occur in habitats having low physio-chemical stress. Periodic generation of elements of the *Skolithos* ichnofacies, on the other hand, represents the flourishing of a community of opportunistic organisms in an unstable, highly stressful, physically-controlled environment. This basic pattern is not only characteristic of Cretaceous strata of the Western Interior Seaway, but has been recognised in numerous other deposits, ranging in age from Ordovician to Oligocene (Table IV-6).

Complete tempestite successions are characterised by: (1) sharp erosional bases, with or without basal lags; (2) low angle parallel to subparallel laminated sandstone intervals, corresponding to HCS, SCS or QPL; (3) common presence of fugichnia, reflecting the escape of entrained or buried organisms; (4) the dwelling burrows of opportunistic organisms near the tops of beds, locally penetrating deeply into the bed; (5) local preservation of remnants of waning flow deposits; (6) gradational burrowed tops showing the resident (equilibrium) fairweather suite cross-cutting the opportunistic suite; and (7), the return to fairweather deposition and re-establishment of the equilibrium trace fossil suite (Figure IV-6). This alternation of suites typically reflects the mixed *Skolithos-Cruziana* ichnofacies (Figure IV-5). Figure IV-7 schematically shows the progressive colonisation of a tempestite and the variable effects of later erosional amalgamation on the preserved record.

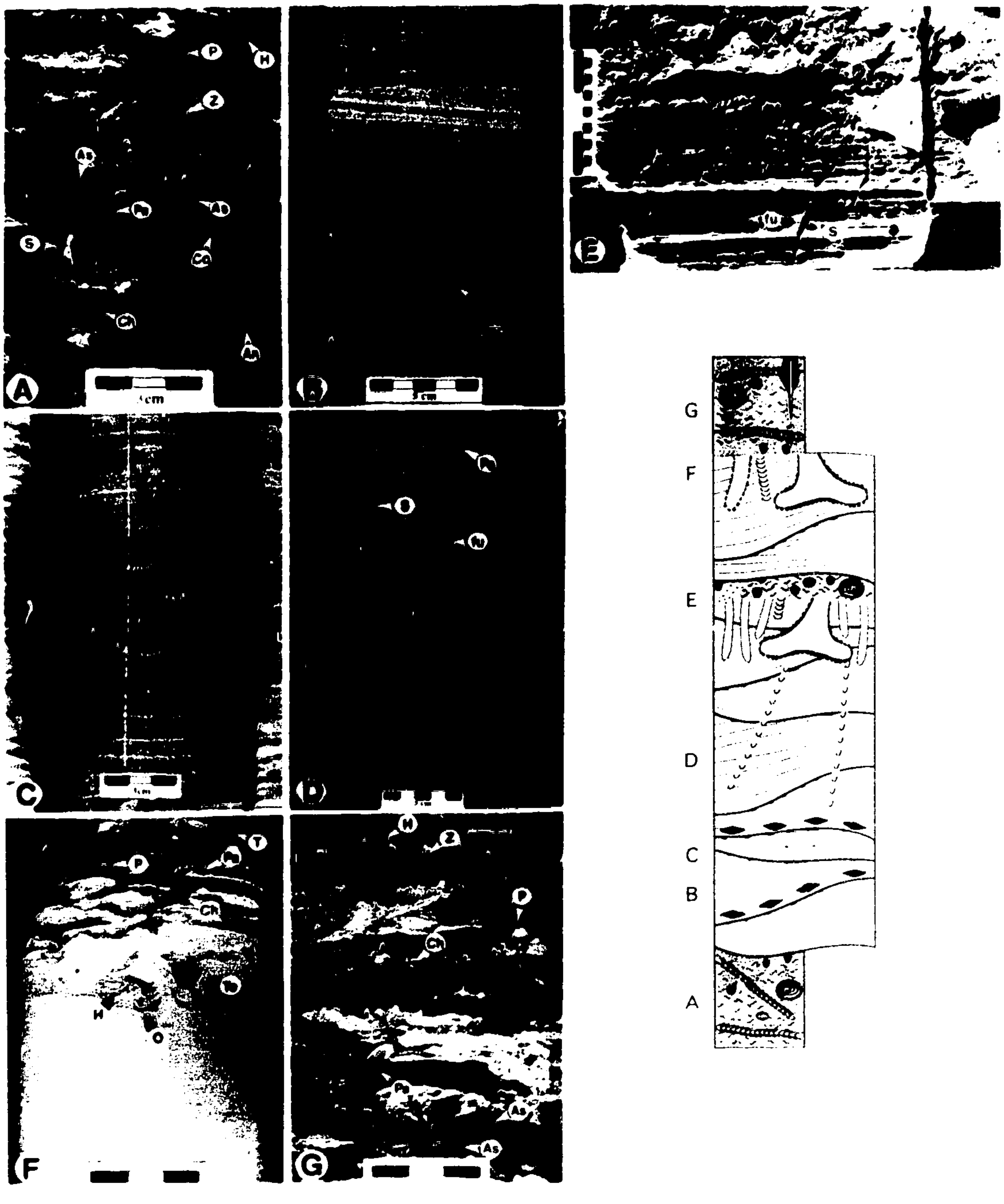
PRESERVATIONAL POTENTIAL

The increasing awareness of event bed deposition in the ancient record, or "uniformitarianist catastrophism" (Kumar and Sanders, 1976) has correspondingly led to much consideration of the preservability of such beds (*e.g.* Guinasso and Schink, 1975; Dott, 1983; 1988; Wheatcroft and Jumars, 1987; Wheatcroft, 1990). Observations of tempestites in various depositional settings demonstrates a wide variety of preservation styles (Figure IV-8). The fundamental parameters revolve around the net sedimentation rate, the biogenic mixing rate, and the magnitude of physical reworking, although most proposed quantitative models operate under the assumption that the

Table IV-6. Comparative Ichnology of Storm *Versus* Fairweather Deposits (modified from Pemberton and Frey, 1984 and Vossler and Pemberton, 1988).

Age	Formation	Ichnofossil (fairweather)	Ichnofossils (storm)	Reference
Mid-Upper Ordovician	Martinsburg Formation	none given.	*Planolites*, fugichnia.	Kreisa 1981
Lower Silurian	Ross Brook Formation	mottling, *Chondrites, Helminthopsis.*	*Skolithos, Palaeophycus.*	Hurst & Pickerill, 1986
Lower Silurian	Hughley Formation	*Scolicia, Walcottia, Rusophycus, Cruziana.*	*Diplocraterion, Palaeophycus, Chondrites, Skolithos.*	Benton & Gray 1981
Middle Silurian	Thorold Formation	*Arthrophycus, Chondrites, Cruziana, Daedalus, Diplichnites, Dolopichnus, Arenicolites, Lobichnus, Lingulichnus, Monomorphichnus, Palaeophycus, Planolites, Polycylindrichnus, Rusophycus, Teichichnus.*	*Skolithos, Diplocraterion*	Pemberton & Risk, 1982
Lower Carboniferous	Courceyan & Arundian Formations	none given.	*Rhizocorallium, Zoophycos, Planolites*, fugichnia.	Wu, 1982
Lower Jurassic	Neill Klinter Formation	*Rhizocorallium irregulare, Gyrochorte comosa, Parahaentzschelinia surlyki, Curvolithus multiplex, Taenidium serpentinum, Gyrophyllites kwassicensis, Planolites beverleyensis, Helminthopsis magna, Nereites* sp., *Phycosiphon* sp., *Scolicia* sp., *Phoebichnus trochoides.*	*Arenicolites, Ophiomorpha.*	Dam, 1990
Lower Cretaceous	Choshi Group	none given.	*Planolites, montanus, Nankaites*, steeply inclined *Palaeophycus.*	Katsura*et al.*, 1984
Upper Cretaceous	Frontier Formation	*Asterosoma, Teichichnus.*	*Ophiomorpha.*	Winn *et al.*, 1983
Upper Cretaceous	Shannon Sandstone	*Asterosoma, Skolithos*, gastropod trails, *Teichichnus* 'donut burrows' (possibly *Schaubcylindrichnus*), *Thalassinoides.*	*Skolithos.*	Tillman & Martinsen, 1985
Upper Cretaceous	Cardium Formation	*Chondrites, Planolites, Cochlichnus, Phoebichnus, Meunsteria, Rhizocorallium, Zoophycos, Planolites, Thalassinoides, Cylindrichnus, Rosselia, Gyrochorte.*	*Skolithos, Diplocraterion, Palaeophycus.*	Pemberton & Frey, 1984a; Vossler & Pemberton, 1988, 1989
Upper Cretaceous	Star Point Formation	*Scolicia, Palaeophycus herberti, Palaeophycus tubularis, Cylindrichnus concentricus, Thalassinoides suevicus, Teichichnus rectus, Planolites beverleyensis, Planolites montanus, Ancorichnus capronus, Ophiomorpha annulata.*	*Ophiomorpha nodosa, Skolithos linearis.*	Howard & Frey, 1984
Upper Cretaceous	Cape Sebastian Sandstone	*Ophiomorpha, Planolites, Scolicia, Sabellarites Thalassinoides, Macaronichnus segregatis.*	*Ophiomorpha.*	Hunter & Clifton, 1982
Upper Cretaceous	Cape Sebastian Sandstone	*Ophiomorpha, Planolites, Scolicia, Sabellarites Thalassinoides.*	fugichnia, *Scolicia, Ophiomorpha.*	Bourgeois, 1980
Upper Cretaceous	Blackhawk Formation	*Ophiomorpha annulata, Rosselia socialis, Terebellina* sp., *Planolites montanus, Planolites beverleyensis, Cylindrichnus concentricus, Palaeophycus heberti, Chondrites* sp.	*Ophiomorpha nodosa, Cylindrichnus concentricus.*	Frey, 1990
Mid Tertiary	Arno	*Imbrichnus, Scolicia, Planolites.*	*Ophiomorpha.*	Ward & Lewis, 1975
Oligocene	Magazine Pt. Formation	*Thalassinoides.*	*Ophiomorpha.*	Lewis, 1980

Figure IV-6. Characteristic Features of Tempestites. Photos A-G correspond to the designated intervals of the hypothetical section, corresponding to amalgamated tempestites within an upper offshore environment. **(A)** Bioturbated upper offshore sandy shales with an equilibrium fairweather *Cruziana* suite, consisting of *Zoophycos* (Z), *Helminthopsis* (H), *Anconichnus* (An), *Cosmorhaphe* (Co), *Planolites* (P), *Chondrites* (Ch), *Skolithos* (S) and *Asterosoma* (As). Cardium Fm., 10-01-35-08W5, 2574.6 m. **(B)** Rip-up clasts (arrow) present as a lag along the basal scour surface of a tempestite. Bluesky Fm., 06-10-75-08W6, 1560.3 m. **(C)** Main body of a tempestite, consisting of low angle parallel to subparallel laminated sandstone. The stratification reflects HCS, SCS or QPL. Towards the top of the tempestite is well-developed waning flow stage, aggradational combined flow ripple lamination, truncated by an overlying erosionally amalgamated tempestite. Cadotte Mbr., Peace River Fm., 07-08-64-02W6, 2126.5 m. **(D)** Tempestite with a basal lag of mudstone rip-up clasts, passing into parallel to subparallel laminated sandstone. Escape traces [*i.e.* fugichnia (fu)] are characteristic biogenic structures, reflecting the attempted escape of animals entrained in the flow or buried by the event bed to reach the new sediment-water interface. This example shows waning flow stage oscillation ripple lamination, cross-cut by opportunistic *Skolithos* (S) and *Palaeophycus* (Pa). Bluesky Fm., 06-10-75-08W6, 1560.0 m. **(E)** Tempestite displaying fugichnia (fu) and a high density of opportunistic *Skolithos* (S) shafts penetrating from the top of the bed. The tempestite is more highly burrowed upwards, passing into a fairweather assemblage. Appaloosa Sandstone, Bearpaw-Horseshoe Canyon Transition, Drumheller, Alberta. **(F)** Tempestite top, with an opportunistic suite of *Ophiomorpha* (O) reburrowed by *Helminthopsis* (H), as well as *Teichichnus* (Te). This is overlain by silty mudstone, reflecting post-storm fallout of mud from suspension, which typically impedes initial colonisation, compared to fairweather deposits. The post-storm suspension fallout deposit is burrowed with *Helminthopsis*, *Terebellina* (T), *Chondrites* (Ch), *Palaeophycus* (Pa) and *Planolites* (P). Viking Fm., 10-14-66-22W5, 1375.0 m **(G)** A return to bioturbated sandy shale of the upper offshore, with a fairweather equilibrium *Cruziana* suite, consisting of *Zoophycos* (Z), *Helminthopsis* (H), *Planolites* (P), *Chondrites* (Ch), *Palaeophycus* (Pa) and *Asterosoma* (As). This corresponds to the re-establishment of the resident fairweather community after prolonged non-storm (ambient) conditions. Cardium Fm., 07-14-28-05W5, 2435.7 m.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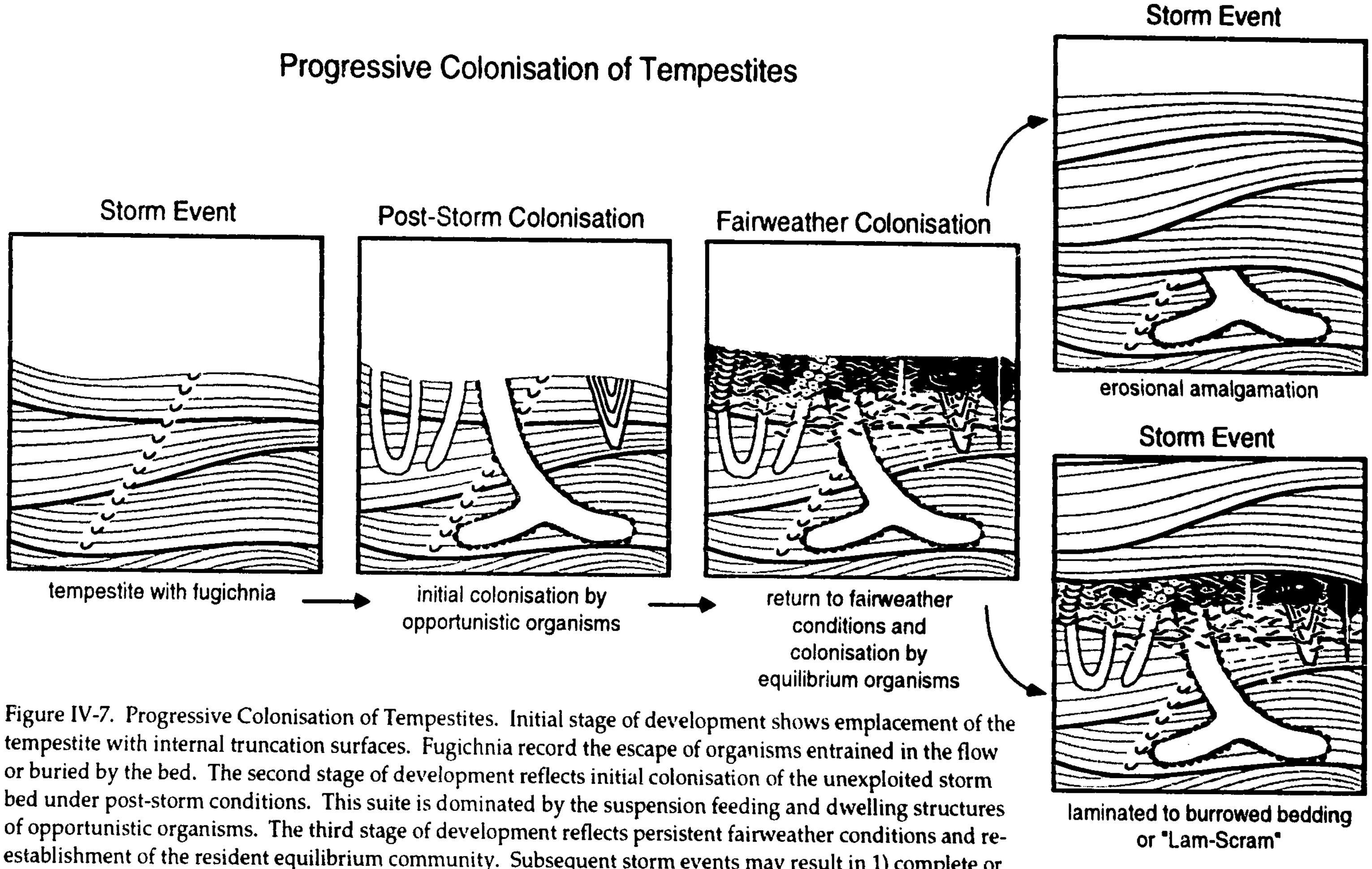
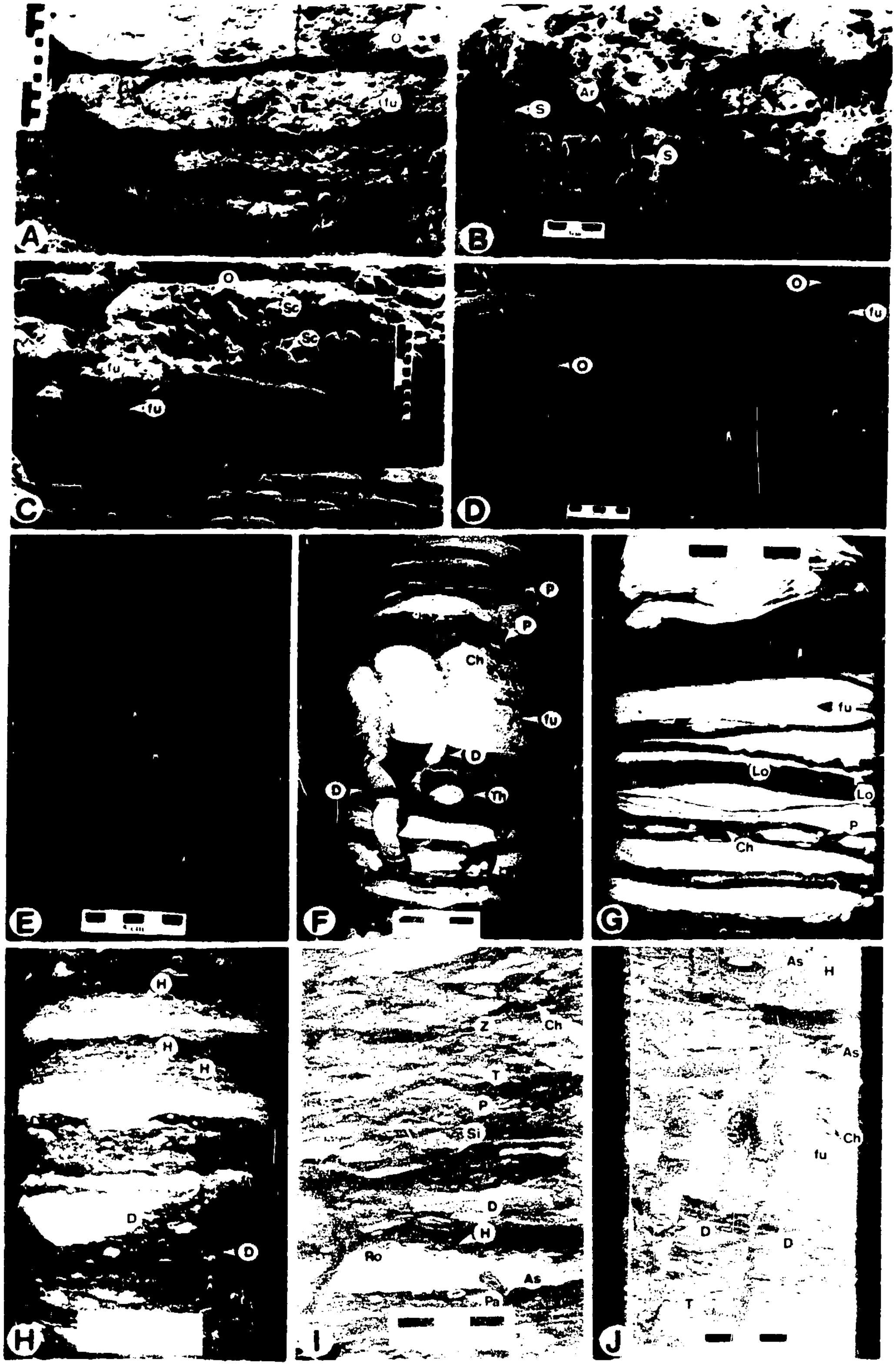


Figure IV-7. Progressive Colonisation of Tempestites. Initial stage of development shows emplacement of the tempestite with internal truncation surfaces. Fugichnia record the escape of organisms entrained in the flow or buried by the bed. The second stage of development reflects initial colonisation of the unexploited storm bed under post-storm conditions. This suite is dominated by the suspension feeding and dwelling structures of opportunistic organisms. The third stage of development reflects persistent fairweather conditions and re-establishment of the resident equilibrium community. Subsequent storm events may result in 1) complete or virtually complete removal of evidence of post-storm colonisation (some deeply penetrating structures and escape structures may survive) or 2) minimal erosional amalgamation of storm beds, preservation of the opportunistic storm suite, and ocally, partial preservation of the fairweather suite, producing "laminated-to-burrowed" bedding.

Figure IV-8. Tempestite Preservation Styles. (A) Lower shoreface tempestites showing virtual biogenic obliteration. Although the discretely bedded nature of the tempestites is preserved, most internal stratification is biogenically disrupted. Fugichnia (fu) and *Ophiomorpha* (O) are visible. Sussex Sandstone, Casper Wyoming. **(B)** Lower shoreface tempestites, displaying nearly complete biogenic obliteration. The high abundance of *Skolithos* (S) and *Arenicolites* (Ar) reflect a dense opportunistic assemblage. Sussex Sandstone, Casper Wyoming. **(C)** Lower shoreface tempestites, with preserved low angle parallel stratification, internal scour surfaces and fugichnia (fu). Storm bed colonisation is reflected by overlying bioturbated sandstone containing *Schaubcylindrichnus* (Sc) and *Ophiomorpha* (O). Sussex Sandstone, Casper Wyoming. **(D)** Burrowed sandstone, truncated by an erosionally amalgamated lower to middle shoreface tempestite, containing fugichnia (fu) and *Ophiomorpha nodosa* (O). Appaloosa Sandstone, Bearpaw-Horseshoe Canyon Transition, Drumheller, Alberta. **(E)** Stacked, erosionally amalgamated, lower to middle shoreface tempestites. The absence of biogenic structures is characteristic of strongly storm-dominated successions. Bluesky Fm., 03-28-74-11W6, 1796.9 m. **(F)** Thin, sharp-based tempestites deposited in the offshore. The fugichnia (fu) and opportunistic *Diplocraterion* (D) cause little disruption of the beds. The fairweather trace fossil suite shows event bed avoidance, is restricted to the mudstones, and consists of *Planolites* (P), *Chondrites* (Ch) and *Thalassinoides* (Th). Viking Fm., 16-18-66-21W5, 1326.7 m. **(G)** Distal (offshore), oscillation ripple and wavy parallel laminated tempestites, weakly burrowed with fugichnia (fu), *Lockeia* (Lo), *Planolites* (P) and *Chondrites* (Ch). The paucity of burrowing is attributed to high frequency tempestite emplacement with associated mud drapes due to post-storm suspension fallout. Viking Fm., 00/10-05-65-20W5, 1456.8 m. **(H)** Distal (offshore) tempestites, only moderately disrupted by *Diplocraterion* (D) and, to a lesser extent, *Helminthopsis* (H) which reworks the graded tops. Burrowing is largely restricted to intervening post-storm beds, reflecting event bed avoidance by the infauna. Small trace sizes minimise disruption. Viking Fm., 16-18-66-21W5, 1328.3 m. **(I)** Distal (offshore) tempestites, displaying biogenic modification by *Rosselia* (Ro), *Diplocraterion* (D), *Terebellina* (T) and *Asterosoma* (As). *Zoophycos* (Z), *Chondrites* (Ch), *Planolites* (P), *Siphonichnus* (Si) and *Palaeophycus* (Pa) are also present. Viking Fm., 02/10-19-63-11W5, 1411.3 m. **(J)** Distal (upper offshore) tempestite, showing strong disruption by *Diplocraterion* (D) and fugichnia (fu). The fairweather suite consists of *Terebellina* (T), *Asterosoma* (As), *Helminthopsis* (H), *Chondrites* (Ch), *Planolites* and *Teichichnus* . Viking Fm., 12-04-64-11W5, 1458.7 m.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latter factor is absent. Wheatcroft (1990) demonstrated that neither sedimentation rate nor biogenic mixing rate are easily defined, both of them masking important, complex affiliated processes and interactions. Few of these have been addressed in detail, despite the effect they have on event bed preservation. In contrast to previous models, which have concentrated mainly on layer thicknesses of event beds and mixing zones, Wheatcroft (1990) focused on time scales. The result has been a model relating transit time (*i.e.* the time necessary to bury the event bed beyond the reach of the burrowing infauna) and the dissipation time (*i.e.* the time required to biogenically destroy the event bed). Clearly, in circumstances where the event bed is thicker than the zone of burrowing, the fraction that exceeds the burrowing zone will be preserved regardless of the duration of biogenic reworking. Compelling though this model is, the inherent variability of the physical and biological responses to the depositional event greatly limits the accuracy of this quantification and thus limits its utility to the interpretation of the ancient record.

Transit Time

Previous workers have calculated the transit time by dividing the thickness of the zone of biogenic reworking by the sedimentation rate. Wheatcroft (1990) pointed out that the thickness of the event bed itself was important in the calculation of transit time, and proposed that the combined thickness of the biogenic reworking zone and event layer, less one half of the thickness of the event layer, all divided by the sedimentation rate was a more accurate estimation of the transit time.

Several interactions exist in the determination of transit time, which are probably impossible to quantify in the ancient record. The first is the thickness of the biogenic mixing zone. Clearly this is, in part, related to the size of the animals constituting the benthic community. Although burrow size can be related to organism size in some instances, in many it cannot, and the common overprinting of the trace suite by later deep burrowers serves to obscure much of this data. Further, the degree of bed penetration is not simply a function of the animal size, but is also closely related to the behaviour engaged in during its generation. Many grazing and foraging structures tend to be restricted to the sediment-water interface, and do not deeply penetrate the bed (Figure IV-8 H). Mobile deposit feeders and carnivores tend to be more deeply penetrating. In contrast, vertical dwelling structures of suspension feeders or passive carnivores may be very deeply penetrating (*e.g. Ophiomorpha*; Figure IV-8 D), but once constructed, have little more effect on the bed. Unless the dwelling structures become very closely spaced and overprint one another (*e.g.* Figure IV-8 B), it is unlikely that such suites will totally obscure an event bed. The nature of organism behaviour also has important implications for dissipation time (see below).

In general, the zone of biogenic reworking is thinnest in the lower offshore to abyssal depths, where diminutive grazers and foragers dominate the benthic community. The zone thickens through the upper offshore, where more robust and mobile deposit feeders dominate. The fairweather *Skolithos* ichnofacies may extend the zone of biogenic reworking much deeper in lower shoreface and shallower settings, but is also characterised by a decrease in effective homogenization of the bed at those depths.

Sedimentation rate is highly problematic to resolve quantitatively, even using modern settings as analogues. The most obvious problem revolves around the use of the average or fairweather (ambient) sedimentation rates. The mere presence of an event bed in the interval in question demonstrates that sedimentation rates are inherently unsteady and unpredictable in the setting. An offshore zone may experience months of fairweather deposition at a rate that is totally overshadowed by the accumulation of a single tempestite deposited over the course of days. Since these events are unpredictable, both with respect to their frequency and the magnitude of deposition, they currently defy reliable quantification and inclusion into calculated sedimentation rates of most settings.

Dissipation Time

Dissipation time corresponds to the time required to biogenically destroy an event bed. Wheatcroft (1990) demonstrated that there is a fundamental difference between destruction of an event bed characterised by a discrete mineralogy and chemistry (*e.g.* ash beds or iridium anomalies) and destruction of an event bed distinguishable only by its lithology and fabric (*e.g.* HCS beds and turbidites). The former anomalies may survive considerable biogenic reworking, becoming mixed over a considerable thickness of interval and yet still remaining detectable. In contrast, the latter is recognised on the basis of far more easily obliterated criteria (sedimentary structures, *etc.*) and is therefore more sensitive to the duration of biogenic activity. Since this paper is concerned with the nature of tempestites, the effects of dissipation time on the lithology and fabric of event beds will only be considered. Dissipation time is comparatively more difficult to determine than is transit time.

Previous discussion regarding the characteristics of the benthic community touched on two parameters strongly affecting dissipation time. The most obvious parameter is the size of the animals constituting the infauna. Robust organisms can displace or mix sediment a greater distance per unit time than can diminutive ones. For example, some sandstones may contain large numbers of amphipod burrows, but because of their small size, minimal displacement of grains may be evident, and primary stratification may be well preserved (Howard and Elders, 1970). In a very general sense, organism sizes tend to be larger in shallower water settings than in deep water, although each benthic community typically contains a wide range of infauna sizes, attributable to a large number of factors, ranging from differences in genera or species, to relative proportions of juveniles and adults (Dörjes and Hertweck, 1975).

More important with regard to dissipation time is the behaviour engaged in by the organism. As touched on above, mobile deposit feeders and carnivores tend to produce much greater disruption of the bed, in both a vertical and lateral sense, than are generated by grazers and foragers. The grazing/foraging behaviours may result in rather intense reworking of the sediment, but this is generally restricted close to the sediment-water interface (Ekdale, 1980). Continuous, slow accumulation of fairweather deposition may promote thorough homogenization of the sediment laterally, but the tracemakers tend to show little propensity to penetrate deeply into the substrate (Howard, 1975; Dott, 1983, 1988). An exception is the *Zoophycos* tracemaker, which may display substantial vertical penetration into the substrate (Kotake, 1989). However, the biogenic structure rarely shows intense reworking of the event bed, which typically has little in the way of deposited food (Frey and Goldring, 1992). Typically, the *Zoophycos* trace crosses through the event bed with minimal disturbance, until a resource-rich interval, generally constituting a buried fairweather or ambient deposit, is encountered. Thorough reworking of the buried fairweather sediment may then occur (Vossler and Pemberton, 1988).

Dwelling structures and suspension feeding structures may show appreciable vertical penetration into an event bed, but typically displays minimal volumetric modification of the bed's fabric. The structures may deepen or extend areally over the lifetime of the tracemaker, but such structures clearly do not result in the degree of homogenization imparted by mobile infauna (Pemberton and Frey, 1984; Frey, 1990). As such, the actual thickness of the biogenic mixing zone is less important than the nature of the behaviour employed by organisms within the mixing zone.

Perhaps one of the most under-appreciated factors regarding the dissipation time is associated with the dynamic interplay between the benthic community and the depositional event itself. In many cases, the event bed follows a disturbance which largely displaces or destroys the resident benthic community. Biogenic modification may not simply begin immediately after the event. Instead, the site may remain unpopulated for a considerable period of time. Once recolonisation is initiated, it may take even more time for the community to achieve the density it possessed prior to the disturbance (Sousa, 1984). Shallower water settings, characterised by persistent and generally higher degrees of stress may show repopulation within 11 months of a disturbance, whereas more highly sensitive deep sea settings may take more than double that time to recover (Dauer and Simon, 1976; Grassle, 1977).

Complete destruction of the benthic community may occur in two main ways. The most obvious is related to the severity of the disturbance producing the event bed. This is particularly evident in shallower water settings, where erosional amalgamation of beds is more pronounced and locally, cannibalistic (Aigner and Reineck, 1982; MacEachern and Pemberton, 1992). Under these conditions, the entire benthic community is typically washed out of the substrate and transported elsewhere. The severity of such disturbances decreases basinward, such that distal tempestites, and in particular turbidites may show well preserved fairweather/resident trace fossil suites on their basal surfaces (*e.g.* Seilacher, 1962; Crimes, 1977; Crimes *et al.*, 1981; Pemberton and Frey, 1984; Frey and Goldring, 1992).

The second major factor resulting in destruction of the benthic community is associated with the thickness of the event bed laid down. Once the organisms become buried, they attempt to burrow up through the bed to reach the new sediment water interface. If the event bed is too thick, none of the original resident community will survive to repopulate the post-storm substrate, minimising the time of "effective" bioturbation (Kranz, 1972). On the other hand, thinner event beds may be repopulated more quickly, since most of the benthic community may escape burial. Some biogenic modification of the event bed will occur, purely as a function of the escape structures. Tempestites show a general basinward thinning and initially it may seem, therefore, that the thinner beds of the shelf and lower shoreface may be rapidly colonised. In actuality, because organisms of these basinal benthic communities tend to be diminutive in size, few animals may be able to reach the top of even a relatively thin event bed. As well, few tracemakers of the shelf and more basinal settings possess carapaces, and therefore are unlikely to survive entrainment in a tempestite or turbidite flow, unlike some organisms of shallower water settings. For example, Föllmi and Grimm (1990) described turbidite deposits in the Miocene Monterey Formation and the Oligocene-Miocene San Gregorio Formation of California which contained *Thalassinoides* and *Gyrolithes* interpreted to have been generated by thalassinidean crustacea which survived sediment-gravity flow transport from shallow water settings to the basin floor.

Another important factor surrounding the dissipation time is associated with the desirability of the event bed as a site for colonisation and as a repository of food resources. The event bed generally varies markedly from the normal ambient (fairweather) sediment, to which the resident community are suited. Even those organisms which burrow out of the event bed may, upon reaching the sediment-water interface, find a substrate devoid of suitable food resources, and subsequently die. Those which do survive, as well as opportunistic organisms whose larvae managed to find their way to the unexploited substrate are trophic generalists. They typically do not burrow through the bed, but rather, establish domiciles and engage in suspension feeding, or carry out surface deposit feeding and scavenging strategies (Jumars, 1993). Penetrating domiciles show minimal lateral disturbance of the bed, and exceedingly dense populations are needed in order to entirely obliterate a bed (*e.g.* Figure IV-8 B). Once suitable amounts of ambient sediment accumulate and the resident faunal community re-establishes itself, the infauna generally show little inclination to penetrate deeply into the event bed, but rather, engage in behaviours suited to the ambient conditions (Rees *et al.*, 1977). This avoidance pattern appears most pronounced in basinal settings (Figure IV-8 F, H, I), where the contrast between behaviours suited to the event bed and those suited to the ambient substrate are greatest. This is most common where turbidites are deposited in abyssal settings. In upper offshore conditions, where robust and diverse tracemakers of more proximal *Cruziana* ichnofacies predominate, the differences between event bed and ambient deposit behaviours are less pronounced (Figure IV-8 I). In lower shoreface and middle shoreface settings, no preference for fairweather burrowing over event bed burrowing may be noted (*e.g.* Pemberton *et al.*, 1992c), and for all intents and purposes, both suites are identical.

The final factor regarding dissipation time is the absolute time available for burrowing. As in the discussion of sedimentation rates, there is obviously considerable variability in burrowing time in any setting characterised by episodic deposition. In the case of tempestites, one may suspect minimal burrowing times to occur in shallower water settings, with progressively more time available basinward. This primarily reflects the greater probability of storm interaction with the sea floor in shallower water, regardless of storm magnitude. In the case of turbidites, however, variability in burrowing time is more closely related to basin paleogeography and, if present, the configurations of any submarine fan systems.

In general, the above factors impose fundamental controls on the effectiveness of biogenic modification of event beds, and consequently, on their preservation potential. Unfortunately, these factors appear to resist quantification, and therefore severely limit the effectiveness of existing mathematical models to explain event bed preservation in the rock record.

Physical reworking of the substrate is typically avoided in most of the models proposed, but clearly has a profound effect on the preservation of both the event bed and the fairweather deposits. In the case of tempestites, enhanced physical reworking is associated with shallower water settings, with higher magnitude storms, and with higher frequency storms. The latter factor principally reflects minimal fairweather accumulation on the tempestite and minimal colonisation of the substrate, both of which serves to enhance the ability of successive storm events to rework earlier tempestites (Figure IV-8 D, E). Under proximal conditions, successive tempestites may become highly cannibalistic (Aigner and Reineck, 1982), resulting in only minor preservation of the beds.

Despite the difficulties in mathematically modeling preservation potential of tempestites, there are a number of proximal-distal trends evident on the basis of empirical observations (Figure IV-9). In general, shallow water settings favour the preservation of event beds, since higher numbers of storms enhance erosional amalgamation and minimise the time available for burrowing, factors which are also responsible for the minimal preservation of fairweather deposits. These appear to overcome the factors favouring biogenic modification of event beds, such as larger animal sizes, greater bed penetration, suitability of the event bed to colonisation by the resident benthic community, and higher rates of recolonisation following a disturbance. Shallow water deposits are dominated by vertical to subvertical domiciles, minimising event bed modification. These settings typically correspond to proximal lower shoreface and middle shoreface environments (*e.g.* Figures IV-2; IV-8 C, D).

Distal settings also favour preservation of event beds, but for markedly different reasons. Fairweather deposits also have a high preservation potential, unlike shallow water settings. Factors favouring preservation of tempestites are minimal erosional amalgamation, minimal bed penetration by infauna, diminutive size of infaunal organisms, general avoidance of event beds as a viable substrate, sensitivity of the benthic community to environmental disturbances, and slow rates of recolonisation following a disturbance. These serve to overshadow conditions favouring event bed modification, such as long durations of fairweather conditions, slow rates of ambient sediment accumulation, and reduced potential of event bed accumulation. Such settings are typical of shelf and lower offshore settings in the Cretaceous of the Western Interior Seaway (Figures IV-3; IV-8 F, H, I).

The lowest preservation potential for tempestites appears to occur somewhere between the proximal and distal extremes. Under such conditions, erosional amalgamation is not as effective and displacement of the resident suite is not as common. Further, the reduced sensitivity of the benthic community to disturbances and generally higher rates of recolonisation, all favour more rapid biogenic modification of the event bed. The variability in organism type and behaviours employed insures that the tempestite will be suitable to some of the benthic community as a viable

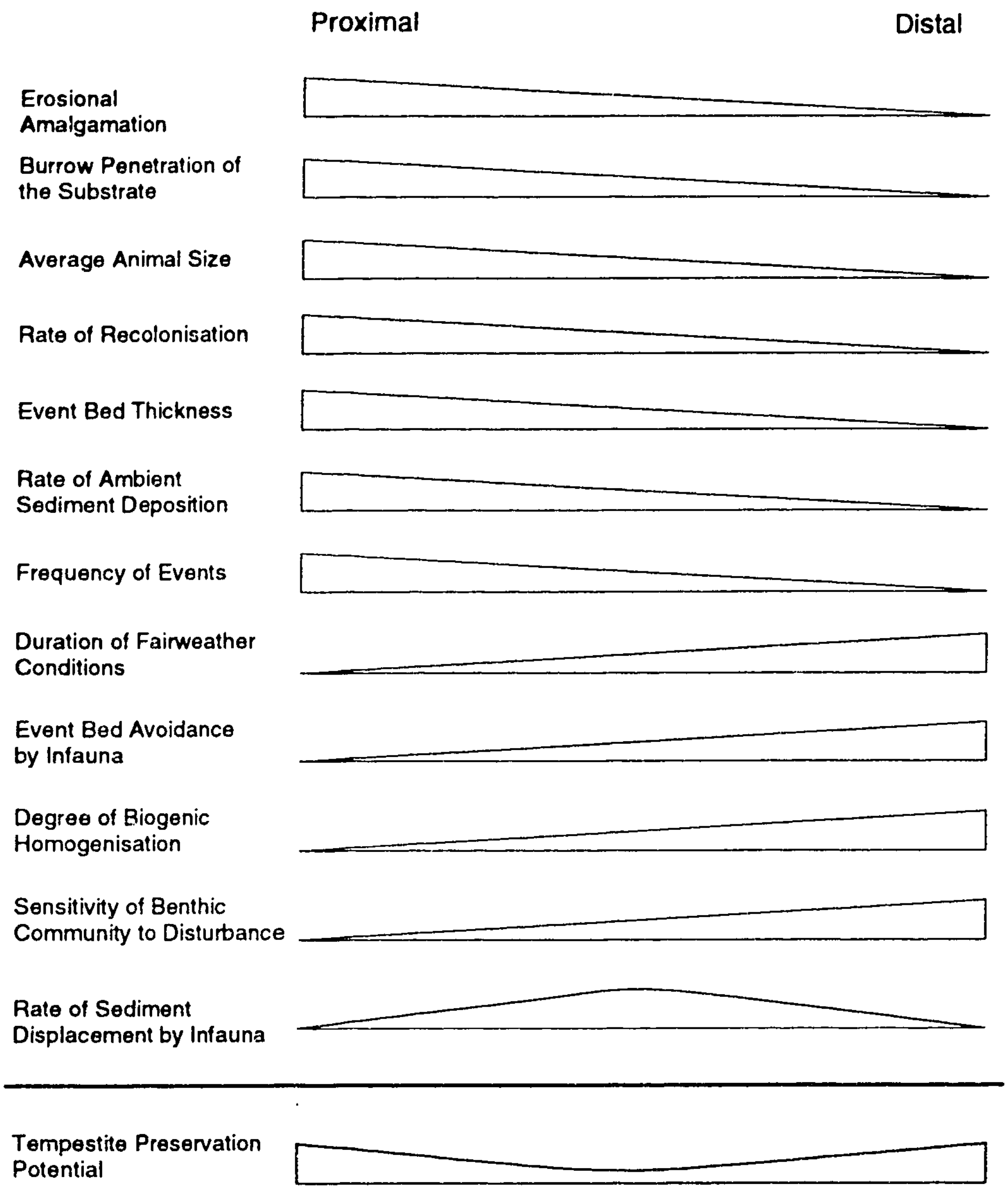

Figure IV-9. Schematic representation of the main factors affecting tempestite preservation and their relative importance with respect to proximal and distal depositional positions. Note that in general, tempestite preservation potential appears lower in intermediate depositional settings. Higher preservability occurs in proximal and distal settings, although for markedly different reasons.

medium for burrowing. The higher numbers of mobile deposit feeders and carnivores favours rapid and thorough modification of bed fabrics within the biogenic mixing zone, while the introduction of suspension feeders also promotes the development of deeply penetrating vertical structures. Such zones appear to correspond to proximal *Cruziana* ichnofacies suites of the upper offshore and distal portions of the lower shoreface (Figure IV-8 A, B, C, I).

The tempestite preservation potential (Figure IV-9) seems to be consistent with observations of many modern and ancient examples (Kumar and Sanders, 1976; Pemberton and Frey, 1984; MacEachern and Pemberton, 1992; *cf.* Table IV-6). Dott (1988) used the deposit of Hurricane Carla to outline this variability of preservation potential. McGowan (reported in Dott, 1988) was unable to identify the prominent tempestite resulting from Hurricane Carla, reported on by Hayes (1967), a mere 15 years after the event. Bioturbation had apparently obliterated much of the record. However, Nummedal (reported in Dott, 1988) managed to recognise the event bed further offshore (beyond 18-20 m of water depth), where biogenic modification of the tempestite had been less intense.

The low preservation potential of hurricane-induced tempestites may also reflect the infrequent nature of such disturbances. In these settings, the tempestite is exposed to long periods of biogenic colonisation and modification before it is buried below the reach of infauna. In contrast, many high latitude settings are characterised by cyclic variations in storm activity. Such settings are characterised by a winter storm season, where disturbances are both frequent and of high magnitude, and a summer fairweather season, where storms are less frequent and of lower intensity (Cook and Gorsline, 1972; Owens, 1977; Hunter *et al.*, 1979). Under such conditions, tempestites accumulate rapidly during winter seasons with little or no time for biogenic colonisation. Summer fairweather seasons favour biogenic colonisation and modification of the tempestites, however, this is largely restricted to the top of the uppermost event bed. Any tempestites that may accumulate in response to the infrequent and lower intensity storms typical of the fairweather season may show significantly greater degrees of biogenic mottling. Storm seasonality is interpreted to account for the storm-dominated successions typical of the Bluesky Formation, the Falher Member cycles, and the Cadotte Member of the Peace River Formation (*cf.* Chapter VI).

SUMMARY

Storms represent an important mode of deposition in most basins. Their deposits commonly contain a trace fossil suite consisting of a stable fairweather assemblage, dominated by traces of equilibrium (K-selected) species, and an unstable storm (or pioneer) assemblage, dominated by traces of opportunistic (r-selected) species. The integration of these distinct, juxtaposed ichnological suites with sedimentology provides a depositional model which facilitates the reliable recognition of tempestites in the rock record.

Tempestites are characterised by: (a) a sharp erosional base, with or without a basal lag; (b) a main sandstone interval with low angle, parallel to subparallel laminations (HCS, SCS or QPL); (c) escape structures; (d) rare waning flow deposits, mainly consisting of oscillation or combined flow ripple laminae, towards the top of the bed; (e) dwelling burrows of opportunistic organisms near the tops of beds, representing initial colonisation; (f) gradational burrowed tops with fairweather suites cross-cutting the opportunistic assemblage; passing into (g) thoroughly burrowed fairweather deposits containing an equilibrium trace fossil suite. The alternations between opportunistic suites of the *Skolithos* ichnofacies and fairweather suites of the *Cruziana* ichnofacies reflect *in loco* fluctuations in energy, rather than variations in sea level. Proximal-distal trends are primarily discerned by changes in the fairweather trace fossil suite.

Tempestite preservation potential involves complex inter-relations between a number of largely unquantifiable parameters, such as the degree of physical reworking, duration of fairweather conditions, frequency and severity of environmental disturbances, variability in sedimentation rate, infauna size, nature of infaunal behaviours, intensity and rate of burrowing, sensitivity of the benthic community to a disturbance, degree of event bed avoidance by the infauna, thickness of the biogenic mixing zone, and recolonisation rates following a disturbance. Empirical observations of tempestites and modern benthic communities suggest that tempestite preservation is favoured in shallow water (*e.g.* proximal lower shoreface and middle shoreface) settings, although fairweather deposits are manifest by a low preservation potential. Basinal (*e.g.* lower offshore and shelfal) settings favour the preservation of both tempestites and fairweather deposits. In contrast, intermediate settings (upper offshore and distal lower shoreface environments) display a low preservation potential for tempestites and enhanced preservation of fairweather sediments.

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CHAPTER V

AN INTEGRATED ICHNOLOGICAL-SEDIMENTOLOGICAL MODEL OF CRETACEOUS SHOREFACE SUCCESSIONS AND SHOREFACE VARIABILITY IN THE WESTERN INTERIOR SEAWAY OF NORTH AMERICA[4]

INTRODUCTION

The shoreface consists of a seaward-sloping sediment wedge extending from the low tide mark, generally to the fairweather (minimum) wave base, corresponding to approximately 10-20 m of water depth. With greater storm-domination, effective wave base is lowered to depths approaching storm weather wave base. As a result, erosively amalgamated tempestites of "lower shoreface" affinity may actually be deposited well below fairweather wave base. The shoreface setting is dominated by wave energy and, as a result of decreasing wave interaction with the substrate in a seaward direction, shows a pronounced basinward fining. The shoreface is classically divided into three subenvironments (from seaward to landward): the lower, the middle and the upper shoreface. The boundaries between these are not always clearly defined (Reinson, 1984). Although the large-scale regional context may vary, the specific subenvironments of the shoreface are not significantly different whether they occur as part of a strandplain, barrier island or wave/storm-dominated delta (free from interference from active distributary channels).

The shoreface grades distally into offshore units and landward into foreshore deposits. A complete shoreface progradational succession reflects offshore to foreshore environments; consequently, these adjacent environments bear inclusion in any discussion of shoreface deposits *per se*.

There are several excellent outcrop examples of Cretaceous shoreface deposits in the Western Interior Seaway, including the Turonian Cardium

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[4] A version of this chapter has been published. MacEachern, J.A. and S.G. Pemberton. 1992. *In*: S.G. Pemberton (ed.), Applications of ichnology to petroleum exploration- a core workshop. Society Economic Paleontologists and Mineralogists Core Workshop 17: 57-84.

Formation, the Campanian Virgelle Member of the Milk River Formation, the Campanian Appaloosa Sandstone of the Bearpaw-Horseshoe Canyon Transition, and Maastrichtian Blood Reserve Sandstone, of southern Alberta. The Late Albian-Cenomanian Bootlegger Member of the Blackleaf Formation and Campanian Eagle Sandstone of Montana, as well as the Campanian Star Point and the Blackhawk formations of the Book Cliffs, Utah are also examples. In addition, there exist large numbers of excellent shoreface successions preserved within the subsurface of Alberta, such as the Albian Bluesky Formation, the Albian Cadotte Member of the Peace River Formation, the Albian Viking Formation and the Turonian Cardium Formation. The integration of the sedimentology and ichnology within these deposits affords the opportunity to characterise the facies and facies successions (Figure V-1), and to explain the observed facies variability.

SHOREFACE SUBENVIRONMENTS

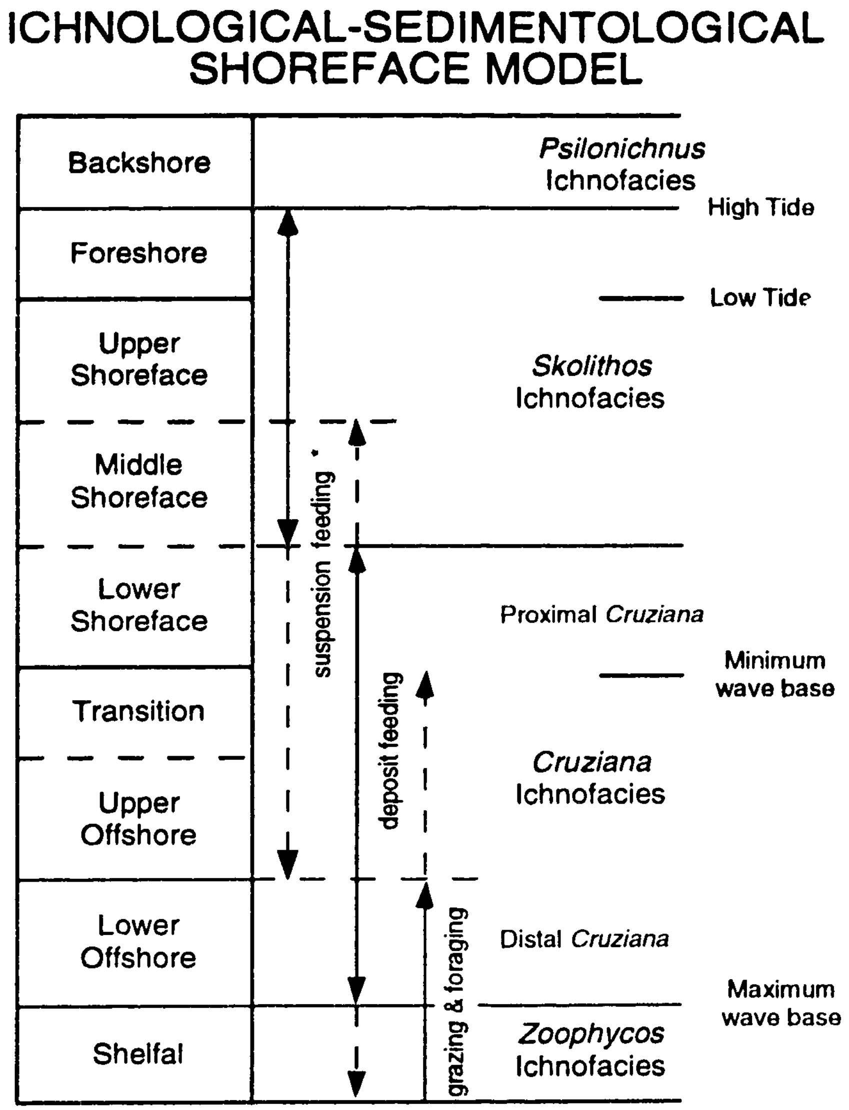
The shoreface and adjacent environments can easily be grouped into three depositional complexes. Each complex corresponds to discrete depositional parameters, both with respect to physical processes and biogenic structures.

Offshore Complex

The offshore zone is regarded to lie below minimum (fairweather) wave base and above maximum (storm-weather) wave base. The offshore is commonly subdivided into a lower and upper subzone (*e.g.* Pemberton *et al.*, 1992a). Howard and Frey (1984) subdivided the offshore into "lower", "middle" and "upper" offshore subzones, based on outcrops within the Book Cliffs of Utah; in many respects, their "lower" offshore is more reminiscent of shelfal silty shales.

Lower Offshore

The lower offshore, as defined here, comprises dark silty shales, commonly thoroughly homogenized by biogenic reworking. Fine to very fine sandstone beds are present, though in low abundances. Thin beds are predominantly intensely bioturbated, although locally, remnant undulatory



* Many tube dwellers are passive carnivores rather than suspension feeders.

Figure V-1. Idealised shoreface model of ichnofacies successions, based on observation of Cretaceous strata of the Western Interior Seaway of North America (modified after Pemberton *et al.*, 1992a).

parallel laminae are preserved. Thicker beds tend to show sharp, erosive bases, with moderately- to well-developed parallel lamination. Most burrowing is restricted to the tops of beds. These preserved beds are interpreted as distal tempestites.

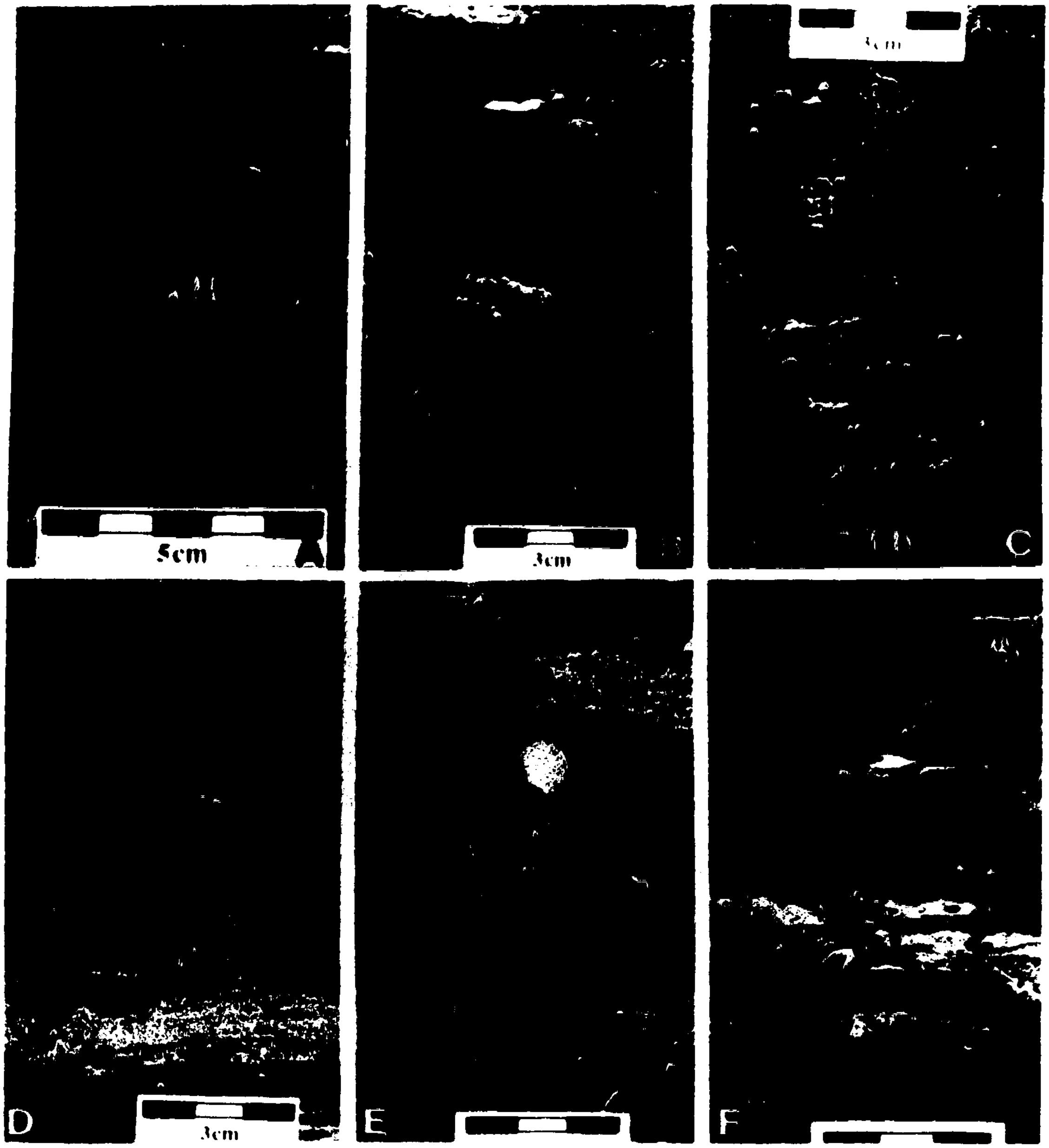
The ichnological suite may be regarded as a "distal" or "outer" *Cruziana* assemblage, incorporating a relatively low diversity of both deposit feeding and to a lesser degree, grazing/foraging structures. Common ichnogenera include small, thin-walled *Terebellina, Planolites, Helminthopsis, Anconichnus horizontalis, Chondrites, Zoophycos* and *Thalassinoides* (Figure V-2 A,B). Less common forms include small *Asterosoma* and rare *Palaeophycus*. These facies are relatively common in the lower cycles of the Viking Formation, in the Cardium Formation. Howard and Frey (1984) also noted the presence of *Thalassinoides suevicus, Ancorichnus capronus* and *Ophiomorpha annulata* in the Book Cliffs of Utah (their "middle" offshore). Frey (1990) observed the additional presence of *Rosselia socialis* and *Cylindrichnus concentricus* within the lower offshore deposits within the Spring Canyon Member of the Blackhawk Formation, Coal Creek Canyon, Utah. *A. capronus, O. annulata, R. socialis* and *C. concentricus* reflect burrows initially established in tempestites, rather than in the fairweather deposits of the lower offshore.

The lower offshore is dominated by diminutive deposit feeding structures and grazing/foraging structures which typically occur in large numbers. Most of these structures show minimal vertical penetration of the bed. Under such circumstances, distal storm beds may show little biogenic reworking, except near their tops, even if the tempestite is relatively thin. Since these distal storm beds are deposited well below fairweather wave base, physical processes during non-storm periods are not competent to modify them, and hence, such beds have a high preservation potential (Dott, 1983, 1988; Wheatcroft, 1990). The fairweather deposits of the lower offshore commonly display high abundances, high diversity and fairly uniform distribution of ichnogenera corresponding to a distal *Cruziana* ichnofacies (Figure V-1).

Upper Offshore

The upper offshore is considerably more variable than the lower offshore, attributable to the greater degree of storm and wave interaction with the substrate. The interval commonly consists of intensely bioturbated silty and

Figure V-2. Offshore Deposits. (A) Lower offshore silty shale, intensely burrowed with *Helminthopsis* (H), *Planolites* and *Chondrites*. Viking Formation, 12-12-54-20W5, depth 2630.4 m. **(B)** Lower offshore silty and sandy shale, thoroughly burrowed with *Zoophycos* (Z), *Helminthopsis* (H), *Chondrites, Planolites* (P) and *Asterosoma*(A). Viking Formation, 10-34-54-20W5, depth 2579.0 m. **(C)** Upper offshore sandy shale, thoroughly burrowed with *Helminthopsis, Planolites, Chondrites, Zoophycos* (Z) and *Thalassinoides* (Th). Viking Formation, 11-29-62-20W5, depth 1706.9 m. **(D)** Upper offshore thoroughly burrowed sandy shale, with a remnant distal storm-generated sandstone bed. *Planolites, Chondrites* (Ch), *Terebellina* (T), *Helminthopsis* and *Teichichnus* (Te) are present. Viking Formation, 07-36-54-20W5, depth 2484.4 m. **(E)** Upper offshore, thoroughly burrowed sandy shale, with remnant distal storm-generated sandstone beds. *Asterosoma, Thalassinoides, Chondrites* (Ch), *Planolites* (P) and *Helminthopsis* are present. Viking Formation, 10-34-54-20W5, depth 2577.0 m. **(F)** Upper offshore thoroughly burrowed sandy shale, with *Zoophycos* (Z), *Helminthopsis, Terebellina* (T), *Chondrites, Planolites* and *Asterosoma*. Cardium Formation, 07-14-28-05W5, depth 2435.7 m.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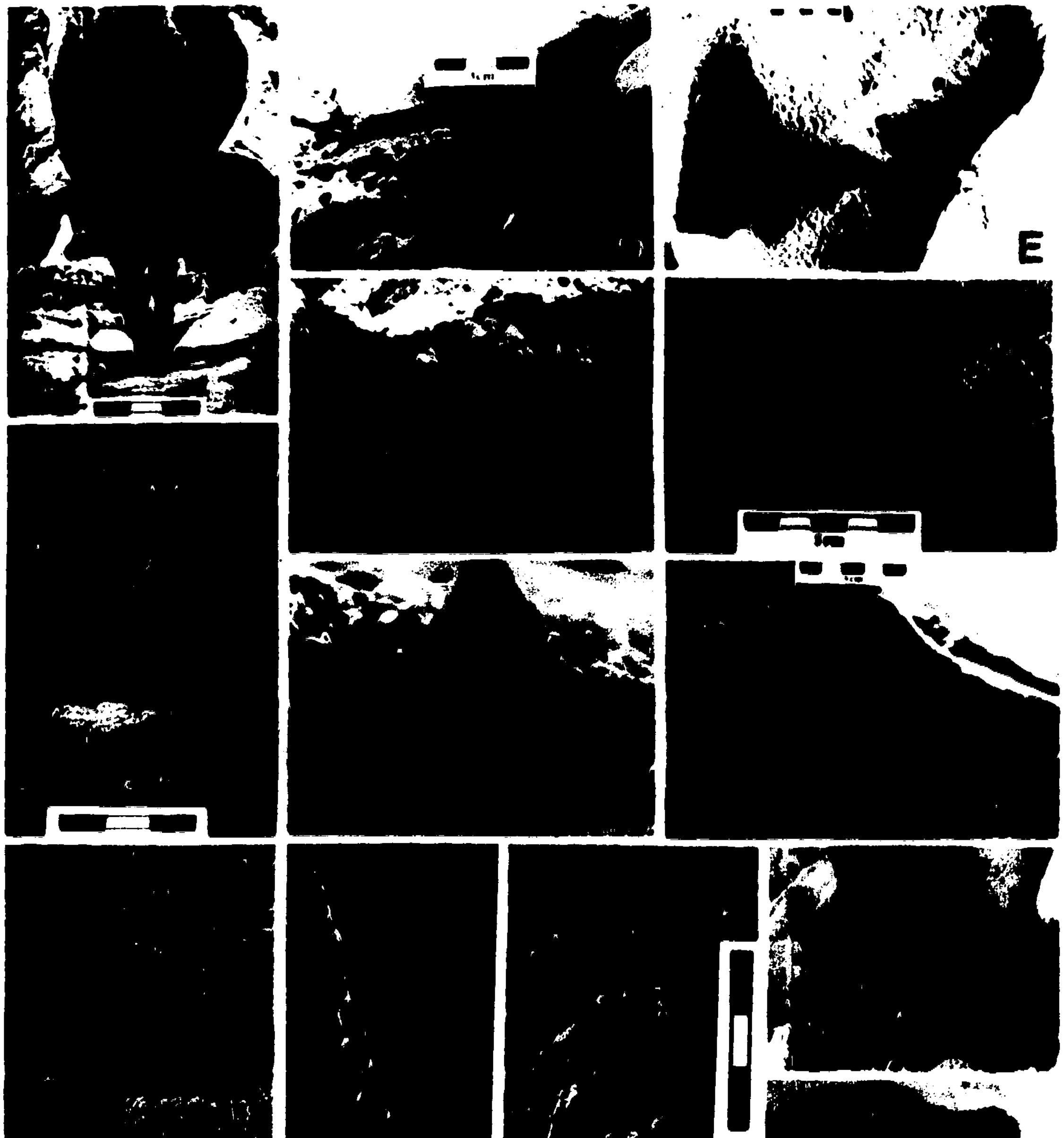
very fine- to fine-grained sandy shales, interbedded with thin, very fine- to fine-grained sandstone beds. The sandstones range from virtual biogenic homogenization to erosively based beds possessing remnant low angle (<15°) parallel laminae and oscillation or combined flow ripple laminae. These beds are interpreted as storm-generated in origin, with local preservation of waning flow deposits. Less intensely burrowed upper offshore intervals may show more regular interbedding of shales and storm-generated sandstones (see Chapter IV, Figures IV-4 G, IV-8 F,G), probably reflecting greater storm domination, greater storm frequency, and/or high sedimentation rates. This has been referred to as the "offshore transition". More commonly, tempestites show moderate to intense degrees of burrowing near their tops.

The ichnological suite may be regarded as a diverse *Cruziana* assemblage. Some grazing/foraging structures such as *Helminthopsis*, *Ancorichnus horizontalis* and *Zoophycos* may also be included. The bulk of the suite consists of ichnogenera such as *Planolites*, *Teichichnus*, *Terebellina*, *Palaeophycus*, *Thalassinoides*, *Cylindrichnus*, *Chondrites*, *Siphonichnus*, *Lockeia*, small *Asterosoma*, small *Rosselia*, and rare *Ophiomorpha* and *Rhizocorallium* (Figure V-2 C-F). Rare suspension feeding structures, such as *Skolithos*, *Arenicolites* and *Diplocraterion*, may also be present in sandier fairweather units, although they are also associated with tempestites. Tempestites may contain fugichnia as well. This facies is well-developed in the Viking Formation, the Cardium Formation and within the Aberdeen Member of the Blackhawk Formation in the Book Cliffs, Utah. Within the Book Cliffs, *Ancorichnus capronus* (Figure V-3 G), the crawling structure *Scolicia* (Howard and Frey, 1984; Frey, 1990) and *Cosmorhaphe* (Figure V-3 K) have also been noted. Some of the sandstone beds may also contain *Ophiomorpha nodosa* and *Skolithos linearis*, probably reflecting opportunistic colonisation of distal storm beds.

As in the lower offshore silty shales, burrowing in the upper offshore is typically intense, with a high diversity and uniform distribution of ichnogenera. This suite displays an overwhelming dominance of deposit feeding behaviour over grazing/foraging behaviour. The introduction of small numbers of suspension feeding structures within fairweather deposits, as well as those associated with tempestites, is distinctive. The ichnological assemblage is characteristic of the *Cruziana* ichnofacies (Figure V-1). Distal tempestites deposited in the upper offshore typically display a greater degree

Figure V-3. Characteristic Lower Shoreface Trace Fossils. **(A)** *Rosselia*. Cardium Formation, 12-19-35-08W5, depth 2747.8 m. **(B)** *Teichichnus* (Te) and *Terebellina* (T). Bow Island Formation, 07-02-08-21W4, depth 855.2 m. **(C)** *Palaeophycus* (Pa), *Planolites* (P) and fugichnia (f). Bluesky Formation, 06-32-74-12W6, depth 1796 m. **(D)** *Asterosoma*. Aberdeen Member, Coal Creek Canyon, Book Cliffs, Utah. **(E)** *Ophiomorpha nodosa* (bedding plane). Bearpaw-Horseshoe Canyon Formation Transition, Drumheller, Alberta. **(F)** *Rhizocorallium* (bedding plane). Cardium Formation, Seebe, Alberta. Photo courtesy of R.W. Frey. **(G)** *Ancorichnus capronus* (bedding plane). Panther Tongue, Spring Canyon, Book Cliffs, Utah. **(H)** *Gyrochorte* (float). Cardium Formation, Ram Falls, Alberta. Photo courtesy of R.W. Frey. **(I)** *Taenidium* (Ta) and *Mammalichnus* (M) (bedding plane). Kenilworth Member, Coal Creek Canyon, Book Cliffs, Utah. **(J)** *Schaubcylindrichnus* (cross section). Aberdeen Member, Coal Creek Canyon, Book Cliffs, Utah. **(K)** *Cosmorhaphe* (bedding plane). Kenilworth Member, Woodside Canyon, Book Cliffs, Utah. **(L)** Sideritised *Cylindrichnus concentricus* (transverse view), Bearpaw-Horseshoe Canyon Formation Transition. Drumheller, Alberta. **(M)** Sideritised *Cylindrichnus concentricus* (bedding plane view). Bearpaw-Horseshoe Canyon Formation Transition, Drumheller, Alberta.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of biogenic reworking than the thinner storm beds of the lower offshore. This reflects the greater vertical penetration of the substrate by the more robust benthic organisms that inhabit the upper offshore (Dörjes and Hertweck, 1975).

The lower and upper offshore are commonly dominated by fairweather deposition, although on strongly storm-dominated shorefaces, the offshore complex may consist of shaly zones interbedded with relatively unburrowed, thin tempestites.

Fairweather deposits are characterised by abundant burrowing, manifest by high diversity and uniform distribution of ichnogenera. The suites lack domination by individual forms. The ichnological assemblages for this depositional complex display an equilibrium or K-selected behaviour, characteristic of fully marine, unstressed settings (Pianka, 1970; Jumars, 1993).

Lower-Middle Shoreface Complex

Lower Shoreface

The lower shoreface proper begins at the lower limit of fairweather (minimum) wave base, but where offshore processes continue to operate (Reinson, 1984). Under progressive storm-domination, facies of lower shoreface affinity are deposited basinward of fairweather wave base, because effective wave base is significantly lowered. Wave energy is the dominant physical process controlling deposition of the interval and most structures reflect storm deposition, including hummocky cross-stratification (HCS) (*cf.* Dott and Bourgeois, 1982; Duke, 1985), rarer swaley cross-stratification (SCS) (*cf.* Leckie and Walker, 1982) and quasi-planar lamination (QPL) (*cf.* Arnott, 1993). Intervals not dominated by erosional amalgamation may show waning stage oscillation or combined flow ripple lamination capping these structures. Fairweather-generated oscillation ripples may be present but are relatively uncommon. The intensity of burrowing is highly variable, depending upon the degree of storm dominance. High intensity and high frequency storm events favour minimal preserved burrowing, while low intensity and infrequent storm events lead to thorough homogenization of the tempestites and accumulation of thick fairweather intervals.

Biogenic features are dominated by the *Cruziana* ichnofacies, with considerable contributions from the *Skolithos* ichnofacies. Rarer grazing/foraging structures, largely confined to muddy zones (Figure V-3 A-M) are also locally present. Deposit feeder and mobile carnivore structures of the *Cruziana* ichnofacies include robust *Rosselia, Asterosoma, Teichichnus, Cylindrichnus, Schaubcylindrichnus, Terebellina, Planolites, Thalassinoides, Ancorichnus, Siphonichnus,* horizontal *Ophiomorpha nodosa, O. irregulaire,* rare *O. annulata, Chondrites* and *Rhizocorallium*. Pemberton and Frey (1984) also noted the presence of *Gyrochorte, Taenidium* (*Muensteria*) and *Phoebichnus* within outcrop examples of the Cardium Formation, Seebe, Alberta. Grazing/foraging structures include *Helminthopsis, Cosmorhaphe, Zoophycos, Scolicia* and *Aulichnites*. *Anconichnus horizontalis* are present within storm-generated sandstones, but are generally rare. Elements of the *Skolithos* ichnofacies include *Skolithos, Conichnus,* rare *Diplocraterion,* rare *Bergaueria,* and the passive carnivore structure *Palaeophycus*. In addition, escape traces (fugichnia) and those of various opportunistic organisms may also be common, generally colonising the tops of storm beds.

The lower shoreface trace fossil assemblage shows a dominance of deposit feeding behaviour, with significant contributions of suspension feeding structures, suggesting that persistent wave shoaling (*i.e.* above fairweather wave base) is important in displacing suspended mud offshore and suspending food particles above the bed, and shifting sand at the sediment-water interface. The observed fairweather trace fossil suite corresponds to a proximal *Cruziana* assemblage (Figure V-1).

Storm events impart considerable control on the character of the lower shoreface. Storms tend to uproot, destroy and/or bury resident (fairweather) benthic communities (Pemberton and Frey, 1984; Frey, 1990; Pemberton *et al.*, 1992b). During post-storm recovery, initial colonisation of the tempestite generally records opportunistic dwelling/suspension feeding structures, which do not typically reflect the original resident community. Continued fairweather conditions may see a return to the original trace fossil suite (*cf.* Chapter IV). Depending upon the degree of storm dominance, the preserved record of the lower shoreface can be quite variable.

Some thin tempestites may escape thorough biogenic reworking (*cf.* Kachel and Smith, 1986; Wheatcroft, 1990) under conditions of high frequency storms, moderate to low energy storm conditions and high sedimentation rates. Saunders and Pemberton (1986) and Saunders (1989) noted that thin storm beds common in the lower shoreface deposits of the Appaloosa sandstone of the Bearpaw-Horseshoe Canyon Formation transition, Alberta, permitted *Rhizocorallium jenense*, *Teichichnus rectus* and *Rosselia socialis* to re-equilibrate their burrows to each successive sediment-water interface. *Rosselia socialis* reflects this re-equilibration by vertically stacking their burrows (Figure V-4 A). A spectacular example of this occurs in core of the Albian Grand Rapids Formation of Alberta, where stacked *Rosselia* burrows record repeated post-storm re-establishment at least seven times during the life of a single tracemaker (Figure V-4 B).

Middle Shoreface

The middle shoreface extends over the zone of shoaling and initial breaking of waves (Reinson, 1984), and is characterised by high wave energy. Longshore bars are commonly present near the upper portion of the middle shoreface within intermediate (barred) states of shoreface morphodynamics (Wright *et al.*, 1979; Thom *et al.*, 1986). Preserved deposits of longshore bars are rarely intercalated within middle shoreface intervals, since under fairweather conditions, bars migrate landward and weld to the foreshore (Davidson-Arnott and Greenwood, 1976; Davis, 1978). The sandstones tend to be well-sorted, well winnowed, and medium- to fine-grained, with only minor shale, silt and shell layers. Preserved structures are predominantly low angle wedge-shaped sets of parallel laminae, constituting SCS and lesser HCS, or QPL. Oscillation ripple laminae, combined flow ripple laminae, and rarer trough cross-stratification are locally present. Storms have a strong influence on the middle shoreface, greater even than in the lower shoreface, and may constitute much of the depositional record of this zone. The SCS or QPL tempestite beds are typically erosionally amalgamated, becoming progressively more cannibalistic upwards (Aigner and Reineck, 1982) with increasing shallowing and associated enhancement of storm-induced scouring. As a result, the degree of bioturbation is highly variable.

Ichnologically, the middle shoreface corresponds to a dominance of suspension feeding behaviours (constituting the *Skolithos* ichnofacies; Figure V-1) over predominantly deposit feeding behaviours (the *Cruziana* ichnofacies), although the latter traces continue to persist as subordinate elements (Howard, 1972; 1975). The bulk of the assemblage consists of *Skolithos*, *Conichnus*, *Diplocraterion*, *Ophiomorpha* (commonly vertical components), *Arenicolites*, *Bergaueria* and *Palaeophycus* (Figure V-5 A-F).

Figure V-4. Stacked *Rosselia.*, Marking Stages of Re-Equilibration. (A) Two, vertically stacked, siderite-cemented *Rosselia* in lower shoreface sandstones, reflecting re-equilibration of the burrow following storm bed deposition. Bearpaw-Horseshoe Canyon Formation Transition, Drumheller, Alberta. **(B)** Heavy oil stained (black) sandstone of the lower to middle shoreface, showing at least seven re-positionings of *Rosselia* as a result of episodic storm bed deposition. This indicates that approximately 2.2 m of tempestite sandstones accumulated within the life span of a single tracemaker. Base of core is at the lower left (B) and read upwards towards the upper right (T). Grand Rapids Formation, 13-10-81-21W4, depth 2218-2221 m. Scale is 15 centimeters.

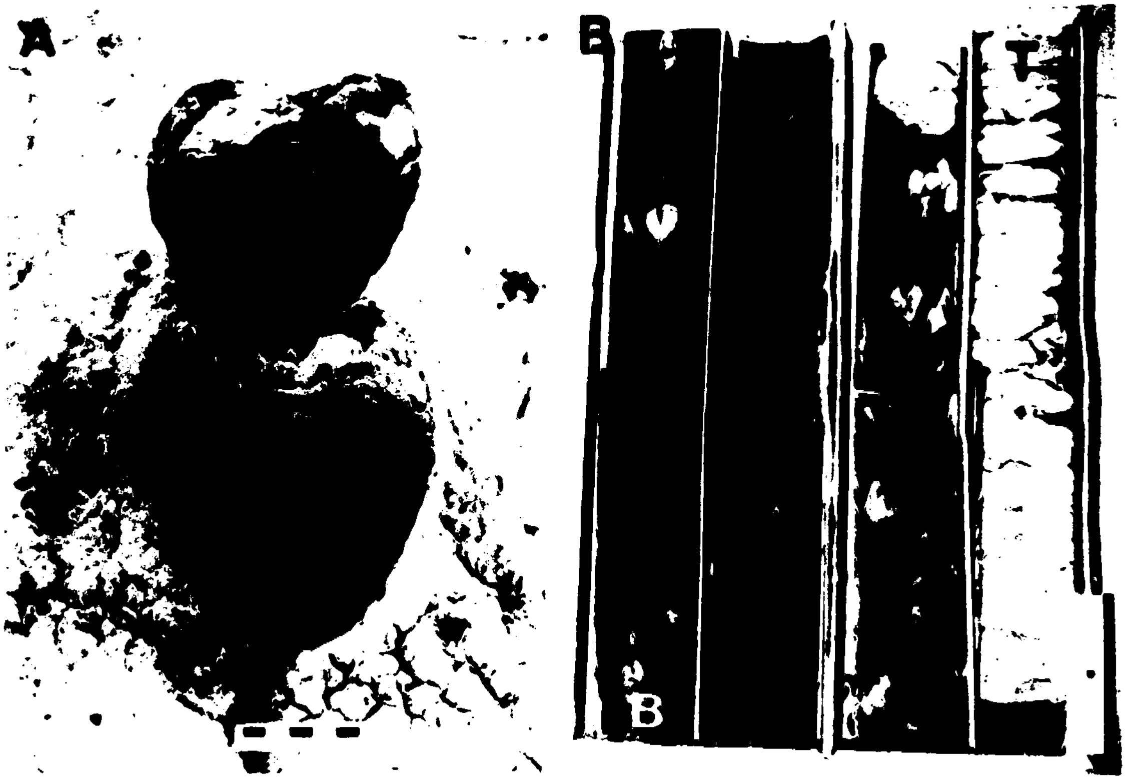
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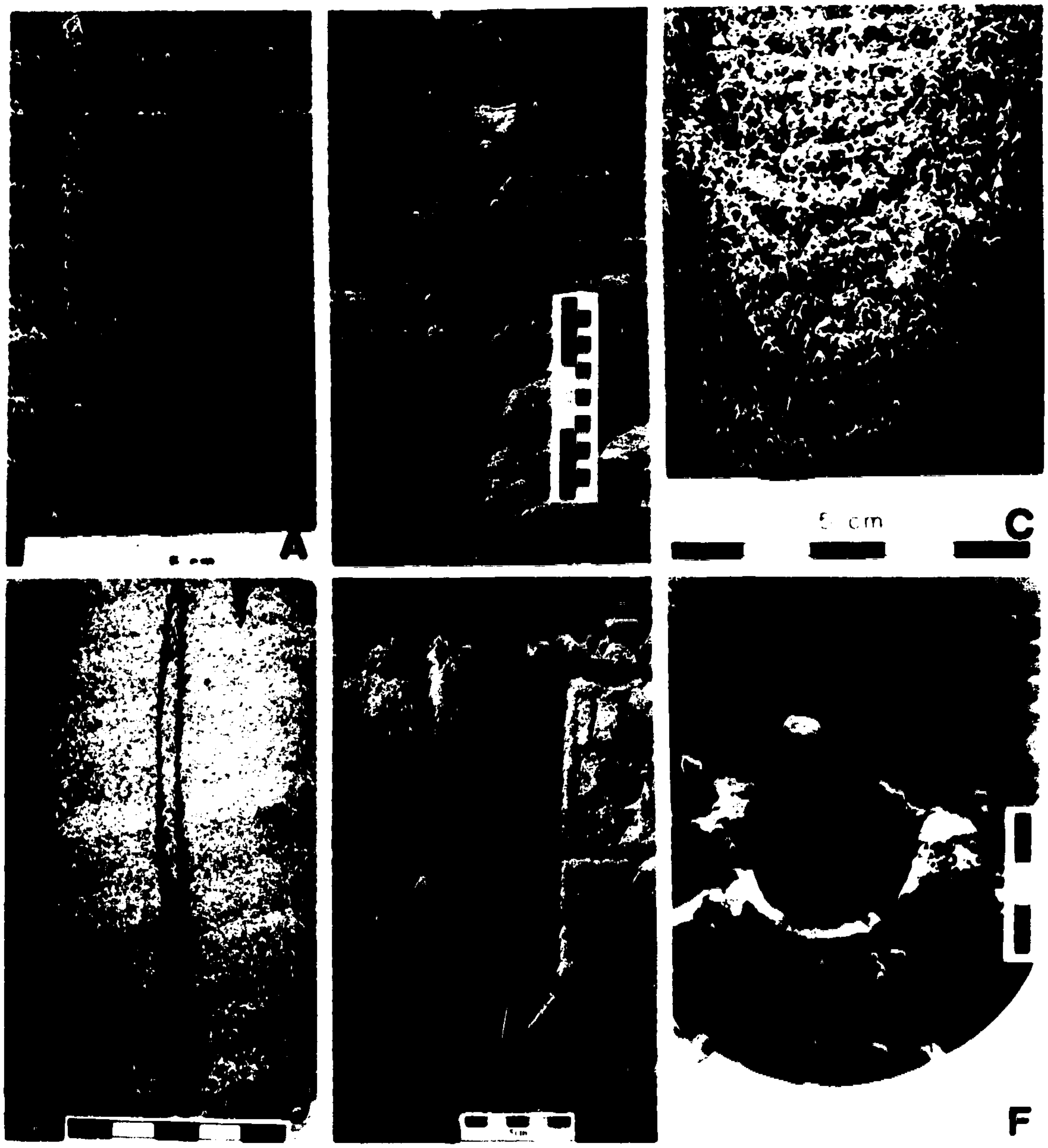
Figure V-5. Middle Shoreface Trace Fossils. **(A)** *Skolithos* in swaley cross-stratified sandstone. Cadotte Member, Peace River Formation, 11-25-64-07W6, depth 2402.1 m. **(B)** *Conichnus conicus* (cross section) in swaley cross-stratified sandstone. Bearpaw-Horseshoe Canyon Formation Transition, Drumheller, Alberta. **(C)** *Diplocraterion* in medium- to coarse-grained sandstone. Viking Formation, 02-03-55-16W5, depth 1986.6 m. **(D)** Vertical *Ophiomorpha* in swaley cross-stratified sandstone. Viking Formation, 07-30-61-10W5, depth 1782 m. **(E)** *Arenicolites* (Ar) (cross section) in storm-bedded sandstone. Panther Tongue, Book Cliffs, Utah. **(F)** Cast of *Bergaueria* on base of sandstone (bedding plane). Viking Formation, 11-35-61-20W5, depth 1755.1 m.


5 cm
A
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Howard and Frey (1984) also noted *Medousichnus loculatus* within intervals of the Book Cliffs, Utah (their "upper" shoreface). Howard (1971a,b; 1975) and others have noted that *Ophiomorpha* systems tend to shift from horizontal to vertical in orientation as energy levels increase. This shift in orientation may accompany the transition from the lower to middle shoreface. Fugichnia may be common, particularly associated with tempestites.

Cruziana ichnofacies elements include robust *Rosselia* (*R. socialis* dominates; *R. chonoides* is also recognised in the Book Cliffs), *Asterosoma*, *Schaubcylindrichnus*, *Terebellina*, *Planolites*, *Teichichnus*, *Cylindrichnus*, rare *Rhizocorallium*, and locally abundant, though generally rare *Chondrites*. *Chondrites* is largely restricted to muddy zones. Frey (1990) noted that *Cylindrichnus* and *Rosselia* become more steeply inclined as energy levels increase. This enhancement in inclination may also accompany the transition from the lower to middle shoreface, mimicking the trend observed for *Ophiomorpha*.

As in the lower shoreface, variability in storm intensity and frequency strongly affects the character of the middle shoreface, both sedimentologically and ichnologically. As the storm effects become more pronounced, the diversity of deposit feeding structures declines markedly. This appears to be attributable to the abundance of well winnowed sand and the general paucity of deposited food for the *Cruziana* ichnofacies tracemakers to feed upon. Notable exceptions include *Rosselia socialis*, *Asterosoma* and, to a lesser degree, *Cylindrichnus*, which may persist upwards well into the middle shoreface.

The preservation potential of biogenic structures in the middle shoreface is intrinsically associated with the character of tempestite accumulation. In storm-dominated conditions, as tempestites become progressively more cannibalistic, only deeply penetrating structures, particularly *Ophiomorpha nodosa* and fugichnia, may be recorded. It is not uncommon for storm-dominated middle shoreface sandstones to show little or no burrowing. Unfortunately, discerning whether their absence corresponds to high intensity storms (greater erosional amalgamation) or to high frequency storms (minimal time for re-establishment of benthic communities) is virtually impossible.

Like the offshore complex, the lower to middle shoreface complex consists of sediments accumulated during both fairweather and storm conditions. In contrast to the offshore, however, the preserved depositional record of the lower-middle shoreface complex of many successions is characterised by a predominance of tempestite beds, with fairweather sediments constituting a common, though subordinate, component of the interval (Kumar and Sanders, 1977; Niedoroda *et al.*, 1984).

Ichnology of Storm Deposits

The ichnology of storm deposits has been discussed at length in the literature (*e.g.* Aigner and Reineck, 1982; Pemberton and Frey, 1984; Aigner, 1985; Vossler and Pemberton, 1988; Frey, 1990; Aigner and Seilacher, 1991; Pemberton *et al.*, 1992b) and is summarised in Chapter IV. The abrupt transition from fairweather conditions to the erosive action of storm waves on the substrate, followed by rapid deposition of HCS, SCS or QPL sandstones, typically destroys, displaces and/or buries the resident infauna (Figure V-6). Escape traces (fugichnia) record the attempt of organisms to burrow up through the tempestite in order to reach the new sediment-water interface. Following storm abatement, the fairweather community is temporarily diminished or displaced (Saunders and Pemberton, 1986) and a relatively clean sandy substrate is available for colonisation. These post-storm conditions provide a favourable setting for colonisation of the substrate by infaunal opportunists. Opportunistic organisms employ an r-selected strategy in population kinematics, enabling them to quickly locate and exploit a new habitat such as a storm bed. This r-strategy is characterised by high reproduction rates, rapid larval dispersal, broad environmental tolerances, and nonspecialised (generalised) feeding behaviour (Pianka, 1970; Levinton, 1970; Pemberton and Frey, 1984; Jumars, 1993). Dominant ichnogenera are *Ophiomorpha nodosa* (vertical), *Ophiomorpha borneensis*, *Skolithos linearis*, *Arenicolites*, *Teichichnus*, *Conichnus conicus*, *Diplocraterion* and rare *Rhizocorallium*.

As conditions following the storm event revert to fairweather, the pioneer community of opportunists are ultimately displaced by succeeding colonists of the equilibrium community (Pemberton and Frey, 1984), analogous to the "doomed pioneers" described from turbidites (Föllmi and Grimm, 1990). The traces of this community cross-cut the opportunistic suite and persist into the overlying fairweather deposits. The fairweather trace fossil suite records the

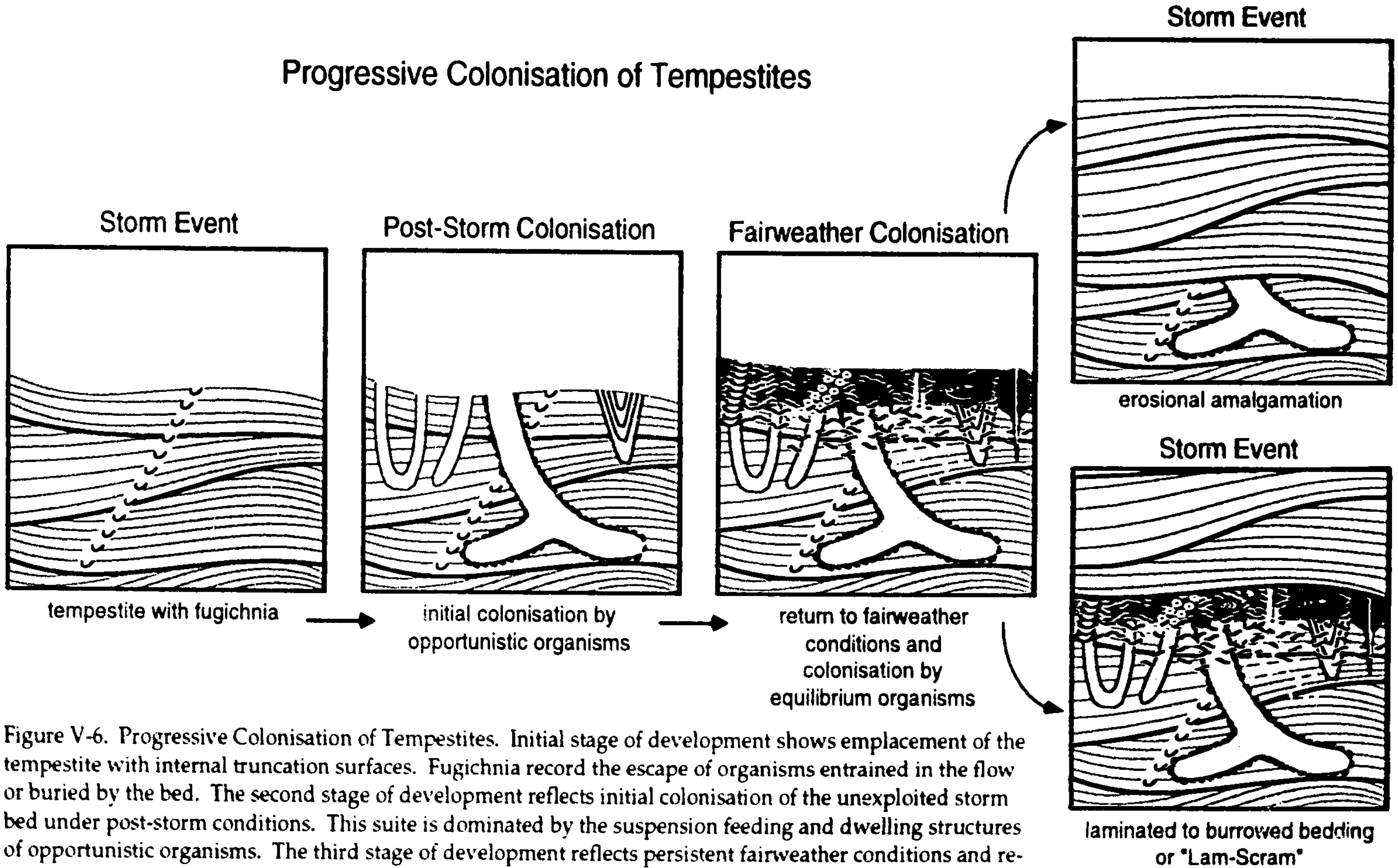


Figure V-6. Progressive Colonisation of Tempestites. Initial stage of development shows emplacement of the tempestite with internal truncation surfaces. Fugichnia record the escape of organisms entrained in the flow or buried by the bed. The second stage of development reflects initial colonisation of the unexploited storm bed under post-storm conditions. This suite is dominated by the suspension feeding and dwelling structures of opportunistic organisms. The third stage of development reflects persistent fairweather conditions and re-establishment of the resident equilibrium community. Subsequent storm events may result in 1) complete or virtually complete removal of evidence of post-storm colonisation (some deeply penetrating structures and escape structures may survive) or 2) minimal erosional amalgamation of storm beds, preservation of the opportunistic storm suite, and ocally, partial preservation of the fairweather suite, producing "laminated-to-burrowed" bedding.

behaviour of the resident equilibrium community, and therefore provides data regarding the average (ambient) conditions operating in the environment. As a result, recognition of the fairweather suite is essential in resolving the position of the environment along the depositional profile. The preservation potential of these fairweather deposits is highly variable, depending on the degree of erosional amalgamation of the tempestites (Figure V-6). Under intermediate energy conditions, much of the fairweather suite may be preserved, whereas strongly storm-dominated conditions may result in erosional removal of all or virtually all biogenic structures. The juxtaposition of opportunistic, largely suspension feeding traces and fairweather assemblages commonly produce either a *Skolithos* or a mixed *Skolithos-Cruziana* ichnofacies (Figure V-7), but this primarily reflects ***in loco*** fluctuations in energy rather than changes in sea level or variations in distance from the shoreline (Pemberton and Frey, 1984).

Upper Shoreface-Foreshore Nearshore Complex

Upper Shoreface

The upper shoreface is situated in the high energy build-up and surf zones, and lies landward of the breaker zone (Clifton *et al.*, 1971; Davidson-Arnott and Greenwood, 1976; Hunter *et al.*, 1979; Greenwood and Mittler, 1985). The landward margin corresponds to the low tide mark. The upper shoreface has been grouped with the foreshore (Davies *et al.*, 1971), referred to as the shoreface-foreshore transition (Howard, 1972; Howard and Frey, 1984). The upper shoreface also corresponds to the "Outer Rough", "Outer Planar" and possibly part of the "Inner Rough" zones of Clifton *et al.* (1971), where the bulk of sediment transport is related to multidirectional current flow (Carter, 1978; Davis, 1978). Within this zone, wave- and storm-driven currents paralleling the shoreline (*e.g.* longshore drift, *etc.*) interact with shore-normal currents generated by translatory flow associated with plunging waves, producing multidirectional, sinuous-crested subaqueous dunes.

Under intermediate barred states (*cf.* Davidson-Arnott and Greenwood, 1976; Greenwood and Davidson-Arnott, 1979; Hunter *et al.*, 1979; Wright *et al.*, 1979; Thom *et al.*, 1986), wave- and storm-induced currents flow obliquely shoreward over the bar, turn shore-parallel along the longshore troughs, and

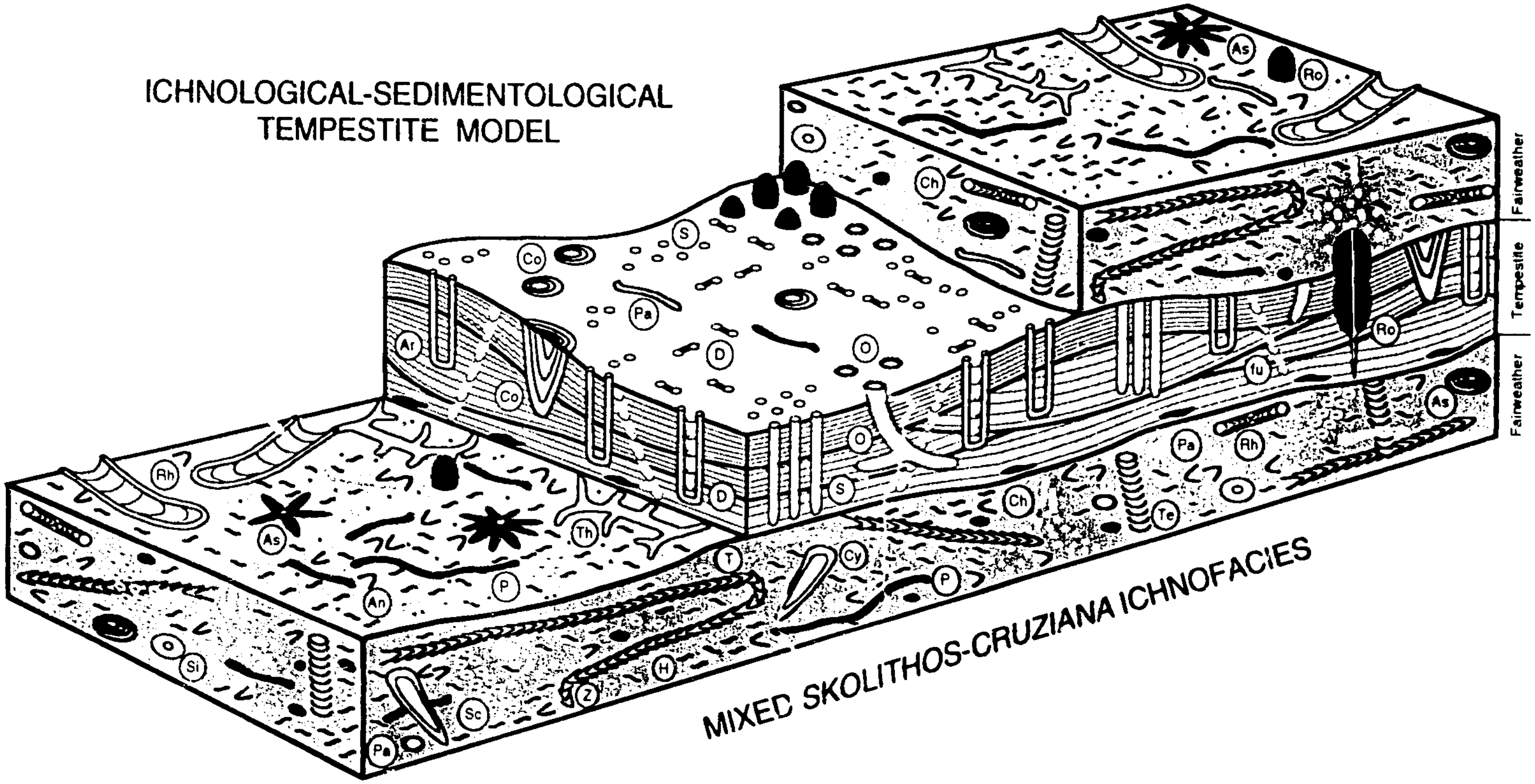


Figure V-7. Idealised ichnological-sedimentological model of a high diversity mixed *Skolithos-Cruziana* ichnofacies, based on observations of Cretaceous strata of the Western Interior Seaway of North America. Fairweather deposits are characterised by thorough bioturbation with a high diversity of deposit feeding and grazing structures. The tempestite is burrowed with a lower diversity suite of mainly suspension feeding and dwelling structures. An: *Anconichnus*, Ar: *Arenicolites*, As: *Asterosoma*, Ch: *Chondrites*, Co: *Conichnus*, Cy: *Cylindrichnus*, D: *Diplocraterion*, fu: fugichnia, H: *Helminthopsis*, O: *Ophiomorpha*, P: *Planolites*, Pa: *Palaeophycus*, Rh: *Rhizocorallium*, Ro: *Rosselia*, Sc: *Schaubcylindrichnus*, Si: *Siphonichnus*, Sk: *Skolithos*, T: *Terebellina*, Te: *Teichichnus*, Th: *Thalassinoides*, Z: *Zoophycos*.

ultimately return seaward through the rip channels. Greenwood and Mittler (1985) pointed out that there is generally little depositional record of a bar complex, based on their study of the Kouchibouguac Bay barred system of New Brunswick. Preserved sediments correspond to fill of longshore troughs and those associated with the seaward slope of the bar itself.

Hunter *et al.* (1979) studied a barred coastline in Oregon, and pointed out that under a barred configuration, an erosional discontinuity, reflecting the base of the deepest rip channels or longshore troughs, will separate the lower-middle shoreface complex from the upper shoreface-foreshore complex. Lateral shift of these channels, coupled with seaward progradation of the entire shoreface system, facilitates the widespread development of this erosional surface. A similar relationship was noted from barred systems in Eastern Long Island, New York (Shipp, 1984), Kouchibouguac Bay, New Brunswick (Greenwood and Mittler, 1985), and was applied to the Cadotte Member of the Peace River Formation, Alberta (Rahmani and Smith, 1988; *cf.* Chapter VI).

The upper shoreface deposits are distinctive in the dominance of multidirectional trough cross-stratification, typically in 15-45 cm thick sets, interbedded with low angle bidirectional planar cross-bedded sets (Davidson-Arnott and Greenwood, 1976; Roy *et al.*, 1980; Reinson, 1984; Thom *et al.*, 1986). Sandstones are typically well-sorted, well-winnowed and medium or coarser in grain size. Conglomeratic and pebbly sandstone intervals tend to have more massive and low angle planar stratified beds. Heavy mineral concentrations may exceed those in the foreshore (Howard and Frey, 1984). Wave-induced liquefaction may locally produce convolute laminae and dewatering structures.

Trace fossils are locally common but rarely abundant, and diversity is characteristically low. Continuously migrating bedforms present a major ecological problem to endobenthic organisms; consequently, there is a general scarcity of animals that are capable of constructing permanent domiciles under such conditions (Howard, 1972; 1975; Saunders, 1989; MacEachern and Pemberton, in press). Those biogenic structures that are formed have a low preservation potential and in general, only deeply penetrating structures are preserved (Howard and Frey, 1984). The main ichnological elements correspond to the *Skolithos* ichnofacies (Figure V-1) and are characterised by the ichnogenera *Skolithos*, heavily lined, vertical or deeply penetrating

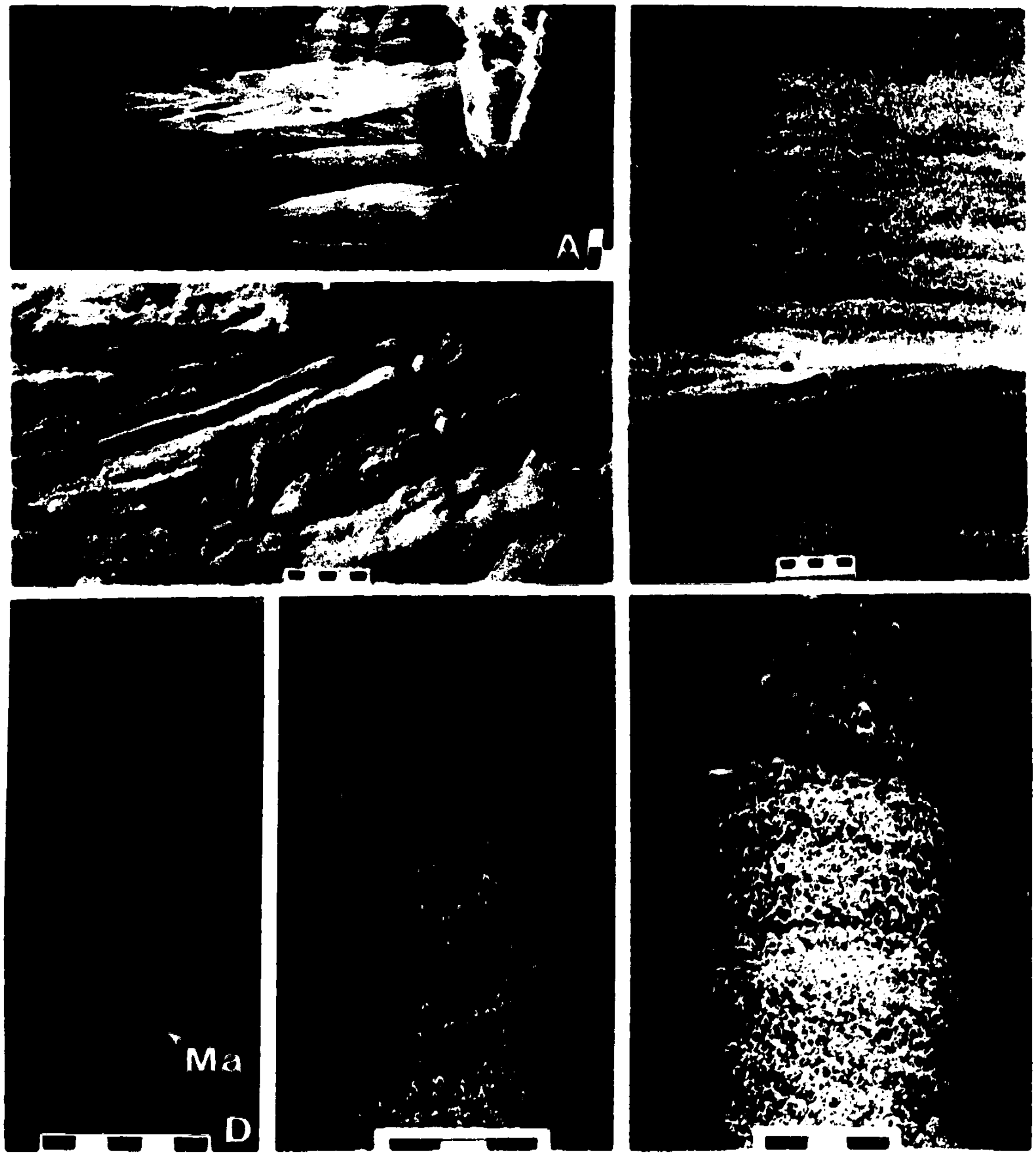
Ophiomorpha nodosa, and *Conichnus conicus* (Figure V-8 A-C). Under very high energy conditions, *Macaronichnus simplicatus* and *M. segregatis* are also locally abundant, such as in the Bluesky Formation at Knopcik (Moslow and Pemberton, 1988) the Cadotte Member at Elmworth and Sinclair (*cf.* Figure V-8 D-F; Chapter VI), the Appaloosa sandstone of the Bearpaw-Horseshoe Canyon transition (Saunders and Pemberton, 1986; Saunders, 1989) and the Blood Reserve sandstone (Nadon, 1988). *Macaronichnus* is typically more common near the upper shoreface-foreshore contact (Saunders 1989; Pemberton and Saunders, 1990), although under more reflective shoreface states, characterised by steeper depositional profiles and coarser grain size, the zone may occur lower down in the upper shoreface. The Cadotte Member contains upper shoreface intervals consisting of conglomerates interbedded with medium- to coarse-grained sandstone beds, many of which possess intensely burrowed zones of *Macaronichnus segregatis* (Figure V-5 F), demonstrating its high energy affinity.

Unlike the lower and middle shoreface, storm effects in the upper shoreface are generally reflected by ridge and runnel systems rather than major depositional events. Ridge and runnel systems indicate erosion of the beachface and transport of sediments to the shoreface, related to short period waves and wave set-up. Post-storm recovery is manifest by landward migration of ridges and longshore bars, which weld to the beachface in response to long period fairweather waves (Davis *et al.*, 1972).

Foreshore

The foreshore is confined to the intertidal zone occupying the area of wave swash. The swash and backwash mechanism produces the distinct subparallel to low angle seaward dipping planar laminations, typically in well-sorted, very well winnowed medium to coarse quartz sandstone (Figure V-9 A,B); although textures may range up to cobble size. Stratification occurs as wedge-shaped sets with internal stratification parallel to subparallel to lower set contacts, commonly referred to as swash-zone stratification. Set boundaries are not truncated, but rather, reflect the changing slope of the prograding beachface during the accretionary phase (Reinson, 1984). Some convolute laminae and flame structures may also be present (Howard and Frey, 1984), possibly reflecting wave-induced liquefaction during intense storm activity. Saunders and Pemberton (1986) noted swash zone bed sets 10-

Figure V-8. Upper Shoreface Deposits. **(A)** Trough cross-stratified, medium-grained sandstones. Spring Canyon Member, Hardscrabble Canyon, Book Cliffs, Utah. Field notebook for scale. **(B)** Toesets of trough cross-stratified sandstone, with *Skolithos* (Sk) and *Conichnus* (C). Spring Canyon Member, Spring Canyon, Book Cliffs, Utah. Scale in centimetres. **(C)** Trough cross-stratified sandstone, with lined *Skolithos*. Spring Canyon Member, Hardscrabble Canyon, Book Cliffs, Utah. **(D)** Trough cross-stratified, medium-grained sandstone, intensely burrowed with *Macaronichnus segregatis* (Ma). Bluesky Formation, 06-32-74-12W6, depth 1800 m. Scale in centimetres. **(E)** Trough cross-stratified, medium-grained sandstone, containing abundant *Macaronichnus segregatis* (Ma) at top. Cadotte Member, Peace River Formation, 14-14-69-09W6, depth 1764.4 m. Scale in centimetres. **(F)** Interbedded trough cross-stratified sandstones and conglomerates. *Macaronichnus* is present in the sandstones. Cadotte Member, Peace River Formation, 06-18-71-12W6, depth 1896 m. Scale in centimetres.


A
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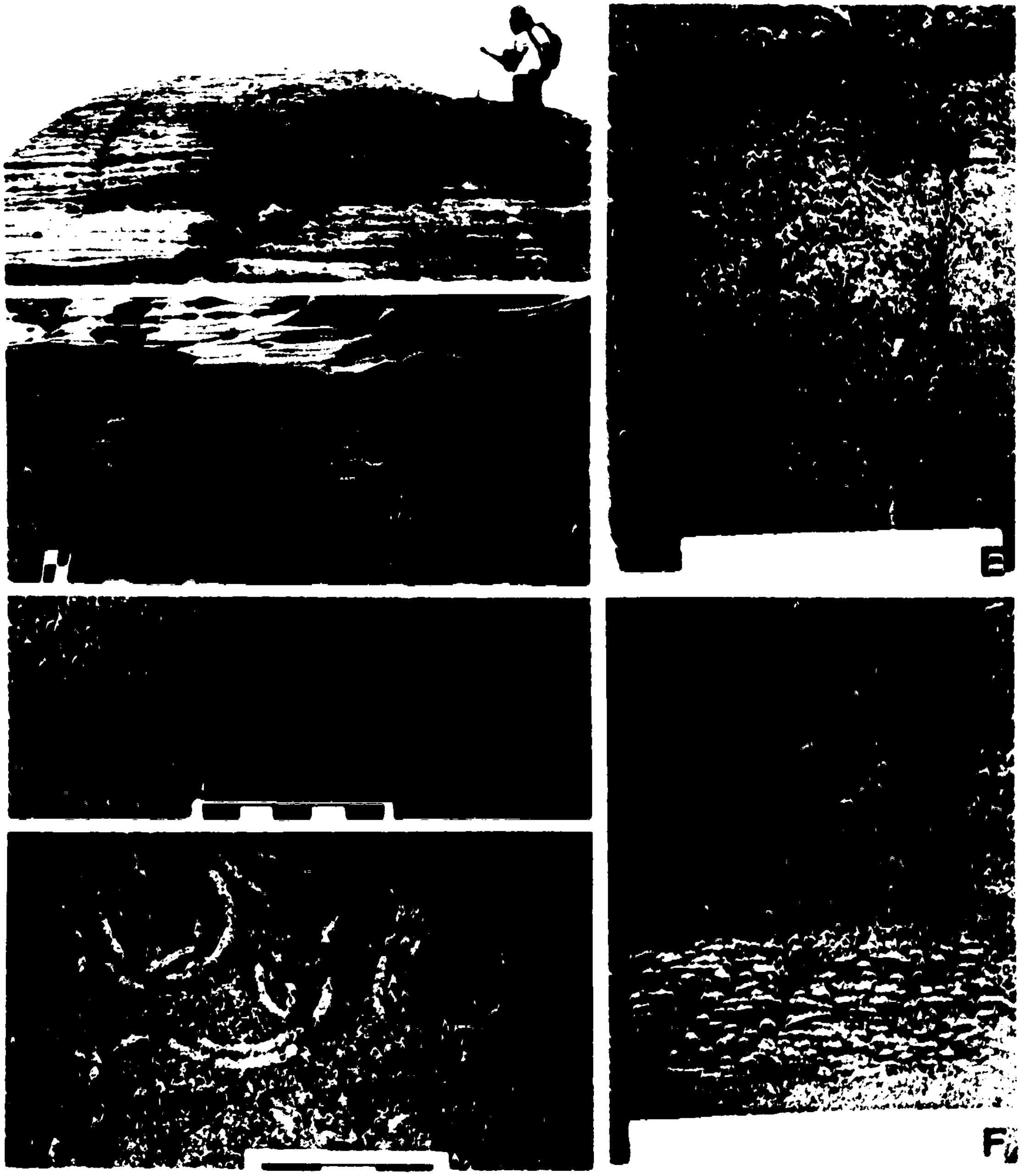
D

Figure V-9. Foreshore Deposits. **(A)** Medium-grained sandstones, showing wedge-shaped, planar cross-stratified sets interpreted as swash zone cross-stratification. Virgelle Member, Milk River Formation, Writing-on-Stone Provincial Park, Alberta. I. Raychaudhuri (1.8m) for scale. **(B)** Trough cross-stratified upper shoreface sandstones, passing upward into low angle planar laminated foreshore sandstones. Spring Canyon Member, Hardscrabble Canyon, Book Cliffs, Utah. Field notebook for scale. **(C)** Low angle planar cross-stratified, medium-grained sandstone, intensely burrowed with abundant *Macaronichnus segregatis*. Bearpaw-Horseshoe Canyon Formation Transition, Drumheller, Alberta. Scale in centimetres. **(D)** Bedding plane view of medium-grained sandstone, containing *Macaronichnus spiralis*. Bearpaw-Horseshoe Canyon Formation Transition, Drumheller, Alberta. Scale in centimetres. **(E)** Medium-grained foreshore sandstone, intensely burrowed with *Macaronichnus segregatis* and rooted at the top. Cadotte Member, Peace River Formation, 07-10-63-01W6, depth 2168.4 m. **(F)** Low angle planar cross-stratified sandstone with a zone of *Macaronichnus segregatis*. Cadotte Member, Peace River Formation, 07-10-63-01W6, depth 2168.8 m.


E
F

50 cm thick with associated low amplitude wave ripples, parting lineation, swash marks and landward dipping decimetre-scale tangential cross-bedding in foreshore deposits of the Appaloosa Sandstone, Bearpaw-Horseshoe Canyon Formation transition in Drumheller, Alberta.

As grain size increases to pebble and cobble size, internal stratification becomes cryptic, and is visible mainly as clast segregations. Stratification, where visible, remains low angle planar. Conglomerates are exclusively clast-supported and locally lack a matrix (open framework). Where matrix is present, it consists of granules or well-sorted sands. Unlike alluvial conglomerates, foreshore conglomerates tend to display good lateral continuity of bedding (Clifton, 1969) and clasts may vary considerably in size over the entire foreshore interval, but are very well-sorted within each bed. Elongate clasts may be imbricated, with long axes parallel to depositional strike. Non-resistant clasts tend to be absent, due to the intensity of wave-reworking.

The diversity and abundance of trace fossils is low, due to harsh environmental conditions, continuously shifting substrates and overall low preservation potential (Howard and Frey, 1984). Most elements reflect the *Skolithos* ichnofacies, particularly the ichnogenera *Conichnus conicus* (dwelling structure of sea anemones), *Ophiomorpha nodosa* (vertical components), *Skolithos linearis*, and lesser *Diplocraterion* and *Arenicolites*, indicating the predominance of suspension feeding behaviour within deeply penetrating domiciles. Some passively predaceous organisms inhabit the foreshore, which may produce *Palaeophycus* and possibly *Schaubcylindrichnus*, but these structures are shallowly penetrating and as such, are rarely preserved (Howard and Frey, 1984).

Clifton and Thompson (1978) noted the presence of a dominantly horizontal trace, formed by a highly mobile infaunal deposit feeding organism, which was named *Macaronichnus segregatis*. The high energy affinity of *M. segregatis* contrasts markedly with the lower energy regime reflected by other deposit feeders (Pemberton and Saunders, 1990). It is believed that the tracemaker feeds preferentially on epigranular bacteria colonising the surfaces of sand grains. The intense swash infiltration into the beachface within the foreshore carries dissolved oxygen and nutrients well below the sediment-water interface and further basinward, permitting epigranular bacteria and other microbes to flourish. The *Macaronichnus* tracemaker is believed to feed on these micro-organisms up to several meters below the sediment-water interface, favouring trace preservation. Saunders and Pemberton (1986) and Saunders (1989) noted that *Macaronichnus segregatis* was concentrated into a narrow zone, 0.6-1.1 m thick within the middle to upper portion of the foreshore in the Appaloosa Sandstone of the Bearpaw-Horseshoe Canyon transition (Figure V-9 C), which they attributed to the mid-tide zone where the bacteria appear to have been abundant.

Many preserved foreshore deposits in the Cretaceous of the Western Interior Seaway reflect abundant burrowing by *Macaronichnus segregatis* (Figure V-9 C-F), such as the Bluesky Formation, the Falher Member, the Appaloosa sandstone, and the Blood Reserve sandstone. *M. spiralis*, indicating higher energy settings, may also be locally associated (Saunders and Pemberton, 1986; Saunders, 1989; Figure V-9 D).

In contrast to the lower-middle shoreface complex, the upper shoreface-foreshore complex shows virtually no storm-induced deposition. Storm events are characterised by pronounced erosion in this zone, where short-period waves cut ridge and runnel systems and plane off the accretionary profile of the beachface (Kumar and Sanders, 1976; Fox and Davis, 1978; Niedoroda *et al.*, 1984; Swift *et al.*, 1985). The bulk of this eroded sediment is transported basinward to the lower-middle shoreface complex. Much of it may be returned to the beach in the form of longshore bars, which migrate landward and weld to the beachface in response to the long-period waves generated during fairweather conditions (Cook and Gorsline, 1972; Davidson-Arnott and Greenwood, 1976). Some sediment, however, is permanently lost to the lower-middle shoreface, where it is mobilised during storms into tempestites. It is not uncommon for upper shoreface-foreshore complexes to acquire an intermediate, barred state during extended storm seasons and return to largely unbarred reflective states during fairweather conditions (Wright *et al.*, 1979;Thom *et al.*, 1986).

SHOREFACE VARIABILITY

Except for textural variations, the upper shoreface-foreshore complex remains relatively consistent in character over a wide range of shoreface morphodynamic states. There are few facies clearly indicative of barred conditions, since most subenvironments show a low preservation potential (Greenwood and Mittler, 1985), and those that are preserved closely resemble the facies of barred systems. As well, the preserved record of the upper shoreface-foreshore complex reflects fairweather conditions, and is characterised by ichnogenera of the *Skolithos* ichnofacies (Figure V-1). In contrast, the lower-middle shoreface complex reflects the greatest degree of facies variability, both sedimentologically and ichnologically. This portion of the shoreface may range from virtually unburrowed HCS, SCS or QPL sandstones to thoroughly bioturbated muddy sandstones, since both storm events and fairweather conditions may produce deposits. Although the offshore also accumulates sediment during both storm and fairweather conditions, the complex is generally fairweather dominated. Additionally, the trace fossil suite occurs in the *Cruziana* ichnofacies (Figure V-1). The lower-middle shoreface complex straddles the transition from the *Cruziana* ichnofacies to the *Skolithos* ichnofacies, enhancing its variability.

Variability in the preserved trace fossil record may locally reflect a combination of water turbidity, water salinity, fluctuating/episodic depositional rates, and storm energy conditions. Reduced oxygenation also has a profound effect upon the trace fossil assemblage (*cf.* Bromley and Ekdale, 1984; Raychaudhuri and Pemberton, 1992), but does not appear to exert a control on the sedimentary facies themselves. The close association that appears to exist between the lithofacies character and the observed trace fossil suite suggests that both occur in response to the same overriding mechanism.

The effects of enhanced water turbidity, as might be experienced near a river entering the coast, or settings proximal to a distributary channel on a storm-dominated delta, will typically be reflected by the virtual absence of suspension feeding structures within the sandstones. High water turbidity interferes with the efficiency of the organism's suspension feeding apparatus (Rhoads and Young, 1971). Water turbidity does not appear to affect predaceous organisms or most deposit feeders, and their traces may continue to occur in large numbers. As well, the nature of physical sedimentation need not necessarily change in response to water turbidity, if deposition occurs above fairweather wave base, since constant wave agitation of the bed keeps mud in suspension and moves it offshore. Fluctuations in water salinity have a marked effect on the entire trace fossil assemblage, extending from the offshore, landward towards the foreshore. Decreasing or (more rarely) increasing salinity is largely manifest by the disappearance of specialised feeding behaviours and the corresponding dominance of trophic generalists (*cf.* Wightman *et al.*, 1987; Beynon *et al.*, 1988; Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; Ranger and Pemberton, 1992). These effects are not restricted to the lower and middle shoreface and should show a recognisable pattern across the entire depositional profile. In river-dominated deltaic settings, water turbidity and salinity fluctuations may go hand in hand, severely limiting the diversity and abundance of the trace fossil suite. Differences between storm/wave-dominated deltas and storm/wave-dominated strandlines, on the other hand, may be exceedingly subtle (*cf.* Chapter VI).

Depositional rates have an important effect on the degree of bioturbation, but unless associated with episodic events, do not appear to impose a control on the ethology of the organisms and thus, not upon the resultant traces. Variations in sedimentation rates are typically coupled with other environmental controls. For example, slow sedimentation rates coupled with well oxygenated, fully marine conditions favour thorough biogenic reworking of the sediment, whereas the same rate of deposition, associated with anaerobic or dysaerobic, stratified and stagnant water, favour virtually unburrowed deposits. Likewise, enhanced depositional rates may merely favour decreased bioturbation, but if coupled with increased water turbidity and reduced salinity, as might be produced in a river-dominated delta, may produce completely unburrowed deposits.

Storms, and to a lesser degree, fairweather waves are the dominant physical processes operating on the lower and middle shoreface. Since these deposits may constitute the bulk of the ancient record of this portion of the shoreface (Kumar and Sanders, 1976; Aigner and Seilacher, 1982; Reinson, 1984; Swift *et al.*, 1985; Elliott, 1986), it follows that much of the observed trace fossil variability may be attributable to variability in the predominance of storm activity. Fluctuations in sedimentation rate are intimately associated with the episodic nature of storm deposition and this appears to control the ultimate character of the preserved lower and middle shoreface deposits.

In general, it is possible to identify three principal "types" of lower and middle shoreface deposits; those that are strongly storm-dominated ("high energy"), those that are moderately affected by storms ("intermediate energy") and those are only weakly affected by storms, or dominated by fairweather deposition ("low energy"). A complete intergradation appears to exist, both along depositional strike, depending on the regional paleogeography, and vertically through the facies succession, related to shallowing and increasing effectiveness of storm action on the bed. Much of the confusion that exists in defining the character of the lower and middle shoreface, as well in determining of the boundaries between the two subenvironments, appears to revolve around the variability imposed by the degree of storm-dominance and preservability of the fairweather deposits (*cf.* Figure V-1).

Strongly Storm-Dominated Shorefaces (High Energy)

Many Cretaceous shoreface sandstones of the Western Canada Sedimentary Basin (*e.g.* Virgelle Member of the Milk River Formation, Cadotte Member of the Peace River Formation, Bluesky Formation) and the North American Interior Seaway (*e.g.* Eagle Sandstone, Montana, Bootlegger Member of the Blackleaf Formation) show strong storm domination (Figures V-10 and V-11), possibly in response to the basin configuration and the strong seasonal storm cycles common to the northern hemisphere (*cf.* Cook and Gorsline, 1972; Owens, 1977; Fox and Davis, 1978; Hunter *et al.*, 1979; Swift *et al.*, 1985; Ericksen and Slingerland, 1990).

Strongly storm-dominated shorefaces typically consist of well-sorted, well-winnowed, fine- to very fine-grained (locally medium-grained) sandstones, comprising erosionally amalgamated storm beds (Figure V-12 A-D). In general, the laminae are subparallel to parallel, and of low inclination (<15°). Hummocky cross-stratification (HCS) possesses convex-upward laminae in addition to low angle scours with parallel to subparallel overlying laminae (Figure V-12 C). The mechanics of HCS deposition and its recognition in the rock record have been excellently documented by Dott and Bourgeois (1982) and Duke (1985). Swaley cross-stratification (SCS), formally documented by Leckie and Walker (1982), consists mainly of scoured swales, mantled by overlying laminae which progressively fill the structure (Figure V-12 D). The similarity of the overall configuration of SCS and HCS, coupled with their close stratigraphic association, suggests a genetic affinity. In SCS, the hummocks, which are diagnostic of HCS, are preferentially eroded and the

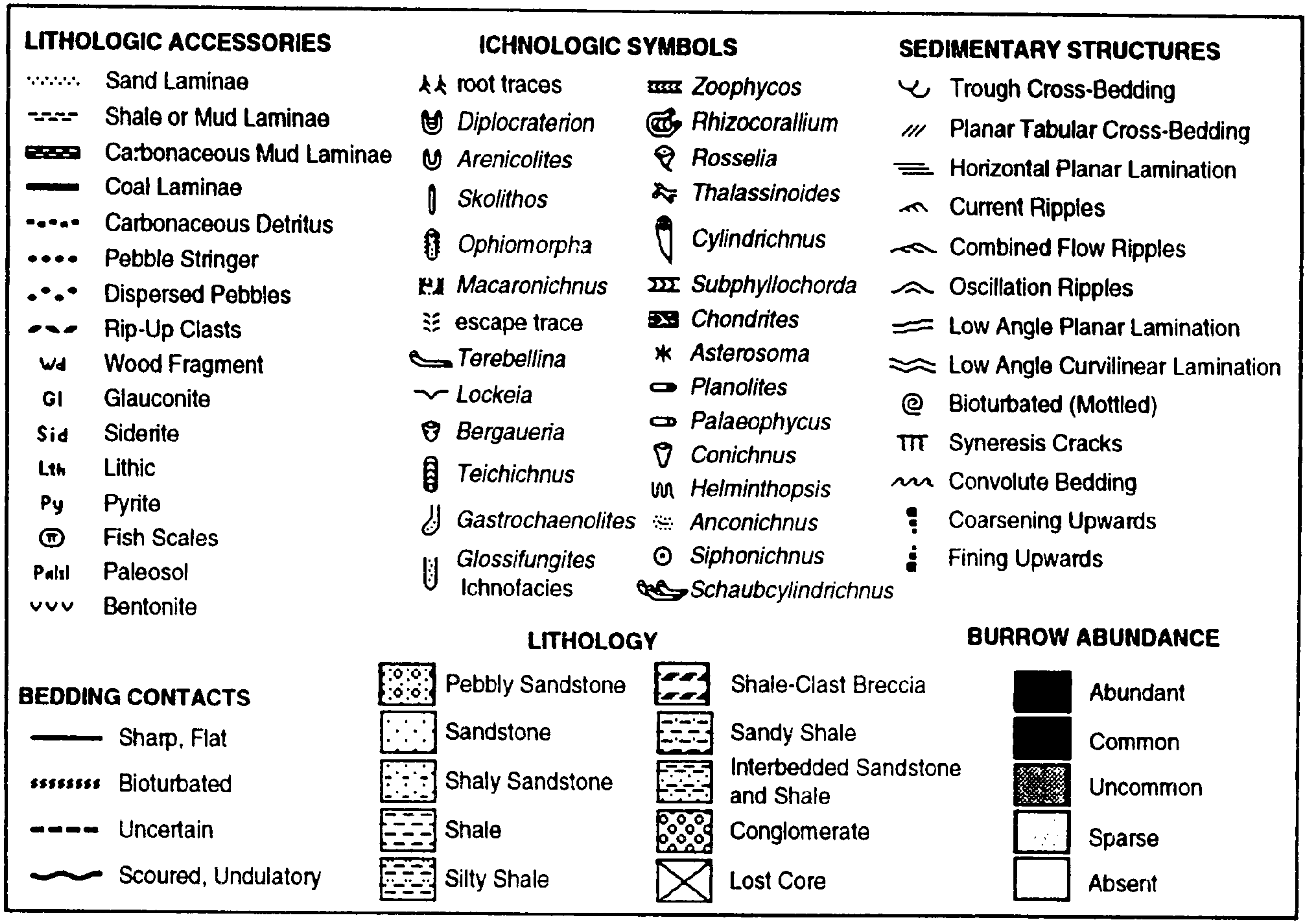


Figure V-10. Legend of Symbols used in Lithologs.

Figure V-11. Lithologs of strongly storm-dominated shoreface successions, Cadotte Member, Peace River Formation, Elmworth-Wapiti Field areas, Alberta. The 07-26-68-09W6 well shows minimal burrowing of the lower-middle shoreface, except in an enigmatic narrow zone around 1893 m. In this zone, the succession acquires a "laminated-to-burrowed" appearance. The litholog also shows the distinctive *Macaronichnus segregatis* zone in the upper shoreface-foreshore transition. The 10-11-69-09W6 well shows the characteristic low degree of burrowing associated with the offshore transition in the Cadotte, passing into virtually unburrowed, amalgamated tempestites of the lower-middle shoreface. The enigmatic burrowed zone immediately below the upper shoreface interval may reflect the preservation of summer season burrowing of tempestites, due to the basinward progradation of the nearshore complex (*cf.* Chapter VI). The litholog also shows the development of the *Macaronichnus segregatis* burrowed zone in the upper shoreface-foreshore transition. The legend of symbols used in the lithologs is given in Figure V-10.

Strongly Storm-Dominated (High Energy) Shoreface

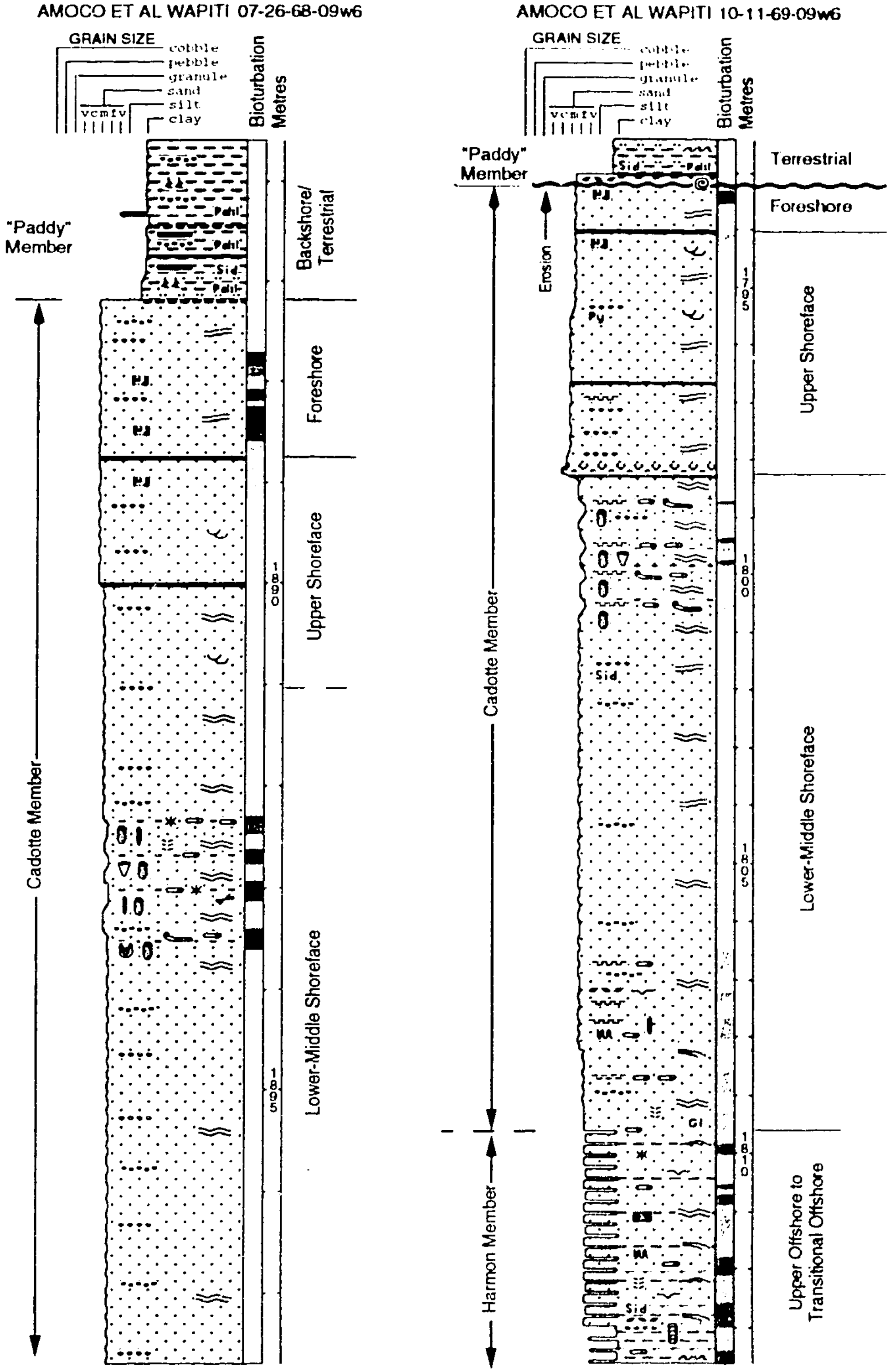
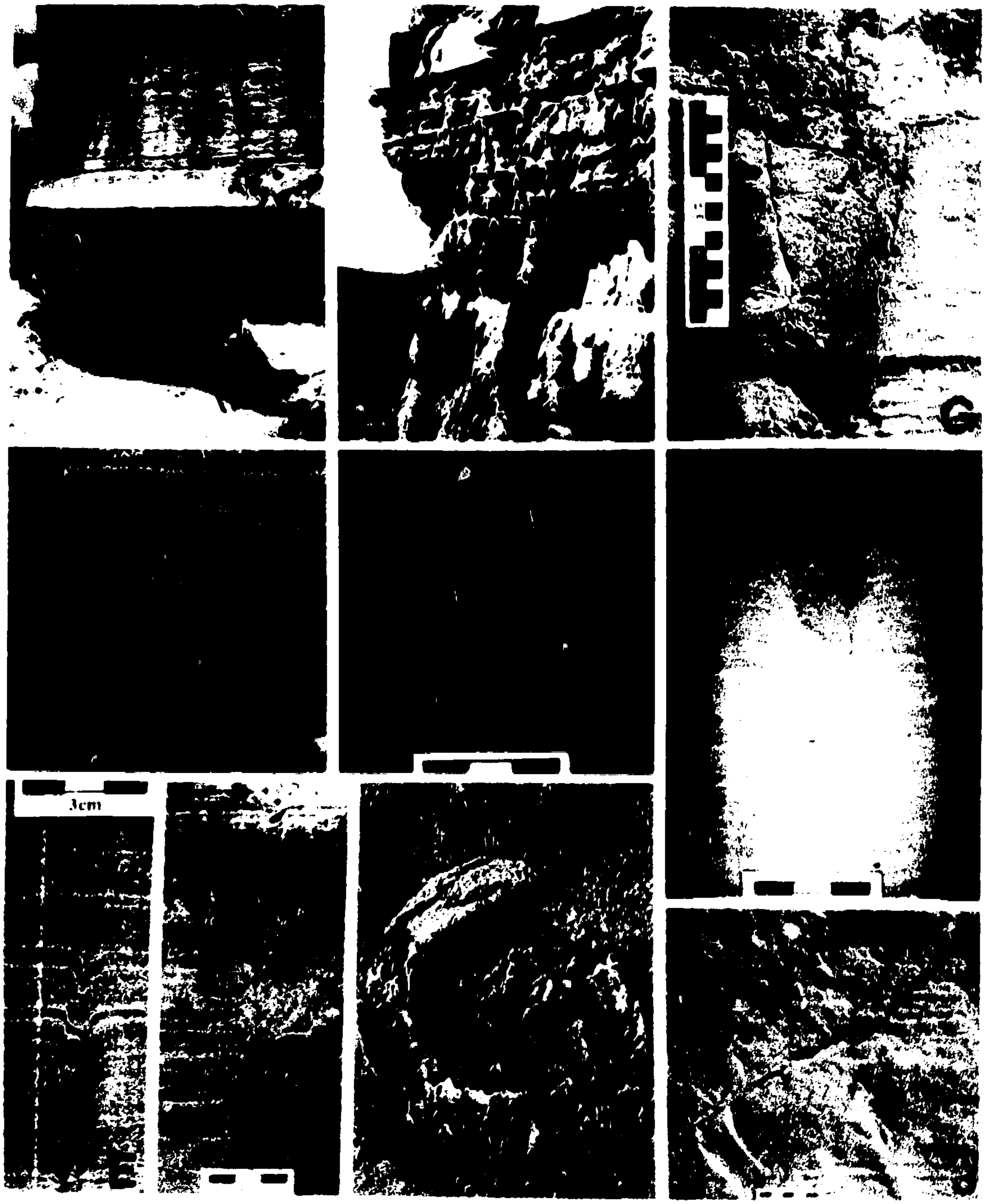


Figure V-12. Strongly Storm-Dominated Shorefaces. (A) Amalgamated swaley cross-stratified sandstone abruptly overlying offshore transition deposits. Eagle Sandstone, Montana Group, south-central Montana. The ice axe (lower right) is approximately 1 m long. **(B)** Offshore transition, passing into basal amalgamated hummocky cross-stratified sandstones of the lower shoreface. Kenilworth Member, Woodside Canyon, Book Cliffs, Utah. The cliff is approximately 10 m high. **(C)** Hummocky cross-stratified sandstones with well-developed, convex-upward laminae overlying the truncation surface. Cadotte Member, Peace River Formation, 06-06-64-25W5, depth 1913.4 m. **(D)** Swaley cross-stratified sandstone with erosional truncation. Bow Island Formation. Photo courtesy of I. Raychaudhuri. **(E)** Swaley cross-stratified sandstone with fugichnia (escape trace). Viking Formation, 07-08-64-02W6, depth 2125.7 m. **(F)** Hummocky cross-stratified sandstone with fugichnia (escape trace). Kenilworth Member, Woodside Canyon, Book Cliffs, Utah. **(G)** Swaley cross-stratified sandstone with robust *Conichnus*. Eagle Sandstone, Montana Group, central Montana. **(H)** Swaley cross-stratified sandstone, with well-developed *Conichnus*. Bow Island Formation, 07-02-08-21W4, depth 859 m. Scale in centimetres. **(I)** Ring-shaped *Ophiomorpha* on the bedding plane of hummocky cross-stratified sandstone. Virgelle Member, Milk River Formation, Writing-on-Stone Provincial Park, Alberta. Burrow is 20 cm across. **(J)** Vertical *Ophiomorpha nodosa* in hummocky cross-stratified sandstone. Sunnyside Member, North Price River Canyon, Book Cliffs, Utah. Scale in centimetres.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swales preserved. This is interpreted to reflect overall higher energy conditions than those proposed for HCS (Leckie and Walker, 1982; Rosenthal and Walker, 1987). Higher energy may translate as either shallower water conditions, more energetic storms and/or more frequent storms. The common vertical transition of HCS into SCS suggests that shallowing and associated enhanced storm erosion of the bed is the dominant control. With persistent shallowing, successive tempestites strongly rework underlying ones, becoming highly cannibalistic (Aigner and Reineck, 1982; Seilacher and Aigner, 1991).

More recently, Arnott (1993) has described a third storm-generated stratification type, from outcrop of the Late Albian to Early Cenomanian Bootlegger Member of the Blackleaf Formation of Montana, and related it to flume studies. This quasi-planar-lamination (QPL) is similar in many regards to HCS and SCS, particularly in the predominance of low angle (<15°) to horizontal parallel stratification. The scale of QPL is considerably greater than for HCS and SCS, with extensive low angle to horizontal, gently undulating erosional truncation surfaces overlain by parallel to subparallel laminae. Undulations show a spacing and height of 2.1 m and 1.8 cm, respectively, giving spacing to height ratios in excess of 100. In contrast to HCS and SCS, QPL possesses paleocurrent data indicating offshore sediment transport, and hence, appears to reflect fundamentally different physical processes of generation. Whereas HCS and SCS are believed to be generated under purely oscillatory processes during storms (Duke, 1985; Cheel, 1991; Duke *et al.*, 1991). QPL is produced by very high energy combined flow processes during storms (Arnott, 1993).

Discrimination between HCS/SCS and QPL is difficult, except at the scale of outcrop. Many cored intervals previously regarded as HCS/SCS probably actually correspond to QPL. However, differentiating between these stratification types in the subsurface is largely impractical, insofar as all three bedding types are tempestites. Where waning flow oscillation or combined flow ripples are well preserved, differentiating HCS/SCS from QPL may be possible.

The ichnologic character of such amalgamated units is typified by minimal bioturbation; it is not unusual for several metres of interval to lack any indication of biogenic activity. Dominant traces include fugichnia, reflecting the attempt of an organism to reach the sediment-water interface following entrainment within the flow or rapid burial beneath the tempestite (Figure V-12 E,F). In HCS-dominated intervals and thinly-bedded QPL, remnant traces of opportunistic pioneers, particularly those that are deeply penetrating, may be preserved below scour surfaces. Such traces may include *Skolithos*, *Ophiomorpha nodosa* and *Conichnus conicus* (Figure V-12 G-J), as well as *Arenicolites* and rarer *Diplocraterion*. Fairweather suites are generally not preserved between the storm beds within strongly storm-dominated settings, reflecting a combination of enhanced scouring depth and storm frequency.

In amalgamated SCS intervals and thickly-bedded QPL, opportunistic traces may be removed by subsequent storm scour, leaving only rare fugichnia to record the existence of a marine benthic community. Within the high energy shoreface, the boundary between the lower and middle shoreface, namely the transition from a *Cruziana*- to *Skolithos*-dominated assemblage (*cf.* Figure V-1), is generally not preserved. On a physical basis, it might be reasonable to assign amalgamated HCS to the lower shoreface and amalgamated SCS to the middle shoreface, if such a subzonation is deemed necessary. In the case of QPL, a data base of examples has not been developed to permit such a subdivision.

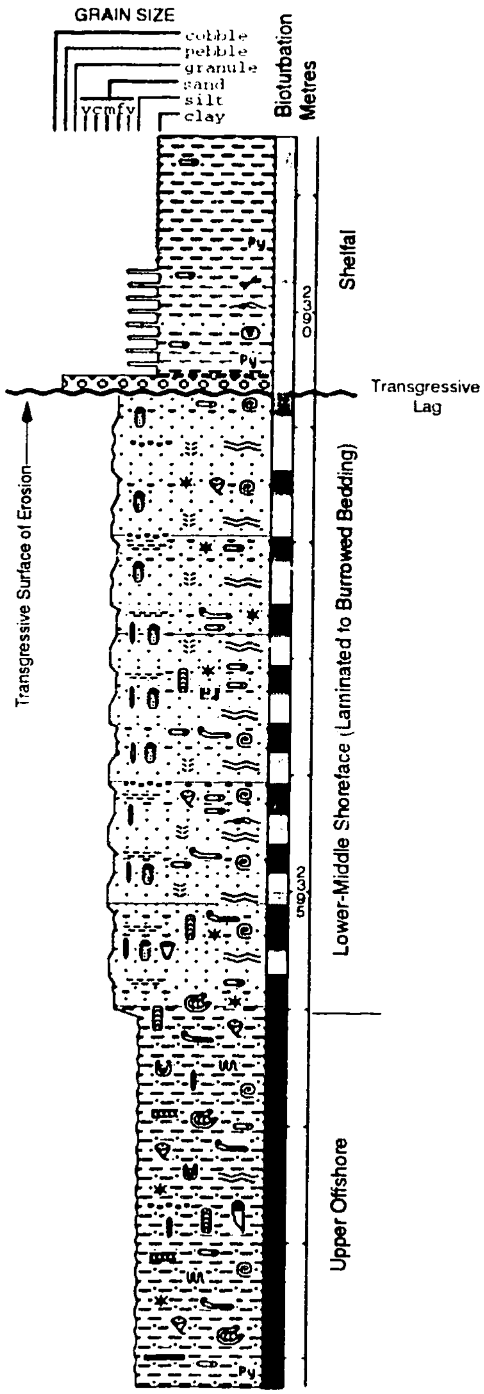
Moderately Storm-Dominated Shorefaces (Intermediate Energy)

A somewhat lower energy, transitional type of shoreface succession is exceedingly abundant in the Cretaceous of North America (*e.g.* several members of the Book Cliffs, Utah, the Shannon sandstone of Wyoming, as well as the Blood Reserve Sandstone, localised intervals of the Cadotte Member, the Viking Formation of the Kaybob Field, the Bow Island Formation and several members of the Cardium Formation, within Alberta; *cf.* Figure V-13), commonly grading laterally or vertically out of the lowest energy type (see below). Less commonly, this intermediate energy shoreface-type may grade upward into a strongly storm-dominated shoreface. These vertical shifts are interpreted to be associated with shallowing.

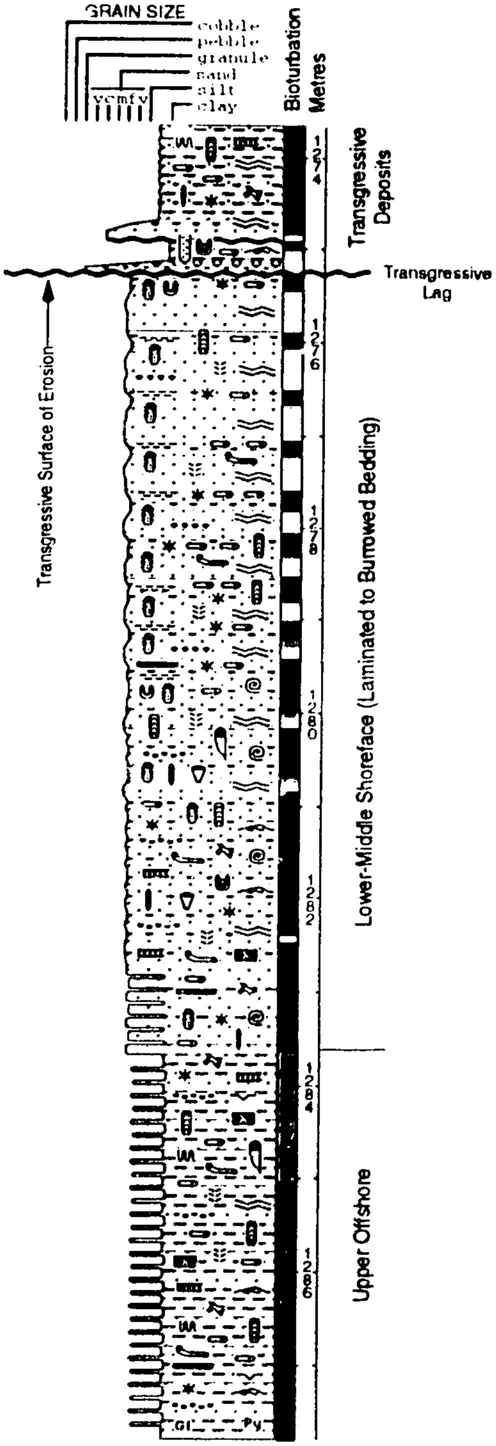
The moderately storm-dominated shoreface typically appears "bedded" with storm-laminated sandstone intervals (typically less than 1 m and commonly 20-50 cm in thickness) alternating with more thoroughly bioturbated muddy sandstone beds, generally ranging from 10-25 cm, though

Figure V-13. Lithologs of moderately storm-dominated shoreface successions in the Viking Formation of west-central Alberta. The upper shoreface deposits have been erosionally removed by high energy marine flooding surfaces (TSE). The lower to middle shoreface deposits display a distinctive "laminated-to-burrowed" character. Note the high diversity of trace fossils preserved in the succession, reflecting both opportunistic colonisation of the tempestites and later fairweather equilibrium colonisation. The succession shows an upward increase in storm-dominance, manifest by decreasing thicknesses of preserved burrowed beds and thickening of tempestites. This is interpreted to reflect progressive shallowing. The legend of symbols used in the lithologs is given in Figure V-10.

AMMIN ET AL WEST PEMBINA 10-08-50-14w5



B.A. GOOSE RIVER 10-03-67-18w5

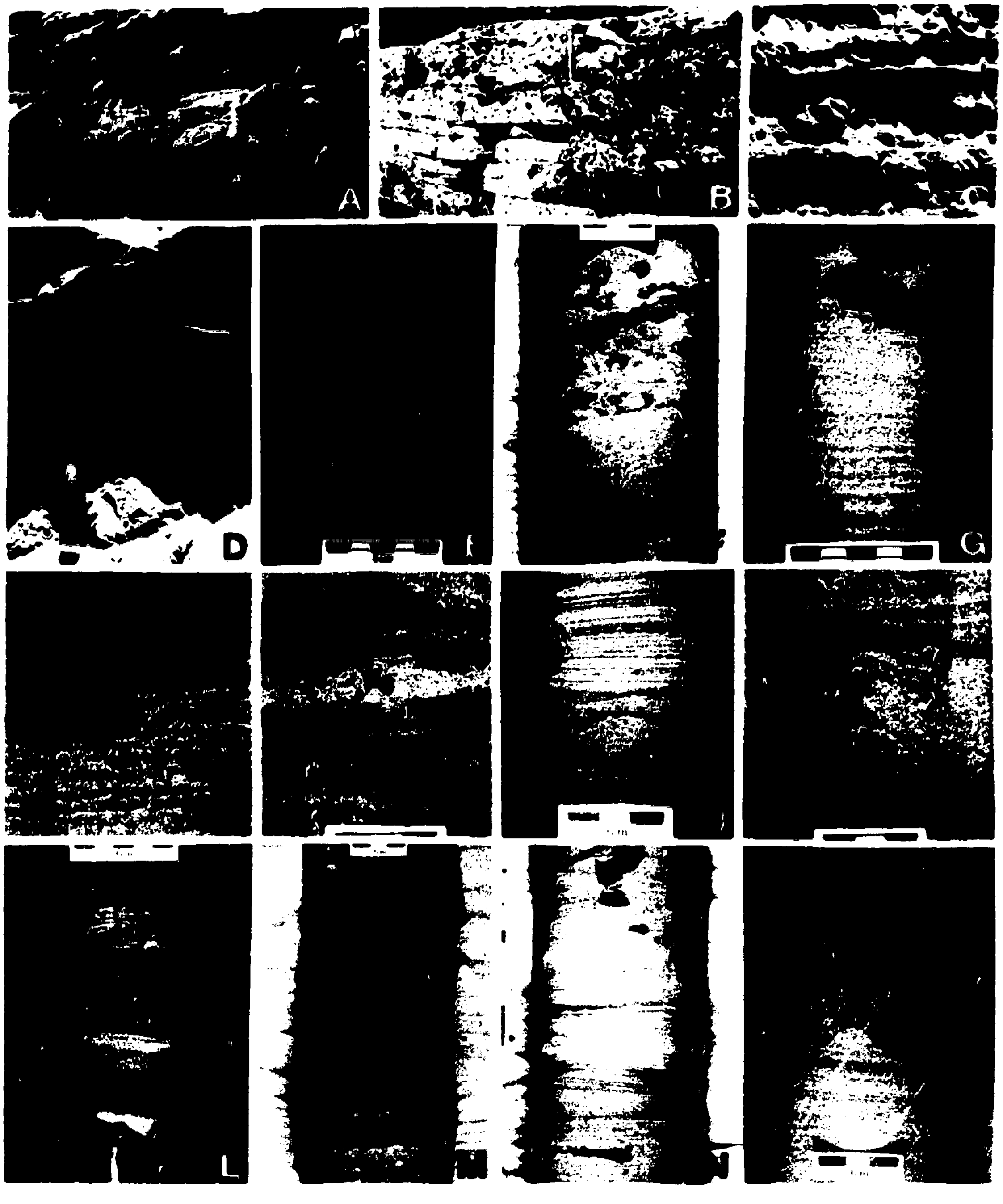


locally considerably greater in thickness. Howard (1971a,b; 1972) termed it "laminated to burrowed" bedding but, commonly, it is informally referred to as "Lam-Scram" because of the apparent "interbedding" of laminated and biogenically "scrambled" intervals (Frey, pers. comm. 1991; Figures V-6 and V-14 A-C).

A closer inspection, however, demonstrates that the individual storm beds are identical to those of the amalgamated, higher energy shoreface successions, but in contrast, the upper portions (typically 15 cm or so) are bioturbated, reflecting post-storm colonisation of the substrate by the pioneer opportunistic community (Figure V-14 E-O). Biogenic reworking is most intense near the tops of the beds largely because the tracemakers are relatively shallow burrowers (Farrow, 1975). A notable exception is the *Ophiomorpha* tracemaker; consequently, *Ophiomorpha*, and particularly the vertical components (Figure V-14 D), dominate many of the opportunistic trace assemblages. With the return to fairweather conditions, the opportunistic suite is replaced, and their traces cross-cut, by the resident fairweather trace fossil suite (Pemberton *et al.*, 1992b). The fairweather assemblage generally occupies less well-sorted, typically muddy overlying sandstones, although some traces may penetrate down into the storm bed; *Rosselia*, and most suspension feeding traces (*e.g. Skolithos*) are common examples. The base of the tempestites are sharply erosive and truncate the underlying fairweather trace assemblage (Figure V-14 J,L), whereas bioturbation generally obscures the upper contact between the storm bed and the fairweather deposit (Figure V-14 E, H, O).

The degree of burrowing within the storm bed and thickness of the fairweather deposits are highly variable and reflect a combination of storm severity (*i.e.* the depth of storm scour into fairweather and previous storm deposits), storm frequency (*i.e.* the thickness of fairweather deposits permitted to accumulate between storms) and relative water depth. Stacked tempestites containing remnant opportunistic suites and lacking preserved fairweather assemblages may correspond to strong storms, frequent storms and/or middle shoreface (shallower water) settings. In contrast, well-developed cross-cutting relationships between opportunistic and fairweather trace fossil assemblages, forming a mixed *Skolithos-Cruziana* ichnofacies (Figure V-7), as well as preservation of thick fairweather deposits, may reflect a combination of weaker storms, infrequent storm activity and lower shoreface (deeper water)

Figure V-14. Moderately Storm-Dominated Shorefaces. (A) Hummocky cross-stratified sandstone passing into burrowed sandstone. Spring Canyon Member, Spring Canyon, Book Cliffs, Utah. Scale is 15 cm long. **(B)** Low angle parallel laminated sandstones passing into burrowed sandstones. Cardium Formation, Ram Falls, Alberta. Scale 30 cm long. **(C)** Laminated to burrowed sandstones (Lam-Scram) in the lower shoreface. Aberdeen Member, Panther Canyon, Book Cliffs, Utah. Scale 15 cm long. **(D)** Bedding plane of *Ophiomorpha nodosa* boxwork. Note the abundant vertical tubes. Blood Reserve Sandstone, Jensen Reservoir, Lethbridge, Alberta. **(E)** Swaley cross-stratified sandstone, burrowed at the top with *Conichnus* (C), *Skolithos* (Sk) and *Planolites* (P). Cadotte Member, Peace River Formation, 10-11-69-09W6, depth 1799.5 m. **(F)** Burrowed portion of a storm bed. Opportunistic suite consists of *Ophiomorpha* (O). Fairweather traces are *Palaeophycus* and *Planolites*. Viking Formation, 03-22-52-19W5, depth 2613.2 m. **(G)** Robust *Ophiomorpha nodosa* recording opportunistic colonisation of hummocky cross-stratified sandstones. Note that the wall margins are siderite-cemented. Cadotte Member, Peace River Formation, 10-11-69-9W5, depth, 1800 m. **(H)** Hummocky cross-stratified sandstone with *Ophiomorpha nodosa* of opportunistic suite. Fairweather burrowing has mottled the sandstone near the top. Cadotte Member, Peace River Formation, 10-11-69-09W6, depth 1800.5 m. Field of view is 6 cm. **(I)** Robust *Ophiomorpha* and *Palaeophycus* visible in mottled sandstone at top of storm bed. Cadotte Member, Peace River Formation, 10-16-69-11W6, depth 1900.8 m. Scale in centimetres. **(J)** Sharp-based storm bed which has truncated an underlying fairweather trace assemblage. Note the *Ophiomorpha*. Bow Island Formation. Photo courtesy of I. Raychaudhuri. **(K)** Sharp-based storm bed, truncating a fairweather trace fossil assemblage consisting of *Ophiomorpha*, *Palaeophycus* and *Planolites*. Cadotte Member, Peace River Formation, 10-16-69-11W6, depth 1901 m. **(L)** Laminated to burrowed sandstone interval. The fairweather trace assemblage is sharply truncated by an overlying tempestite, whose top is thoroughly burrowed. Viking Formation. **(M)** Laminated to burrowed sandstone. Viking Formation, 10-08-50-14W5, depth 2394.1 m. **(N)** Amalgamated swaley cross-stratified sandstone with *Teichichnus* near the top. Bow Island Formation. Photo courtesy of I. Raychaudhuri. Core is 10 cm in diameter. **(O)** Laminated to burrowed sandstone with *Ophiomorpha*, *Palaeophycus* and *Planolites*. Viking Formation, 11-35-61-20W5, depth 1757.1 m.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settings. Determination of the relative importance of these variables clearly requires the vertical and lateral facies context of the stratigraphic succession. Discrimination between lower and middle shoreface subenvironments depends entirely on the resident fairweather assemblage, not on the opportunistic suite, since it is the modal or average depositional conditions that reflect the position along the depositional profile (Figure V-1). Nonetheless, even where fairweather deposits exist, it may be difficult, if not impossible to differentiate the fairweather assemblage from the storm assemblage, particularly in middle shoreface deposits where both suites are characterised by the *Skolithos* ichnofacies. Under such conditions, or where fairweather deposits are poorly-developed, discrimination between lower and middle shoreface deposits may have to be based purely on primary physical structures, such as the degree of erosional amalgamation of the tempestites. Lateral variability in the character of the deposits imposes further difficulties. In the case of strongly storm-dominated successions, discrimination between the lower and middle shoreface may not be viable or even useful.

Weakly Storm-Influenced Shorefaces (Low Energy)

Shorefaces characterised by minor amounts of storm deposits are very common in several Viking Formation fields in the subsurface of Alberta (Figure V-15), such as Giroux Lake, Chigwell (Raychaudhuri *et al.*, 1992), and Joffre (Downing and Walker, 1988); Figure V-16 A-E) and parts of the Spring Canyon and Sunnyside members in the Book Cliffs of Utah (Figure V-16 F-H). These successions reflect extended periods of fairweather conditions, characterised by lower energy shoaling waves. Infrequent and generally weaker storm events generate thin intercalated tempestites, many of which are thoroughly burrowed and are preserved only as remnants. Fairweather deposits typically show few primary physical sedimentary structures, although very rare oscillation ripple laminae may be preserved as burrowed remnants, particularly higher up in the succession. A few rare trough cross-stratified sandstone beds may be preserved towards the top of some middle shoreface deposits. The bulk of the facies dominating the lower shoreface consists of thoroughly burrowed, muddy sandstone, reflecting the lower energy conditions of fairweather shoaling waves and slow but generally uniform rates (Howard and Reineck, 1981). With continued shallowing,

Figure V-15. Litholog of a weakly storm-influenced shoreface in the Viking Formation of west-central Alberta. The well displays stacked parasequences, separated by a low energy (non-erosive) marine flooding surface (parasequence boundary). The succession is characterised by thorough bioturbation with a wide diversity of trace fossils. Note the minimal preservation of tempestites in the succession. The marked increase in vertical suspension feeding and dwelling structures above 2789 m may herald the onset of middle shoreface conditions. The legend of symbols used in the litholog is given in Figure V-10.

Weakly Storm-Influenced (Low Energy) Shoreface

OIL ET AL PECO 11-11-49-17w5

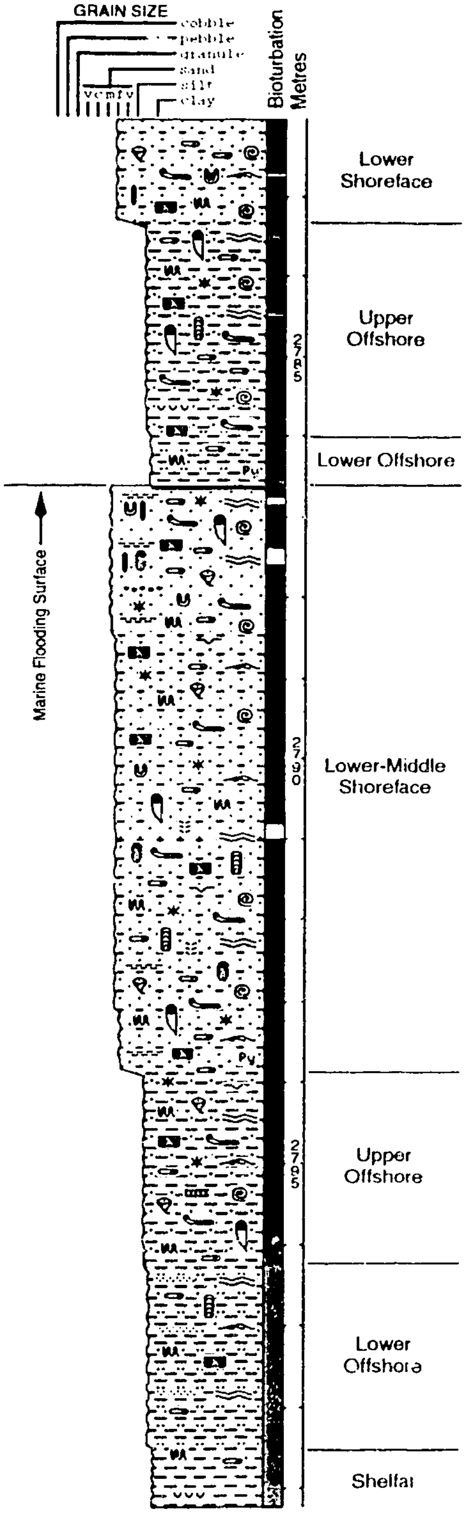
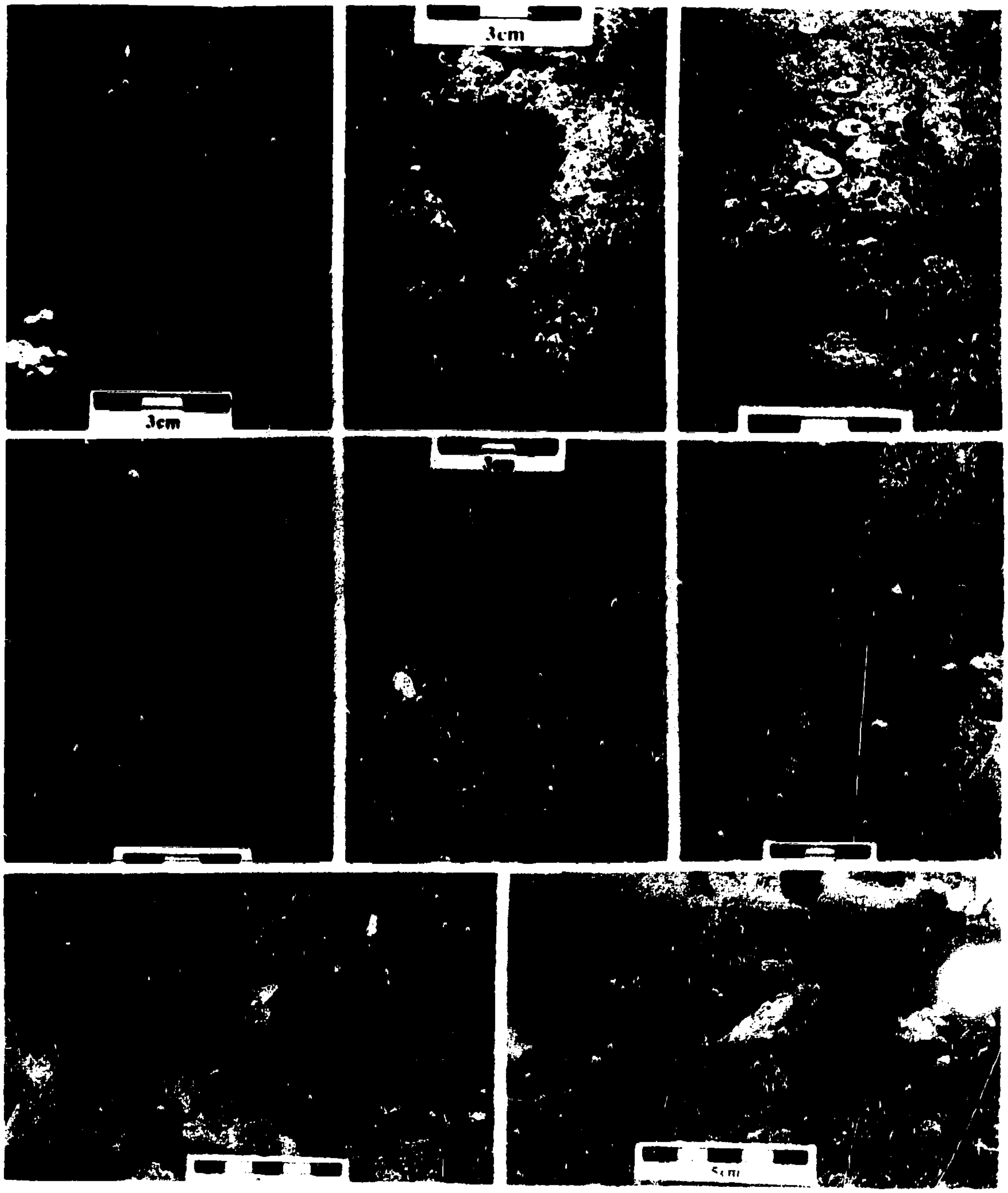


Figure V-16. Weakly Storm-Influenced Shorefaces. (A) Thoroughly burrowed sandstone with *Schaubcylindrichnus* (S), *Terebellina* (T). Viking Formation, 06-28-43-26W4 (Chigwell Field), depth 1411.4 m. **(B)** Mottled lower shoreface sandstone with *Rosselia*. Viking Formation, 02-21-38-26W4 (Joffre Field), depth 1590.4 m. **(C)** *Teichichnus* (Te), *Schaubcylindrichnus* (S) and *Planolites* (P) in thoroughly burrowed lower shoreface sandstone. Viking Formation, 11-29-62-20W5 (Kaybob Field) depth 1702.9 m. Scale in centimeters. **(D)** *Diplocraterion* (D), *Skolithos, Asterosoma* (A) and *Planolites* in thoroughly burrowed sandstone. Viking Formation, 06-29-47-21W4 (Joarcam Field), depth 1039.7 m. Scale in centimeters. **(E)** Mottled muddy sandstone with *Planolites* and *Palaeophycus*. Viking Formation, 16-12-48-21W4 (Joarcam Field), depth 985.7 m. **(F)** Lower shoreface sandstone with robust *Ophiomorpha irregulaire*. Sunnyside Member, North Price River Canyon, Book Cliffs, Utah. Scale in centimeters. **(G)** Lower to middle shoreface sandstone with *Ophiomorpha nodosa* (O), *Planolites* and *Schaubcylindrichnus* (S). Spring Canyon Member, Spring Canyon, Book Cliffs, Utah. Scale in centimeters. **(H)** Mottled muddy sandstone of the lower shoreface. *Skolithos, Schaubcylindrichnus* and *Ophiomorpha* are abundant. Spring Canyon Member, Spring Canyon, Book Cliffs, Utah.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shoaling fairweather waves become more effective at winnowing the bed, and mud content within the sandstones diminish, although burrowing intensity typically remains intense. Such shorefaces tend to be strongly dissipative, possess low gradients and are generally thin (Wright *et al.*, 1979; Boyd and Penland, 1984; Thom *et al.*, 1986).

The trace fossil assemblages in these settings provide a wealth of information about the successions. Lower shoreface suites contain a diverse and abundant *Cruziana* suite (with subordinate grazing/foraging structures and suspension feeding traces). These pass upward into *Skolithos* ichnofacies (with rare grazing/foraging structures exploiting muddy zones and a reduced deposit feeding component), corresponding to the middle shoreface.

Trace fossils tend to be abundant in numbers and uniformly distributed throughout the succession. Diversity of ichnogenera is generally high and no individual forms dominate the assemblage. Specialised or elaborate biogenic structures, particularly evident in deposit feeding and grazing/foraging behaviours, are common. These characteristics demonstrate an equilibrium or K-selected behaviours, reflecting unstressed, fully marine, well oxygenated conditions (Pianka, 1970; Jumars, 1993).

SUMMARY

The integration of ichnology and sedimentology provides a strong depositional model for foreshore to offshore transitions, whether they occur on strandplain, barrier islands or even wave/storm-dominated deltas (*cf.* Chapter 6), removed from the interference of distributary channels. The shoreface zone can be grouped into three main depositional complexes, each of which respond to a different set of physical parameters and displays discrete ichnological characteristics. Within each depositional complex, the subenvironments can be reasonably differentiated through a combination of physical and biogenic features, with the exception of the lower and middle shoreface.

The offshore complex is typically dominated by fairweather conditions and is characterised by a *Cruziana* ichnofacies. The suite displays a predominance of deposit feeding structures with subordinate grazing/foraging structures, and even rarer suspension feeding structures. Storm effects are variable but ineffective in removing the fairweather suite except under high degrees of storm domination (*cf.* Chapter VI). The offshore typically displays a K-selected equilibrium suite of trace fossils, with variable but non-dominating overprint by opportunistic (r-selected) behaviours related to tempestite colonisation.

The lower-middle shoreface complex is strongly affected by both storm and fairweather conditions, and hence, the preserved record shows a great degree of variability. Fairweather trace fossil assemblages range from equilibrium suites of the proximal *Cruziana* ichnofacies in the lower shoreface, to the *Skolithos* ichnofacies in the middle shoreface (Figure V-1), enhancing the observed variability in this depositional complex.

The upper shoreface-foreshore complex is also quite variable, but this is mainly in regard to sediment texture and morphodynamic configuration. Preserved facies are remarkably similar over a wide range of shoreface states and accumulate in response to fairweather conditions. Storm events are non-depositional and strongly erosive. The trace fossil assemblage is generally sparse and corresponds to the *Skolithos* ichnofacies (Figure V-1). Many intervals contain zones of *Macaronichnus segregatis* near the upper shoreface-foreshore transition.

The main variations in the preserved record of a shoreface succession are reflected in the lower-middle shoreface complex. This large degree of variability can be attributed to variations in overall storm intensity, storm frequency and relative water depth. Three main "types" of shoreface successions can be considered, although a complete continuum exists between them. Amalgamated tempestites with minimal preserved biogenic structures constitute the lower-middle shoreface complex of strongly storm-dominated systems. Moderately storm-dominated systems correspond to intermediate energy conditions. The lower-middle shoreface complex consists of stacked, erosively-based storm beds, bioturbated at the top by opportunistic traces and cross-cut by a resident trace assemblage associated with fairweather conditions. The weakly storm-affected shorefaces constitute the lowest energy and most dissipative conditions. The lower-middle shoreface complex is characterised by thoroughly bioturbated sandstones, recording nearly continuous fairweather accumulation, with remnant, largely obliterated, thin intercalated tempestites.

Stronger storm-domination may correspond, in part, to shorefaces which are subjected to severe winter storm seasons, where high frequency events permit thick amalgamated tempestites (*cf.* Cook and Gorsline, 1972; Owens, 1977; Hunter *et al.*, 1979). Lower energy forms may reflect those subjected to the much lower frequency hurricane storms (Dott, 1988; Saunders, pers. comm., 1992). Amalgamated, strongly storm-dominated shoreface successions are relatively abundant in the northern portions of the Western Canada Sedimentary Basin (*e.g.* the Bluesky Formation, the Falher members of the Spirit River Formation and the Cadotte Member of the Peace River Formation, *cf.* Chapter VI). Higher latitudes appear to favour higher frequency and intense winter storms, and this warrants consideration as the overriding factor in the paleogeographic distribution of these shoreface types (Saunders, pers. comm., 1992).

Discrimination between lower and middle shoreface deposits may be possible on an ichnological basis; where well-developed fairweather suites are present the boundary corresponds to a transition from a predominantly *Cruziana* ichnofacies to a *Skolithos* ichnofacies. Under progressively greater storm domination, fairweather suites are insufficiently preserved to resolve the two subenvironments ichnologically and physical characteristics such as coarsening of sediment texture, decrease in thicknesses of fairweather deposits, and replacement of lower energy HCS beds by SCS beds, may have to be employed. In the case of QPL intervals, it is unclear whether such a distinction is possible. In any case, vertical and lateral transitions between shoreface "types" may occur, depending upon relative water depth, storm frequency, storm intensity and shoreline orientation in relation to dominant wave attack. These conditions serve to vary the character of contemporaneous lower and middle shoreface deposits along depositional strike, probably making differentiation of these two subenvironments impractical.

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CHAPTER VI

THE HARMON AND CADOTTE MEMBERS OF WEST-CENTRAL ALBERTA - A CASE STUDY OF A HIGH ENERGY STORM-DOMINATED SHOREFACE

INTRODUCTION

The Harmon and Cadotte members of the Peace River Formation constitute the record of a rapidly northward-prograding strandline system in Middle Albian time. The succession affords the opportunity to integrate ichnology and sedimentology in order to characterise the nature of a strongly storm-dominated shoreface deposit (*cf.* MacEachern and Pemberton, 1992). The succession is easily divisible into a lower-middle shoreface complex, consisting mainly of erosionally amalgamated tempestites recording high frequency and high intensity seasonal storms, and an overlying nearshore complex reflecting coarser-grained facies which accumulated in a barred shoreface state, principally during non-storm seasons. Careful study of the few intervals which preserve biogenic structures, in conjunction with sedimentological elements, is not only useful in the characterisation of strongly storm-dominated successions but also affords insights into the effects of seasonal storm cycles (winter-summer seasons) on shoreface deposits. Storm seasonality appears to be a common phenomenon of high latitude settings (Cook and Gorsline, 1972; Owens, 1977; Fox and Davis, 1978; Hunter *et al.*, 1979; Swift *et al.*, 1985).

STRATIGRAPHIC RELATIONSHIPS AND REGIONAL DEPOSITIONAL HISTORY

The Harmon and Cadotte comprise the basal two members of the Peace River Formation (Figure VI-1). Their deposition records the last in a series of Middle Albian paleoshoreline complexes that prograded northward into the Boreal Moosebar Sea (Figure VI-2). Together with the Falher members and

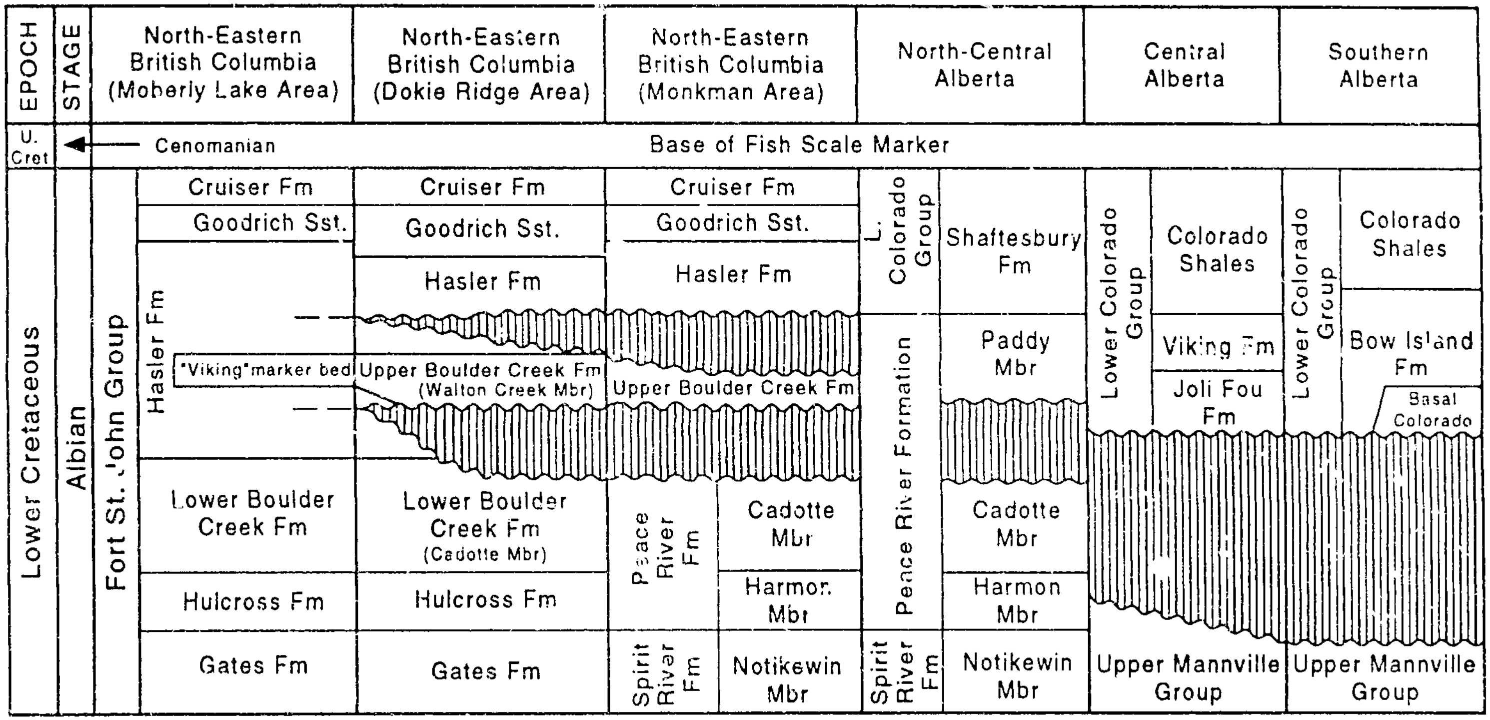


Figure VI-1. Stratigraphic terminology chart of the Peace River Formation and equivalents. Correlations of strata in northeastern British Columbia come from Stelck and Koke (1987), Stelck and Leckie (1990a), Stelck (1991) and Gibson (1992). The Upper Boulder Creek Formation in the Monkman area also corresponds to the Walton Creek Member of Stott (1990) and Gibson (1992).

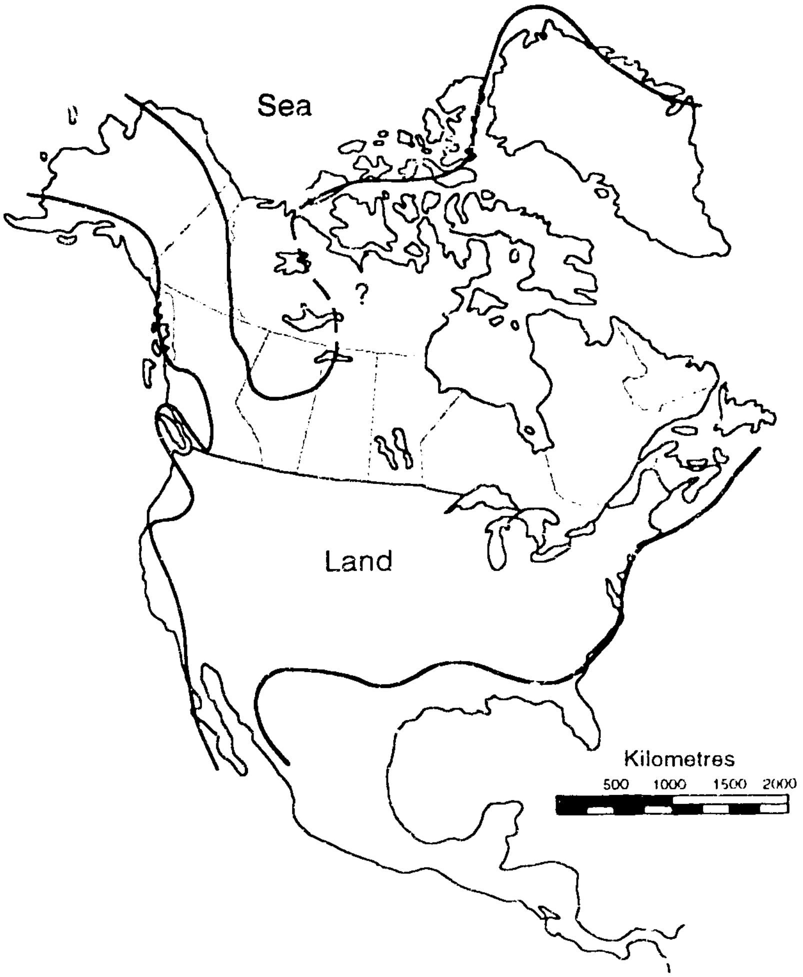


Figure VI-2. Approximate position of the boreal seaway during *Gastroplites* (late Middle Albian) time. The time corresponds to early Cadotte shoreface progradation (Stelck, pers. comm., 1994).

the Notikewin Member, the Harmon-Cadotte form the major progradational wedge - the Fort St. John Group. The Harmon and Cadotte members extend continuously along depositional strike from the foothills of the Rocky Mountains to west of Peace River town, Alberta; a distance of more than 300 km (Leckie, 1988). The study area (Figure VI-3) occurs in west-central Alberta, and extends from Township 63 to 73, Range 18W5 to 13W6.

McConnell (1893) originally named and described the Peace River sandstone for the sandstones and shales which crop out south of Peace River, northward beyond Manning, Alberta. Wickenden (1951) informally subdivided the Peace River Formation into four members: the basal member, the middle shale member, the Cadotte member and the continental member. The latter member was recognised to be over- and underlain by a disconformity. Badgley (1952) and the Alberta Study Group (1954) later assigned the basal member to the Spirit River Formation, calling it the Notikewin Member. They also renamed the middle shale member the Harmon Member, formally defined the Cadotte as a member, and renamed the continental member the Paddy Member. The Peace River Formation overlies the Notikewin Member of the Spirit River Formation and is overlain by the Shaftesbury Formation, originally defined by McLearn and Henderson (1944).

The Harmon Member sharply overlies the Notikewin Member, representing a major middle Albian transgression of the boreal sea from the north, which extended as far south as the northern interior plains (Oliver, 1960; Stott, 1982; Caldwell, 1984). The Harmon Member is stratigraphically equivalent to Hulcross Formation of British Columbia, which contains arenaceous foraminiferal assemblages of the *Haplophragmoides multiplum* subzone of the *Gaudryina nanushukensis* Zone (Figure VI-4). The Harmon and Hulcross ranges from a maximum thickness of about 125 m in northeastern British Columbia to less than 10 m south and east of the study area (Leckie *et al.*, 1990). The southern thinning has been regarded as a combination of a depositional and erosional edge (Leckie *et al.*, 1990).

The Cadotte Member grades out of the Harmon Member and reflects a generally northward progradation during a middle Albian regression. The Cadotte Member ranges from more than 60 m in northeastern British Columbia to less than 10 m north of the Peace River Arch, as well as to the south and east of the study area (Leckie *et al.*, 1990). A notable feature of the

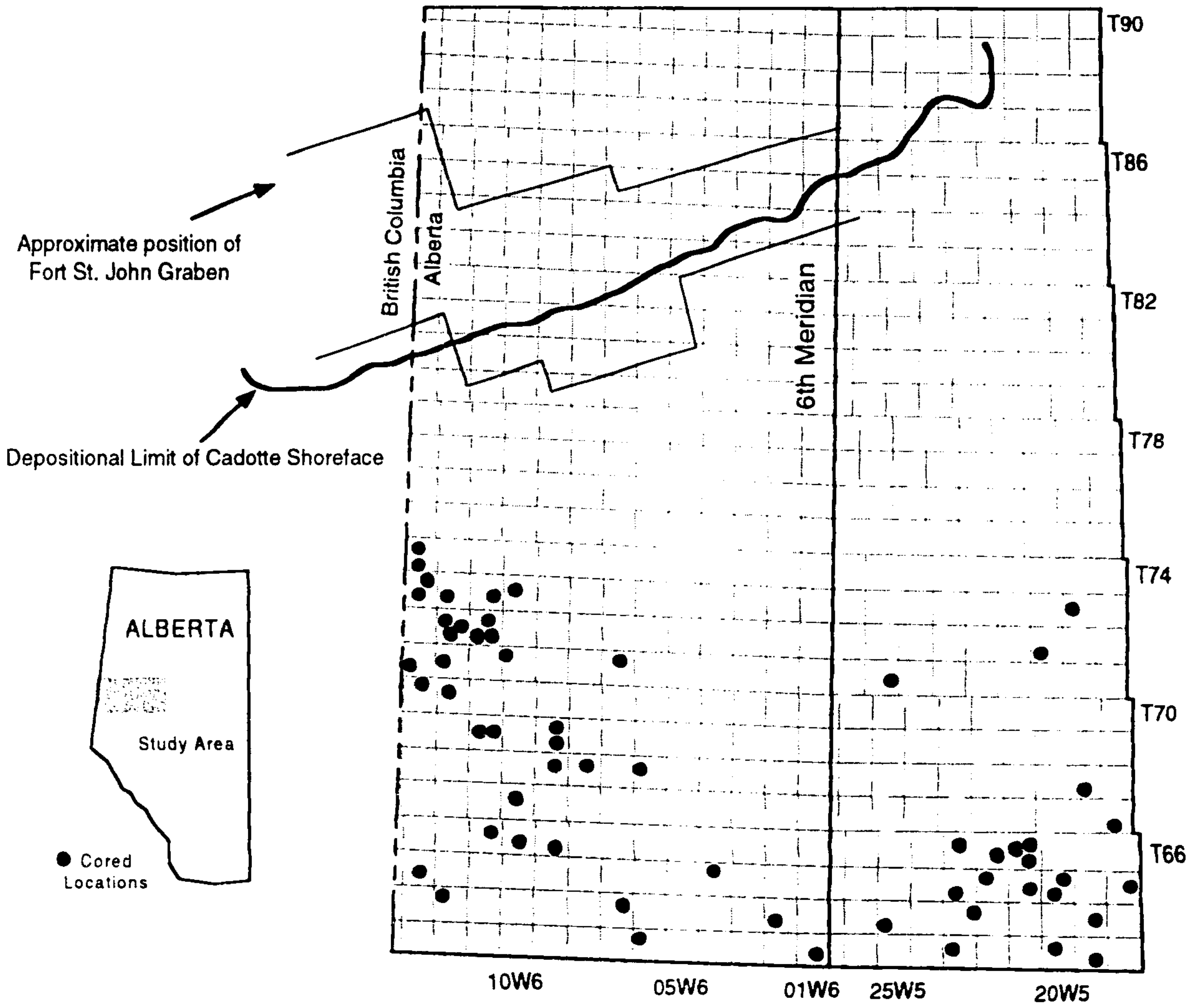


Figure VI-3. Study area with cored locations. Note the close association between the depositional edge of the Cadotte shoreface sandstone and the southern margin of the Fort St. John Graben of the Dawson Creek Graben Complex. The Cadotte Member depositional limit is based on the mapping of Leckie *et al.* (1990). The position of the Fort St. John Graben is based on O'Connell *et al.* (1990).

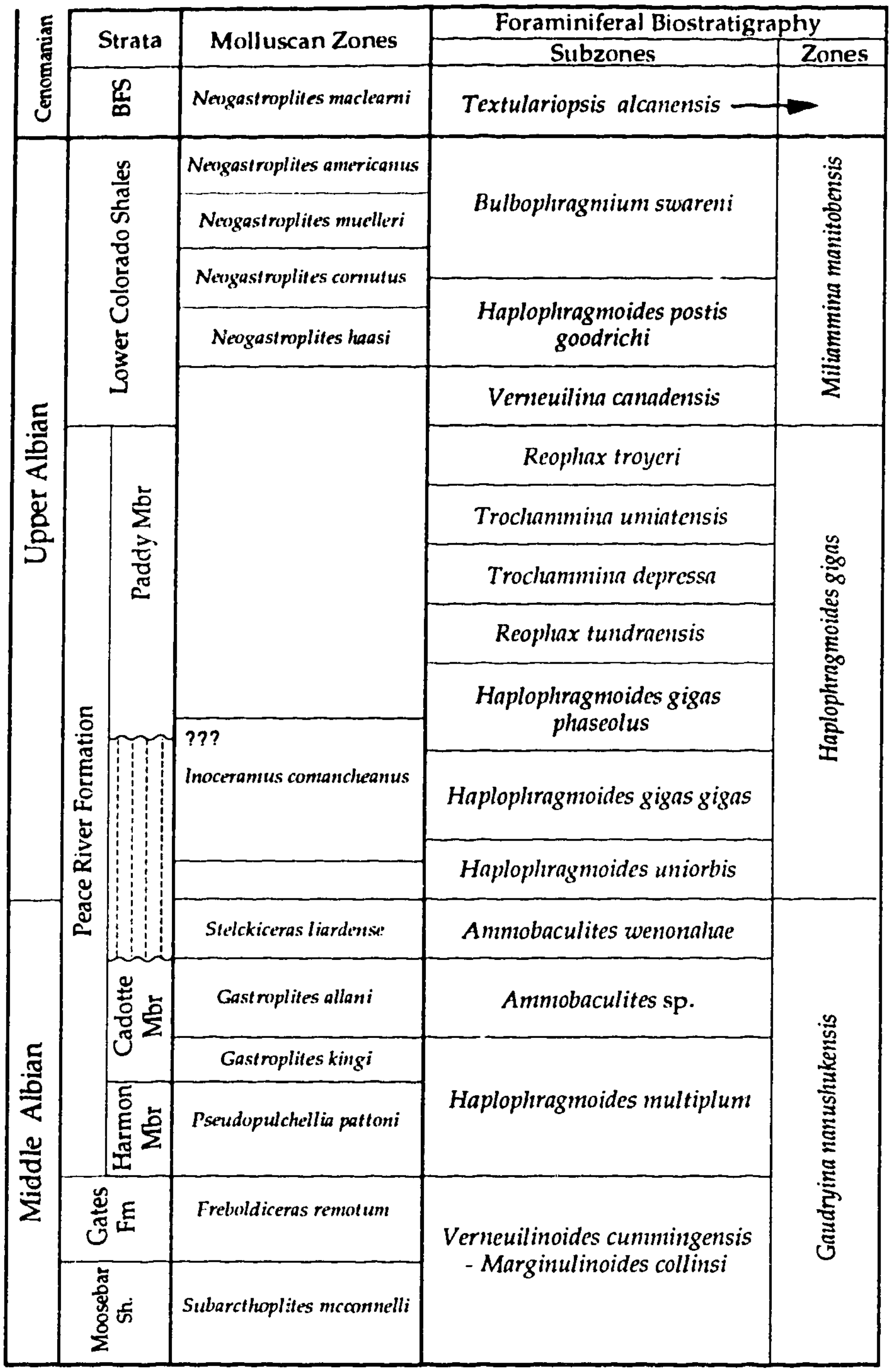


Figure VI-4. Correlation of Molluscan Zones and Foraminiferal Zones/ Subzones within the Albian, and its relationship to the Peace River Formation. BFS refers to the Base of Fish Scales Marker [modified from Stelck (1991) and Stelck (pers. comm., 1993)].

earlier Fort St. John cycles is the repeated confinement of shoreface progradation to a narrow, relatively stable, low subsidence shelf, bounded by an abrupt linear seaward hingeline. Northward of this hingeline lay the foredeep of the basin (Jackson, 1984). The same basic shelf-slope configuration carried through into Cadotte time. Cadotte deposition, however, was clearly preceded by a period of minor basinal adjustment. The hingeline governing the position of the shelf edge shifted northward and assumed a southwest-northeast linear position coincident with the inferred southern margin of the Fort St. John Graben (Barclay *et al.*, 1990; O'Connell *et al.*, 1990). This resulted in a pronounced increase in the breadth of the shelf and enabled the Cadotte shoreline to prograde an enormous distance before encountering and terminally faltering along this unstable edge (Figure VI-3). The eastern and southern limits of the Cadotte Member is also interpreted as a combination of an erosional and depositional edge (Leckie *et al.*, 1990).

The Cadotte Member is equivalent to the lower Boulder Creek Formation (Stott, 1968, 1982; Figure VI-1), and carries an arenaceous foraminiferal assemblage constituting the *Ammobaculites* sp. subzone of the *Gaudryina nanushukensis* Zone (Stelck and Leckie, 1988; Figure VI-3). The Cadotte is locally gradationally overlain by subsurface equivalents of the Walton Creek Member of the upper Boulder Creek Formation (*cf.* Stott, 1990; Gibson, 1992) in the west and southwest portions of the study area, and disconformably by the Paddy Member of the Peace River Formation in the north central portion of the study area (*i.e.* the Peace River area). The Walton Creek Member consists of largely terrestrial deposits with numerous internal diastems, possibly corresponding to an interval encompassing the *Ammobaculites wenonahae* subzone of the *Gaudryina nanushukensis* Zone, to at least the *Reophax tundraensis* subzone of the *Haplophragmoides gigas* Zone (*cf.* Figure VI-4), and possibly as much as to the end of the *Reophax troyeri* subzone of the *H. gigas* Zone (Stelck and Leckie, 1990a,b). In northeastern British Columbia, a second major progradational cycle is manifest by the upper Boulder Creek, reflecting a northward shift of a shoreline during *Reophax tundraensis* subzone time. The disconformity separating the Cadotte and Paddy members west of the Peace River area (Figure VI-1) may extend from the *A. wenonahae* subzone of the *G. nanushukensis* Zone to *V. canadensis* subzone of the *M. manitobensis* Zone (Stelck and Leckie, 1990a).

The Paddy Member is regarded to be homotaxially equivalent to the Walton Creek Member of the Boulder Creek Formation (Stelck and Leckie, 1990b; Gibson, 1992), as well as to the Viking Formation (Leckie, 1988; Leckie *et al.*, 1990; Leckie and Reinson, in press). Samples of shales collected from the Paddy Member in the Goodfare area (Tp 71-72, R 11-12W6) indicate that they carry arenaceous foraminifera of the *Verneuilina canadensis* subzone of the *Miliammina manitobensis* Zone (Stelck and Leckie, 1990a). In this locality, a total of 8 foraminiferal subzones, including the entire *Haplophragmoides gigas* Zone are missing, where the Paddy Member directly overlies the Cadotte Member. Further towards the east, the Paddy Member may be older, corresponding to the *Reophax tundraensis* subzone, indicating a Paddy-Cadotte unconformity encompassing four foraminiferal subzones (Figure VI-4). In the type section of the Paddy Member, *Inoceramus comancheanus* has been recovered, indicating that initial deposition may be as early as Joli Fou time (Stelck, pers. comm., 1994). Locally, upper portions of the Walton Creek Member may be contemporaneous with early stages of Paddy Member deposition. The Paddy Member is transgressively overlain by heterolithic siltstones, very fine-grained sandstones and shales of the basal Shaftesbury Formation. Recently, Bloch *et al.* (1993) have suggested that the basal Shaftesbury, extending from the top of the Peace River Formation to the Fish Scales Zone, be termed the Westgate Formation.

FACIES ASSOCIATIONS OF THE HARMON-CADOTTE PROGRADATIONAL SUCCESSION

The Harmon and Cadotte members of the Peace River Formation reflect a complete offshore to foreshore progradational succession, capped by a thin, laterally variable backshore interval, generally regarded to be of the Paddy Member. Following the general depositional models established by Ethier (1982), Smith *et al.* (1984) and Rahmani and Smith (1988), the succession in the study area is interpreted as a high energy, wave/storm-dominated shoreline succession. The model presented here, however, differs from previous ones in the recognition of a greater deltaic influence. In this section of the paper the facies comprising the succession are grouped into facies associations, and are described and interpreted in ascending stratigraphic order. The integration of the ichnology with the sedimentology greatly refines the interpretation of the facies associations and the shoreface morphodynamic state.

Offshore Transition (Upper Harmon Member): Facies Association 1 (FA1)

The most comprehensive work written on the Harmon Member has been by Bloch (1989, 1990) who described the facies, trace fossils and sulphide diagenesis. Leckie *et al.* (1990) mapped the isopach distribution of the Harmon Member and described the facies character in general. Leckie (1988) briefly described the Harmon Member from the outcrop in the Peace River area. Smith and Rahmani (1988) and Moslow and Pemberton (1988) described the sedimentology and ichnology of the transitional facies between the Harmon and the Cadotte members; both considered these beds as basal Cadotte, rather than as the Harmon.

Bloch (1990) described three main facies types from the Harmon Member. The dominant facies consists of well laminated, virtually unburrowed mudstones, which he interpreted as reflecting slow sedimentation beneath anoxic waters, in a neritic environment, lying well below storm weather wave base.

The second facies consists of interbedded conglomerate and mudstone, representing slow, neritic deposition, punctuated by high energy, episodic deposition of coarse clastics, believed to be derived from the basin margin. Wells containing this facies occur in the vicinity of Tp 80, near the British Columbia-Alberta border.

The final facies, and the only one encountered in cores of the thesis area, consists of interbedded fine- to very fine-grained sandstone, siltstone and shale (*cf.* the laminated to burrowed facies of Bloch, 1990). This facies corresponds to descriptions of the Harmon in outcrop by Leckie (1988), and to basal Cadotte facies of Smith and Rahmani (1988) and Moslow and Pemberton (1988). This interbedded facies occurs both at the base of the Harmon Member, where it overlies the Notikewin Member of the Spirit River Formation, as well as at its top where it grades into the Cadotte Member (Bloch, 1989; 1990). Only this latter context applies to the ongoing discussion.

Sedimentology

Although regarded as a single facies by Bloch (1989; 1990), the Harmon Member, as intersected in cores of the thesis area, actually consists of three distinct facies (Figure VI-5) which comprise a single facies association (FA1).

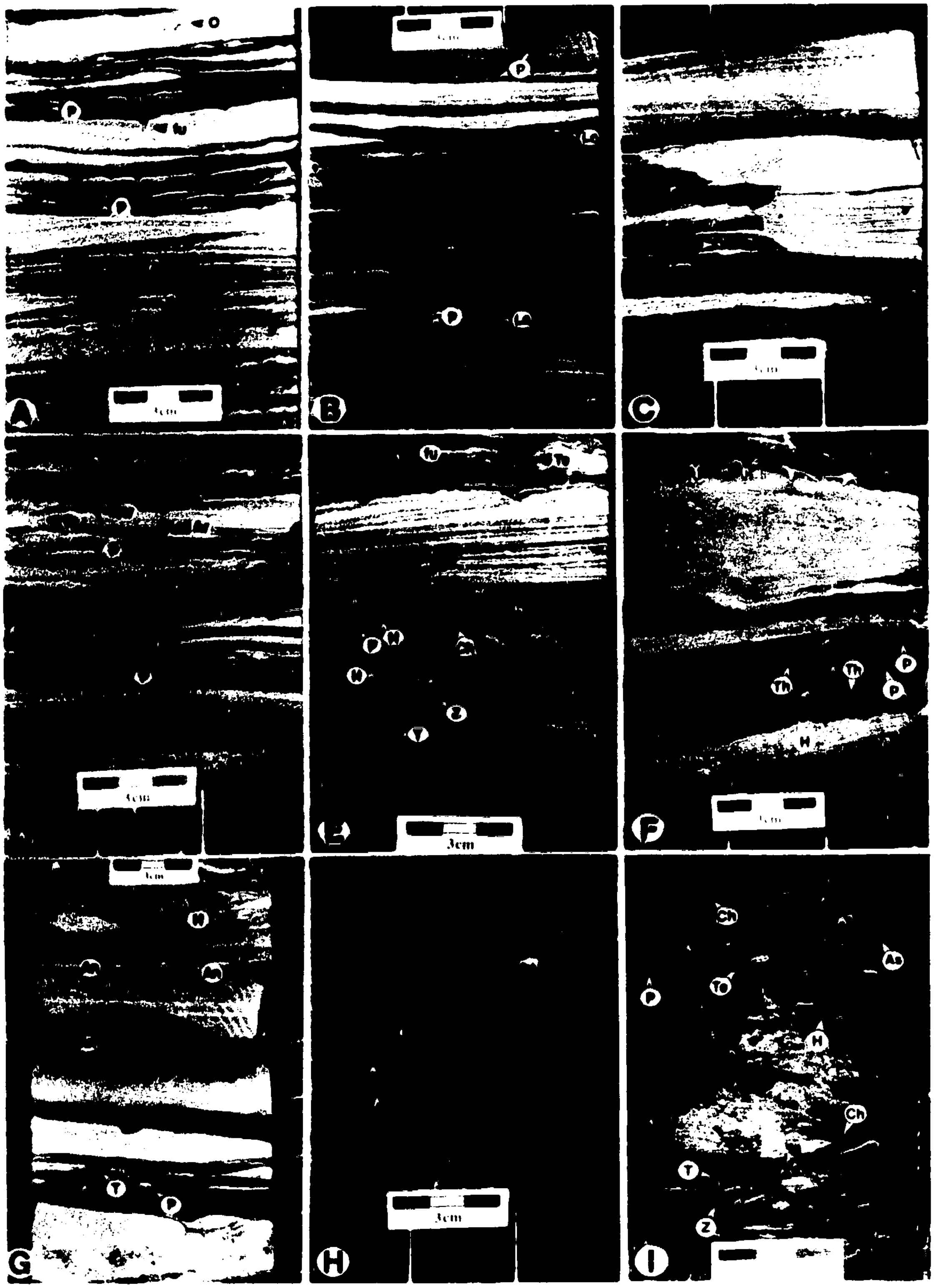
The sandstone facies is characterised by 1-20 cm thick and generally 2-5 cm thick beds, and are typically vfU-fL (3.5-2.5ø) in grain size. Most beds are normally graded, passing upwards into siltstone beds. Sandstone beds generally have sharp, erosional bases and gradational tops, demonstrating episodic emplacement of waning flow events. Some sandstone beds have small-scale gutter casts at the base (Figure VI-5 C). Stratification occurs at the scale of lamina, and is characterised by low angle (<15°) parallel lamination and oscillation ripple lamination. No current ripple lamination was observed, and only very rare combined flow ripple lamination was noted. Carbonaceous detritus (finely comminuted plant debris; *cf.* Buller and Green, 1976), disseminated pyrite, siderite rip-up clasts of intraformational derivation, sideritic nodules and glauconite are accessories of diminishing importance.

The siltstone facies occurs both as the normally graded tops of sandstones beds and as sharp-based beds. In most regards, the character of discrete siltstone beds is similar to the sandstone beds. Bed thicknesses tend to range from 0.5-3.0 cm and typically 1.0-2.0 cm. Grain sizes are finer than 4ø. Stratification is almost exclusively low angle (<15°) parallel lamination, although oscillation ripple lamination is also encountered locally. Carbonaceous detritus is commonly intercalated.

The mudstone facies generally occurs as 0.5-5.0 cm thick beds. The facies is evident either as fissile, dark, organic-rich, sand-poor beds which sharply overlies sandstone or siltstone beds, or as very silty, medium to light grey coloured beds, grading out of some siltstone beds. Pyrite is most common within the dark, fissile shales, but may also occur within the silty mudstones. Sideritic nodules are sporadically distributed throughout this facies, both as incipiently-cemented zones and as displacive nodules.

The succession is generally characterised by a progressive upward increase in frequency and thickness of sandstone beds, as the Harmon grades into the Cadotte. Superimposed upon the primary physical structures of these facies are a variety of penecontemporaneous deformational features, including

Figure VI-5. FA1: Offshore Transition (Harmon Member).
(A) Thin tempestites interbedded with mudstones related to post-storm suspension fallout. Biogenic disturbances are low, with fugichnia (fu) and *Ophiomorpha irregulaire* (O) present. Mudstone beds contain sparse *Planolites* (P). Well 10-11-69-09W6, depth 1815.7 m. **(B)** Interlaminated tempestites and post-storm mudstones. Most storm beds are normally graded. Oscillation ripple laminated bed near the base shows offshoot laminae. Trace fossils are *Lockeia* (Lo) and *Planolites* (P). Well 10-11-69-09W6, depth 1817.8 m. **(C)** Tempestite with a small gutter cast. Thinner tempestites show normal grading into the post-storm mudstones. Trace fossils are mainly limited to *Planolites* (arrows). Well 10-11-69-09W6, depth 1815.8 m. **(D)** Thinly interstratified, normally graded tempestites and silty mudstones. Several zones show small oscillation ripple lamination, particularly towards the top of the core. Burrows include *Teichichnus* (Te), small *Arenicolites* (Ar) and *Planolites* (P). Well 10-11-69-09W6, depth 1819.2 m. **(E)** Tempestites, interstratified with thoroughly burrowed silty to sandy shales. The tempestites contain fugichnia (fu) and *Teichichnus* (Te). The silty to sandy shales display *Helminthopsis* (H), *Chondrites* (Ch), *Planolites* (P), *Zoophycos* (Z) and *Terebellina* (T). Well 10-16-69-11W6, depth 2002.0 m. **(F)** Tempestites interbedded with pyritic dark mudstone. The upper sandstone is also strongly pyritised. Trace fossils include small *Thalassinoides* (Th), *Planolites* (P) and *Helminthopsis* (H). Well 11-01-70-13W6, depth 2035.9 m. **(G)** Siderite-cemented mudstone pebble lag at the base, overlain by normally-graded tempestites. Trace fossils include *Planolites* (P), *Helminthopsis* (H), *Anconichnus horizontalis* (An) and *Terebellina* (T). Well 10-11-69-09W6, depth 1813.0 m. **(H)** Siderite-cemented mudstone pebble and sideritic nodule lag, containing a sand matrix. Facies constitutes one of the anomalous facies of FA1. Clasts are interpreted as intraformational in derivation. Well 09-10-66-10W6, depth 2436.5 m. **(I)** Thoroughly burrowed sandy shale containing a diverse trace fossil suite of *Chondrites* (Ch), *Helminthopsis* (H), *Teichichnus* (Te), *Asterosoma* (As), *Terebellina* (T), *Planolites* (P) and *Zoophycos* (Z). The facies constitutes one of the anomalous facies of FA1. Well 11-01-70-13W6, depth 2035.5 m.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convolute lamination, loading structures, dewatering structures and small-scale gravity faults.

In addition to the three main facies of FA1, two anomalous facies also occur, although in relatively few intervals. In some successions, subangular to subrounded, intraformationally-derived siderite-cemented mudstone clasts form thin (<10 cm) zones of shale clast breccia (Figure VI-5 G, H). The other facies occurs in a single cored interval, and is characterised by a 75 cm thick bed of thoroughly burrowed sandy shale (Figure VI-5 I).

Ichnology

The trace fossil assemblage of FA1 is generally characterised by moderate to high diversity, but with a highly sporadic distribution, and low burrowing intensity. Trace fossils include *Helminthopsis* (r-m), *Anconichnus* (r-m), *Zoophycos* (vr), *Planolites* (m-c), *Chondrites* (r), *Teichichnus* (m), *Thalassinoides* (r), *Lockeia* (r-m), *Terebellina* (vr-r), *Palaeophycus* (r), *Cylindrichnus* (r), *Skolithos* (r-m), *Arenicolites* (r) and fugichnia (m-c).

The dominant elements record the typical character of ecological stresses imparted by episodic depositional events (*cf.* Pemberton *et al.*, 1992b). Fugichnia (escape traces) record the disturbance by animals entrained within, or buried by the flow, as they seek to reach the sediment-water interface. *Helminthopsis, Anconichnus, Planolites* and *Teichichnus* record the re-establishment of grazing and deposit feeding infauna following the event, and typically occur near the tops of beds or within the mudstones capping the coarser clastic beds. Lesser numbers of *Chondrites, Cylindrichnus, Lockeia, Thalassinoides* and *Zoophycos* reflect a mixture of ethologies, although grazing and stationary deposit feeding appears to be the predominant behaviours. The general absence of suspension feeding structures suggests that most sandstone beds were quickly buried by silts and muds following the depositional event, precluding colonisation by organisms favouring sandy substrates. This suggests either suspension fallout of fine-grained sediment closely associated with the episodic event and/or generally high sedimentation rates. The low abundance of fairweather burrowing between event beds supports the interpretation of minimal time available for biogenic disturbances. This, coupled with the large numbers of thin sandstone and siltstone beds in the upper Harmon suggests high frequency emplacement of these short-lived depositional events.

In contrast to the bulk of FA1, the shale-clast breccia anomalous facies are entirely devoid of trace fossils, while the thoroughly burrowed sandy shale anomalous facies contain both a high diversity and a high abundance of trace fossils. This latter anomalous facies (Figure VI-5 I) displays intense degrees of burrowing with *Helminthopsis* (m-c), *Anconichnus* (m), *Zoophycos* (r), *Chondrites* (c), *Planolites* (c-a), *Asterosoma* (r-m), *Teichichnus* (m), *Terebellina* (m), *Thalassinoides* (r-m), *Cylindrichnus* (r) and *Palaeophycus* (r-m). The thorough degree of burrowing, with a high diversity of forms seems to indicate a cessation in the frequency of storms and prolonged fairweather conditions, permitting intense biogenic reworking of the sediment.

Interpretation of FA1

The transitional facies of the Harmon Member are interpreted as lower offshore to upper offshore deposits, lying seaward of the progradational Cadotte shoreline. The primary physical structures of the sandstones and siltstones are consistent with a distal tempestite (storm-bed) interpretation, in a setting lying seaward of fairweather wave base (*cf.* Pemberton and Frey, 1984; Aigner, 1985; Seilacher and Aigner, 1992; MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992b). Many of the tempestite beds record the waning stage of storm action on the substrate, characterised by normal grading, capping by oscillation ripple lamination, and suspension fallout of silts and muds following storm abatement. Penecontemporaneous deformation features are interpreted to record wave-induced liquefaction and dewatering of the bed, related to lowering of effective wave base and subsequent wave impact during storms.

Bloch (1989, 1990) suggested that the middle portion of the Harmon Member represented anaerobic conditions and that the upper Harmon represented dysaerobic conditions, in order to account for the observed pyrite morphology, pyrite distribution and sulphur isotopic values, in addition to the low diversity of trace fossils. Stelck and Leckie (1988) came to a similar conclusion for the Hulcross shales, although they restricted the reduced O_2 conditions to the deeper water sediments, which they attributed to poor circulation of a well-stratified water body. The shallower water deposits of the Hulcross and the Harmon contain large numbers of weakly to non-burrowed tempestites, demonstrating a high frequency of storm action in the offshore, which favours circulation and oxygenation of the water. In addition, the thoroughly burrowed sandy shale interval near the top of the Harmon Member in the 11-01-70-13W6 well (Figure VI-5 I) shows a suite of trace fossils, inconsistent with conditions of prolonged, unabated anoxia.

Moslow and Pemberton (1988) suggested that the upper facies of the Harmon (their basal Cadotte facies) reflected prodelta to distal delta front accumulations and attributed the low-diversity trace fossil suite to harsh ecological conditions related to increased water turbidity and fluctuating rates of deposition from suspension. They interpreted the event beds themselves to be flood-induced, although the primary sedimentary structures are more typical of storm-induced traction transport, than to delta front sediment gravity flows. Nonetheless, there is a close genetic association between storm events and enhanced flood discharge through rivers and distributaries reaching the coast, since storms are commonly associated with high rates of precipitation. Samples collected for foraminiferal analysis from the dark, fissile shale beds in the upper Harmon Member show low numbers of microfossils, low silt and sand contents, and high amounts of detrital organic material, supporting an interpretation of rapid deposition of post-storm suspended fines (*cf.* Allen, 1982; Massari and Parea, 1988; Leithold, 1989). Low burrow intensities may also reflect this rapid, though sporadic, accumulation of fines. Leithold (1989) studied the shelf lying offshore of the Eel River, northern California, and compared it to the analogous Pleistocene Rio Dell Formation of northern California. She concluded that river flood events play an important role in fine sediment accumulation in the offshore, even along high energy, storm-dominated coasts. The high sedimentation rates and rapid suspension fallout of fines in the upper Harmon Member is consistent with prodelta to distal delta front environments, suggesting that in the study area, the Harmon/Cadotte transition may have accumulated in a rapidly prograding, strongly storm-dominated delta setting, rather than in a purely accretionary strandline system. It is interesting that FA1 sediments are remarkably similar to basal facies of progradational wedges in the Dunvegan Formation in the subsurface of Alberta (Bhattacharya, 1989; Bhattacharya and Walker, 1991) and in the Belly River Formation at Lundbreck Falls (Lerand and Oliver, 1975), both interpreted as storm- to wave-dominated delta settings.

CADOTTE MEMBER: SHOREFACE TO BEACH SUCCESSION

The Cadotte Member has been described from the outcrop area near Peace River town, Alberta (Leckie, 1988, 1990), in the subsurface of Alberta (Ethier, 1982; Smith *et al.*, 1984; Moslow and Pemberton, 1988; Smith and Rahmani, 1988; Leckie *et al.*, 1990), and in the subsurface of British Columbia (Hayes, 1988). The stratigraphically equivalent Lower Boulder Creek Formation has been described from outcrop in the foothills of northeastern British Columbia (Gibson, 1992).

Subsurface cores within the study area show the Cadotte Member to consist of 5 main facies, arranged into two discrete facies associations. The two facies associations are separated from one another, in most cases, by a pronounced scour surface, across which a fundamental change in facies character and depositional conditions occurs.

Storm-Dominated Lower to Middle Shoreface: Facies Association 2 (FA2)

Sedimentology

Facies Association 2 (FA2) constitutes the basal portion of the Cadotte Member, and grades out of FA1 of the Harmon Member. FA2 consists of 3 interstratified facies (Figures VI-6 and VI-7).

The first facies consists of low angle parallel laminated sandstone, and dominates FA2. The sandstone occurs in beds 10-50 cm in thickness but are more typically erosionally amalgamated into bedsets up to 10 m in thickness. The sand is well-sorted within each bed; grain sizes may range from vfU-fU (3.5-2.0ø) but within each bed typically remain within 0.5ø (*i.e.* generally one grain size division). Rare beds may be mL (2.0-1.5ø) in grain size. Carbonaceous detritus is common and typically marks lamination. Glauconite is present, though rare. Siderite-cemented nodules are locally present as intraformational rip-up clasts (Figure VI-6 F, G). Despite their nodule-like shapes, not all of these clasts originate as intrastratally-formed nodules and concretions. Closer inspection reveals many to comprise the sideritised "cores" of the trace fossil *Rosselia* and more rarely, *Asterosoma*. Other burrow fragments constituting clasts include mud-lined segments of *Palaeophycus tubularis* and more commonly, minute, quartz grain agglutinated *Terebellina* tubes (Figure VI-6 D, F, G), typically less than one or

Figure VI-6. FA2: Tempestite Physical Structures in the Lower to Middle Shoreface (Cadotte Member). (A) Low angle parallel laminated, fine-grained sandstone with intervening dark mudstone near the base of FA2. The sandstones are interpreted as tempestites, with the dark mudstone interpreted as post-storm suspension fallout deposits. Trace fossils in the mudstones consist mainly of *Planolites* (arrows). Well 11-01-70-13W6, depth 2037.9 m. **(B)** Truncation surface, overlain by subparallel lamination, which decreases in inclination upwards. The stratification is consistent with HCS, SCS or QPL. Well 06-06-64-25W5, depth 1913.4 m. **(C)** Low angle, undulatory parallel to subparallel laminated sandstone, passing into aggradational combined flow ripple lamination. The stratification is interpreted to reflect tempestite deposition, capped by waning flow stage ripples. The top of the succession is truncated by an overlying tempestite, as a result of erosional amalgamation. Well 07-08-64-02W6, depth 2125.9 m. **(D)** Low angle parallel to subparallel laminated sandstones, showing low angle truncation surfaces. Note that overlying laminae are parallel to subparallel to underlying truncation surfaces. A few ?allochthonous *Terebellina* (arrows) fragments are intercalated within the sandstone. Well 07-10-63-01W6, depth 2183.8 m. **(E)** Low angle parallel laminated sandstone, with well-developed fugichnia (arrows). Well 07-08-64-02W6, depth 2125.7 m. **(F)** Low angle parallel laminated sandstone with siderite-cemented mudstone rip-up clasts and probable ?allochthonous *Terebellina* (arrow) fragments. Well 07-10-63-01W6, depth 2189.5 m. **(G)** Stacked, thinly bedded tempestites, with relatively abundant mudstone rip-up clasts (r) and sideritic nodules (s). Ripple laminated waning flow deposits near the base contain *Terebellina* (T), and are truncated by overlying sandstones. Well 10-16-69-11W6, depth 1998.2 m. **(H)** Parallel laminated sandstone interpreted as a tempestite, with small pebbles and granules of chert and other lithic fragments. Well 07-26-68-09W6, depth 1894.7 m. **(I)** Parallel laminated sandstone with chert and lithic pebbles and granules, interpreted as a tempestite. Note the well-developed truncation surface near the lower third of the photo. Well 10-11-69-09W6, depth 1804.7 m.

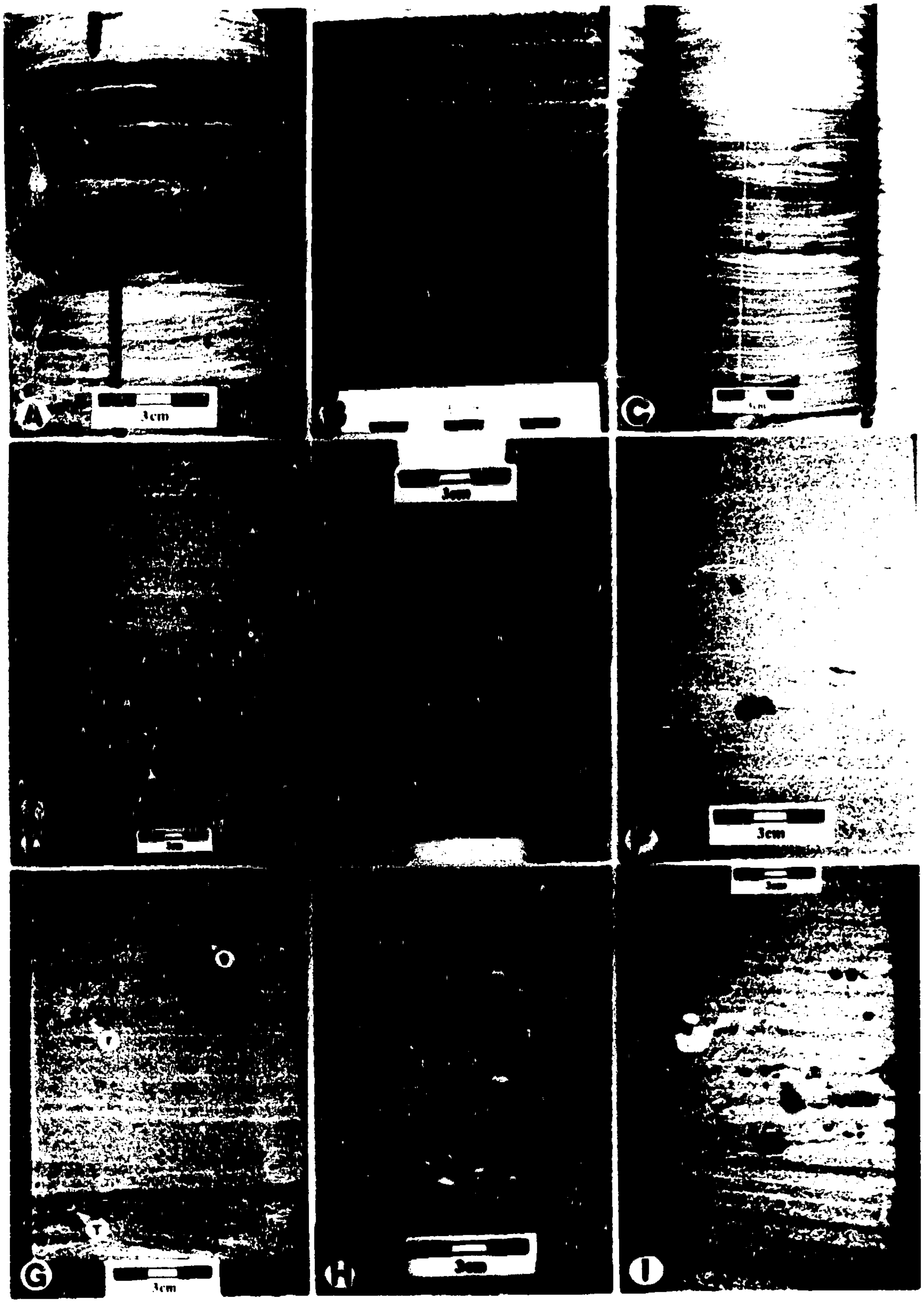
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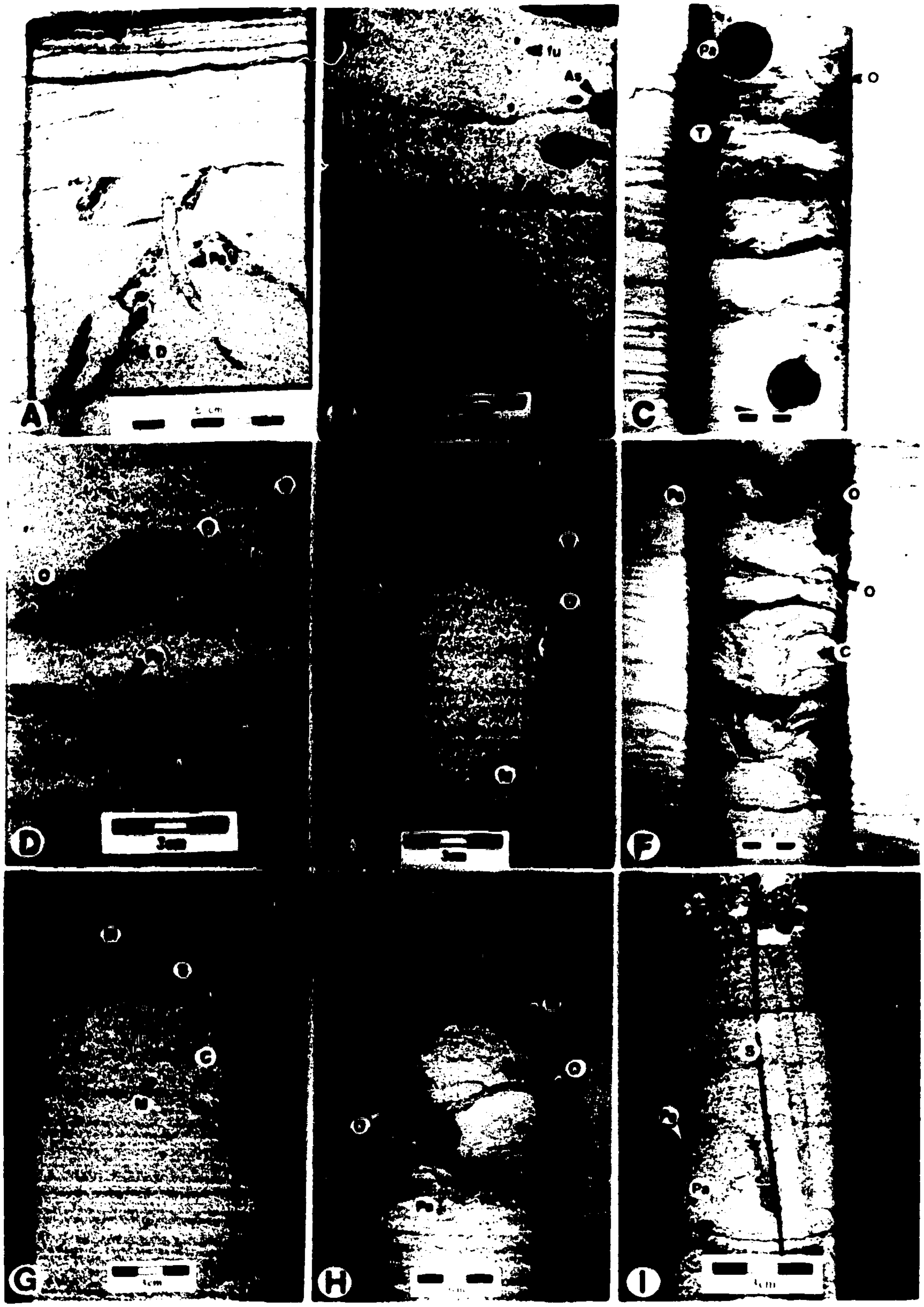
Figure VI-7. FA2: Burrowed Zones Interstratified With Tempestites in the Lower-Middle Shoreface (Cadotte Member). (A) Parallel laminated sandstone with *Palaeophycus* (Pa) and *Diplocraterion* (D), marking opportunistic colonisation of the storm bed, truncated by oscillation ripple laminated sandstone. Well 08-35-62-03W6, depth 2336.0 m. **(B)** Laminated sandstone with abundant mudstone rip-up clasts and probable ?allochthonous *Asterosoma* (As). Fugichnia (fu) is present in the upper tempestite. Well 07-26-68-09W6, depth 1892.7 m. **(C)** Laminated tempestite sandstone near the base grades upwards into thoroughly burrowed muddy sandstone. Visible biogenic structures include *Palaeophycus* (Pa), *Terebellina* (T) and *Ophiomorpha* (O). Interval reflects post-storm opportunistic colonisation of the substrate, possibly overprinted by a fairweather suite. Well 10-26-66-11W6, depth 2374.3 m. **(D)** Burrowed zone within tempestite with heavily-lined, siderite-cemented *Ophiomorpha nodosa* (O) and *Palaeophycus* (Pa). Well 10-16-69-11W6, depth 1900.8 m. **(E)** Parallel laminated fine-grained sandstone, interpreted as a tempestite, containing well-developed, heavily-lined, siderite-cemented *Ophiomorpha nodosa* (O). Note the fugichnia (fu) in the laminated sandstone. Well 10-11-69-09W6, depth 1803.6 m. **(F)** Laminated sandstone near the base of the photo, grading upwards into thoroughly burrowed muddy sandstone. The burrowed zone contains a well-developed *Conichnus* (C), with *Palaeophycus* (Pa) and *Ophiomorpha* (O). Interval reflects post-storm opportunistic colonisation of the substrate, overprinted by a fairweather suite. Well 06-25-69-09W6, depth 1708.5 m. **(G)** Laminated tempestite sandstone, grading into thoroughly burrowed muddy sandstone containing dispersed chert pebbles and granules. Trace fossils include *Conichnus* (C), *Skolithos* (S) and *Macaronichnus* (M). Interval reflects post-storm opportunistic colonisation of the substrate, overprinted by a later fairweather suite. Well 10-11-69-09W6, depth 1802.3 m. **(H)** Laminated tempestite sandstone near base, grading upwards into thoroughly burrowed, muddy sandstone. Burrowed zone contains *Palaeophycus* (Pa), *Ophiomorpha* (O), *Macaronichnus* (M) and *Planolites* (P). Interval reflects post-storm opportunistic colonisation of the substrate, with possible initial development of a fairweather suite. Well 06-25-69-09W6, depth 1711.4m. **(I)** Laminated tempestite sandstone near the base, containing a preserved remnant of an opportunistic suite consisting of *Skolithos* (S) and *Palaeophycus* (Pa). The upper portion of the suite has been truncated by pebbly sandstones of the overlying upper shoreface complex (FA3). Well 05-15-73-13W6, depth 1670.0 m.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two millimetres in diameter. As also noted by Bloch (1990), diffuse siderite cement is locally present within some sandstone beds, particularly where organic detritus is abundant. Chert pebbles and granules are locally dispersed throughout the facies and may also be present as thin, 1-2 pebble thick stringers. Pebble stringers are more common towards the top of FA2.

The sandstone beds are sharp-based and truncation bound. Truncation surfaces are of low inclination (typically <10°) with overlying laminae parallel to subparallel to lower set boundaries (Figure VI-6 B-D). Upwards, erosional amalgamation of the facies dominates, to the exclusion of the other facies; amalgamated bedsets of the laminated sandstones may reach 10 m in thickness. Isolating discrete storm events generally proved to be impossible, owing to the lack of criteria capable of differentiating first-order set boundaries from second-order internal truncation surfaces. Stratification is dominated by low angle (<15°), gently undulatory parallel laminae and low angle planar laminae. Oscillation and combined flow ripple lamination may be preserved locally (Figure VI-6 C), but are uncommon and absent in amalgamated intervals. In a few rare instances, laminae may acquire a vague convex-upward configuration. Penecontemporaneous deformation structures are relatively uncommon, but are locally present as convolute bedding, dewatering structures, and less commonly, micro-faulting.

The second facies of FA2 consists of dark, fissile, organic-rich mudstone beds, locally with thin (<2 cm) fine-grained sandstone stringers (Figure VI-6 A). The shale interbeds are sharp-based and range from 1-10 cm in thickness. In a few localities, sand-filled syneresis cracks may penetrate from sandstone interbeds into the underlying shale. Finely comminuted plant debris, siderite cement, siderite-cemented nodules and/or pyrite may be locally abundant. Sandstone stringers are well-sorted with low angle parallel lamination The shale facies is a minor component of FA2, and is more common towards the base, where it grades out of FA1 of the Harmon Member.

The final facies consists of moderately to thoroughly burrowed variably muddy sandstone (Figure VI-7). Organic detritus is also typically abundant within the facies, imparting a darker colour to the sandstone. The sandstone is moderately-sorted, with sand grain size ranging from vfU to mL (3.5-1.5ø), but typically vfU-fU (3.5-2.0ø). Interstitial silt and mud content may locally be abundant. The facies occurs in intervals 5-25 cm in thickness. Glauconite, pyrite and rarer siderite may also be present. The facies typically has a gradational base, passing upwards out of the parallel laminated sandstone facies, and is generally truncated at the top by overlying parallel laminated sandstone, or by a sharp erosional discontinuity separating FA2 from FA3. Primary physical structures are largely obliterated by biogenic activity, with remnant parallel laminae visible in less thoroughly burrowed intervals. This facies is the least common of the three facies and occurs sporadically throughout FA2. Instead, the only stratigraphic level within the Cadotte succession where this facies is recurrently present is at or near the very top of the amalgamated parallel laminated sandstone beds of FA2, in close proximity to the contact with the overlying FA3 (*e.g.* Figure VI-7 I).

Ichnology

The ichnological record of FA2 is poorly recorded in the succession. Burrowing is typically of low intensity and sporadic in distribution; zones of burrowing are commonly separated by thick intervals of largely unburrowed, erosionally amalgamated parallel laminated sandstone facies.

The trace fossil assemblage observed within the parallel laminated sandstone facies consist mainly of fugichnia (r-m), *Teichichnus* (r), *Macaronichnus simplicatus* (r), *Terebellina* (r-m), *Palaeophycus* (r), *Ophiomorpha nodosa* (r-m), *Arenicolites* (vr-r), and *Skolithos* (r). The bulk of these ichnogenera are recorded near the base of FA2, where erosional amalgamation is less pronounced and oscillation ripple and combined flow ripple lamination is locally preserved. As erosional amalgamation becomes more common, only fugichnia remains as a dominant element to the assemblage (Figure VI-6 E), with only rare to very rare numbers of deeply penetrating structures such as *Ophiomorpha nodosa*, *Arenicolites* and *Skolithos* observed. Otherwise, the only surviving clue as to the composition of trace fossil associations that existed "nearby" consists of transported lag-forming burrow fragments (*e.g. Rosselia*, *Asterosoma*, *Palaeophycus tubularis* and *Terebellina*).

The shale facies interbedded near the base of FA2 are largely devoid of biogenic structures (Figure VI-6 A), typically restricted to rare to very rare numbers of *Planolites*, *Terebellina*, *Teichichnus* and lesser *Helminthopsis*. Trace fossils are typically small in size.

The thoroughly burrowed muddy sandstone facies contains common to abundant degrees of burrowing (Figure VI-7), dominated by *Ophiomorpha* *irregulaire* (c), *Palaeophycus* (m-c), and *Terebellina* (c), *Ophiomorpha nodosa* (m), *Diplocraterion* (r-m), *Arenicolites* (r), *Skolithos* (r-m), *Conichnus* (r-m), *Teichichnus* (m), *Macaronichnus simplicatus* (m) and *Rosselia socialis* (m).

Interpretation of FA2

The facies of FA2 are interpreted to reflect tempestite accumulation within a lower to middle shoreface setting, which prograded northward over offshore deposits of the Harmon Member (FA1). All preserved primary physical sedimentary structures observed in FA2 are attributable to oscillatory or oscillatory-forced processes. The low angle parallel laminated sandstones are interpreted to represent hummocky cross-stratification (HCS; *cf.* Dott and Bourgeois, 1982; Duke, 1985), swaley cross-stratification (SCS; *cf.* Leckie and Walker, 1982) or quasi-planar lamination (QPL; *cf.* Arnott, 1993). Differentiating between the three stratification types in core is largely impractical. In general, bedsets containing convex-upward lamination are regarded as HCS, whereas erosionally amalgamated bedsets are interpreted as SCS or QPL. In any case, the parallel laminated sandstones and thus, the bulk of FA2 are interpreted to record storm bed deposition at and above storm weather wave base. Penecontemporaneous deformation features are attributed to storm wave-induced liquefaction. The occurrence of escape traces within the storm beds records the presence of animals entrained within or buried by the event bed, which attempt to regain the new sediment-water interface. The erosional amalgamation of successive tempestites accounts for the paucity of biogenic structures (Figure VI-8); only the remnants of deeply penetrating *Ophiomorpha nodosa*, *Arenicolites* and *Skolithos* burrows are preserved from the opportunistic and resident fairweather suite (*cf.* Pemberton and Frey, 1984; Pemberton *et al.*, 1992a,b).

The weakly burrowed organic-rich shale beds interstratified with the tempestites record post-storm suspension fallout of fines, possibly associated with contemporaneous flood-water discharge from channels or distributaries debouching at the shoreline (*cf.* Allen, 1982; Massari and Parea, 1988; Leithold, 1989), analogous to those found in FA1 of the Harmon Member. The upward diminishment of these shale beds and progressive increase in tempestite erosional amalgamation corresponds to shallowing and enhancement of the erosive capacity of the storms. The paucity of burrowing in the dark, fissile shale facies may point to a combination of rapid deposition and rapid development of reducing conditions due to the abundant organics contained within the mud (Pearson and Rosenberg, 1978). The traces observed within this facies correspond to grazing and deposit feeding behaviours, reflecting low energy conditions and presence of deposited food. The lack of deeply penetrating structures may be related to an elevated eH zone due to the reducing conditions, inhibiting infaunal colonisation.

The only true record of fairweather conditions in the lower and middle shoreface is recorded in the least common facies of FA2. The thoroughly burrowed muddy sandstone facies which typically grade out of the parallel laminated sandstone facies represents the preservation of the top of the tempestite, and hence, the progressive, post-storm colonisation of that substrate. The details of tempestite colonisation are discussed in some detail by Pemberton and Frey (1984), Aigner (1985), Saunders and Pemberton (1986), Saunders (1989), MacEachern and Pemberton (1992), Pemberton *et al.* (1992 a,b).

Briefly, initial colonisation of the tempestite is afforded by opportunistic suites, dominated by suspension feeders, as well as by deeply penetrating dwelling structures (Pemberton and Frey, 1984; Vossler and Pemberton, 1988; Pemberton *et al.*, 1992 a,b) (Figure VI-8). The organisms colonise the sandy substrate and engage in faunal behaviours consistent with energy conditions *typically* associated with substrates dominated by sand accumulation. Since the event bed provides an *anomalous* substrate and such energy conditions are not consistently present, the opportunistic suite gradually dies off and are replaced by the resident fairweather fauna. The resident fauna correspond to the community that is adapted to the *prevailing* conditions found in the depositional setting. Similar alternating "event-post event" suites have been described from turbidite intervals as well as from tempestites (*e.g.* Seilacher, 1962; Crimes 1977; Crimes *et al.*, 1981). The opportunistic suite is analogous to the "doomed pioneer" faunas described by Föllmi and Grimm (1990).

The mottling of the upper portion of the tempestite imparts a laminated to burrowed or "lam-scram" appearance (Frey, pers. comm., 1991). Within this burrowed facies, *Ophiomorpha nodosa*, *Arenicolites*, *Skolithos*, *Diplocraterion* and *Conichnus* are interpreted as the remnants of the opportunistic assemblage. The fairweather community is dominated by *Teichichnus*, *Terebellina*, *Palaeophycus*, *Planolites*, *Ophiomorpha irregulaire*, *Rosselia*, and *Macaronichnus simplicatus*. This suite, which also occurs near

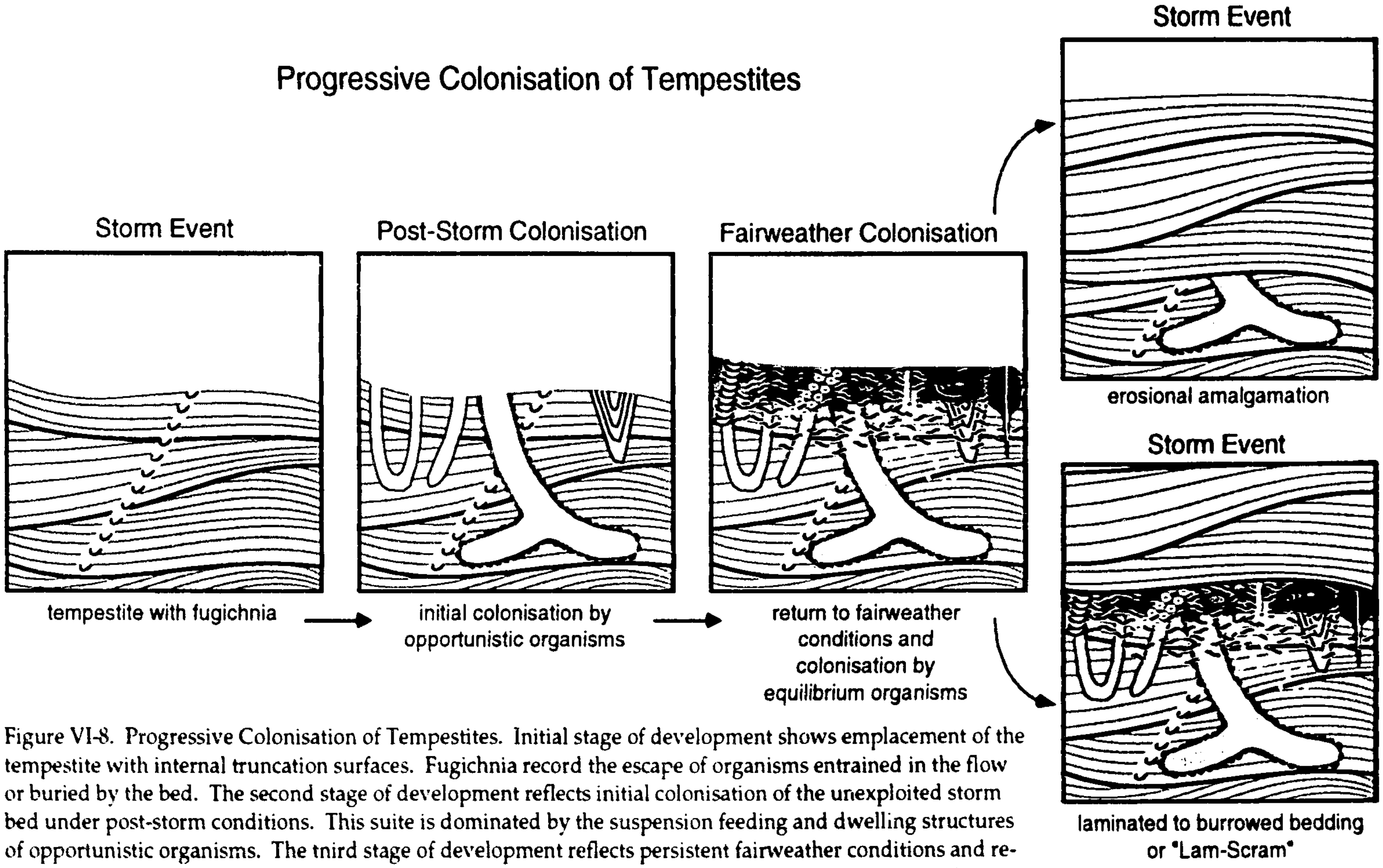


Figure VI-8. Progressive Colonisation of Tempestites. Initial stage of development shows emplacement of the tempestite with internal truncation surfaces. Fugichnia record the escape of organisms entrained in the flow or buried by the bed. The second stage of development reflects initial colonisation of the unexploited storm bed under post-storm conditions. This suite is dominated by the suspension feeding and dwelling structures of opportunistic organisms. The third stage of development reflects persistent fairweather conditions and re-establishment of the resident equilibrium community. Subsequent storm events may result in 1) complete or virtually complete removal of evidence of post-storm colonisation (some deeply penetrating structures and escape structures may survive) or 2) minimal erosional amalgamation of storm beds, preservation of the opportunistic storm suite, and ocally, partial preservation of the fairweather suite, producing "laminated-to-burrowed" bedding.

the top of FA2, reflects a dominance of deposit feeding and passive carnivore behaviour. This, coupled with the prevalence of deposit feeding and grazing structures observed within the shale interbeds supports a lower to middle shoreface setting (Figure VI-9).

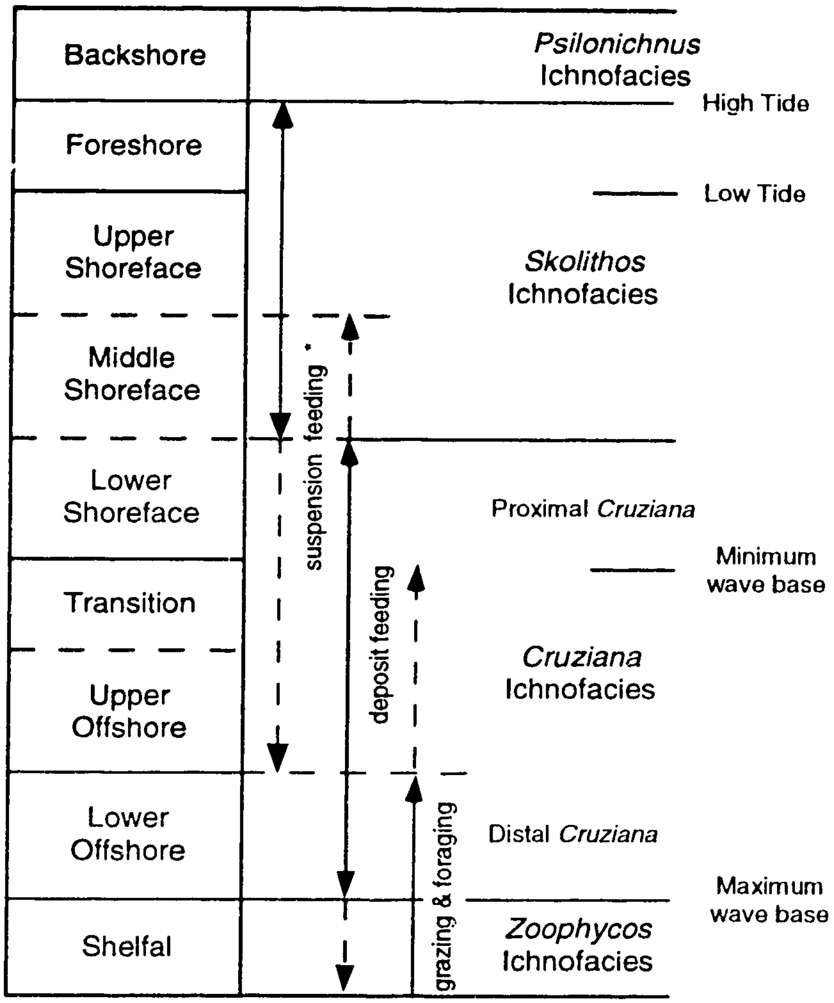
The high degree of storm dominance makes it exceedingly difficult to discern lower shoreface from middle shoreface deposits, since it is the fairweather trace fossil assemblage which characterises the two zones (Howard, 1972; 1975; MacEachern and Pemberton, 1992). Also, the greater the storm-dominated character, the deeper and further offshore storm-weather wave base is shifted. As a result, what may be regarded as "lower shoreface" deposits may actually have accumulated below fairweather wave base. The amalgamated nature of tempestite accumulation makes it virtually impossible to determine where fairweather wave base deposits are encountered. All of FA2 is regarded as "shoreface" despite the possibility that the base may actually lie offshore. Further, the strong degree of storm dominance on FA2 deposition largely precludes differentiation between a true strandline and a wave/storm-dominated delta; little non-storm physical and biogenic structures are preserved in the succession.

Upper Shoreface-Foreshore (Nearshore Complex): Facies Association 3 (FA3)

Sedimentology

Facies Association 3 (FA3) erosionally overlies FA2 in virtually all wells. The facies constituting FA3 are also far more variable in character than those in FA2. The association can be separated into 2 main facies, although each facies typically comprise a variety of subfacies ranging through a continuum of sandstones, pebbly sandstones and conglomerates (Figures VI-10 and VI-11). Many intervals display an interbedding of all three subfacies types.

The basal facies of FA3 consists of trough cross-stratified sandstones, pebbly sandstones and conglomerates (Figure VI-10) and is interpreted to reflect upper shoreface deposition. Virtually all variations in the facies are related to grain size and, where applicable, the proportion of clasts. Although the facies is dominated by trough cross-stratification, current ripple lamination is common, particularly within the sandstone component, while low angle and horizontal planar stratification becomes increasingly common in the more conglomeratic elements of the facies.



ICHNOLOGICAL-SEDIMENTOLOGICAL SHOREFACE MODEL

* Many tube dwellers are passive carnivores rather than suspension feeders.

Figure VI-9. Idealised shoreface model of ichnofacies successions, based on observation of Cretaceous strata of the Western Interior Seaway of North America (modified after Pemberton *et al.*, 1992a).

Figure VI-10. FA3: Trough Cross-Stratified Sandstones, Pebbly Sandstones and Conglomerates of the Upper Shoreface (Cadotte Member). (A) Stacked, small-scale trough cross-stratified sandstone beds. Well 10-11-69-09W6, depth 1796.3 m. **(B)** Parallel laminated sandstones, passing into trough cross-stratified sandstones near the middle shoreface/upper shoreface transition. Note the robust *Skolithos* (arrow) shaft. Scale is in centimeters. Well 11-25-64-07W6, depth 2042.1 m. **(C)** Trough cross-stratified sandstone with fugichnia (fu), *Skolithos* (S) and *Macaronichnus* (M). Well 07-10-63-01W6, depth 2169.3 m. **(D)** Trough cross-stratified sandstone with *Macaronichnus* (arrows). Well 07-26-68-09W6, depth 1888.9 m. **(E)** Trough cross-stratified sandstone with *Macaronichnus segregatis* (arrows). Well 10-11-69-09W6, depth 1795.4 m. **(F)** Trough cross-stratified sandstone showing foresets, truncated and overlain by toesets of an overlying trough cross-bedded sandstone. The sandstones contain *Macaronichnus segregatis* (arrows). Well 14-14-69-09W6, depth 1764.6 m. **(G)** Low angle planar bedded chert pebble conglomerate interstratified with trough cross-stratified pebbly sandstone of the upper shoreface complex. Well 08-02-66-09W6, depth 2366.0 m. **(H)** Trough cross-stratified pebbly sandstone in the upper shoreface. Despite the variability in grain size, note the well developed grain segregation, typical of the facies. Well 06-21-70-12W6, depth 1875.2 m. **(I)** Trough cross-stratified pebbly sandstone, displaying well-developed grain segregations. Well 10-26-66-11W6, depth 2370.9 m.

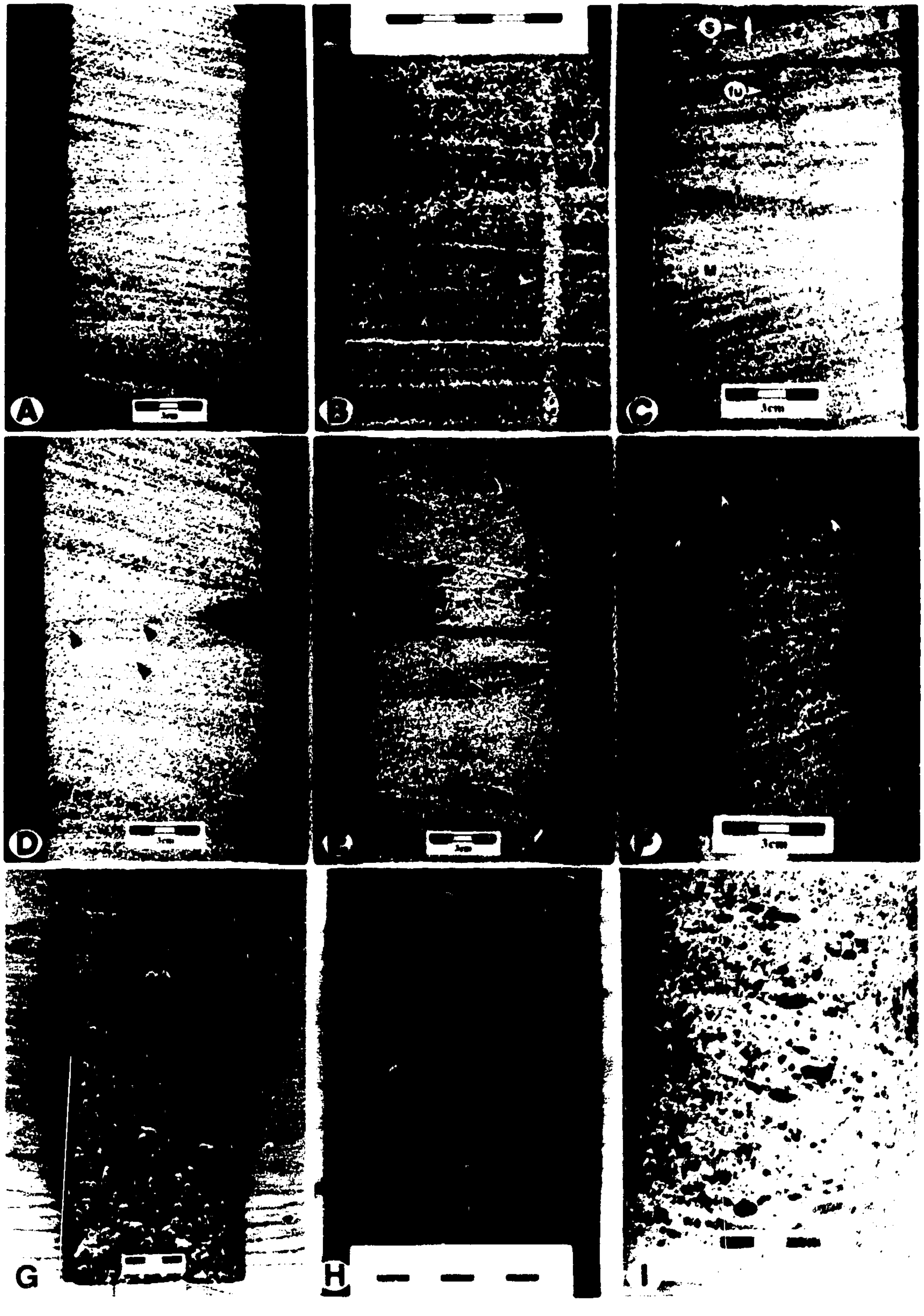

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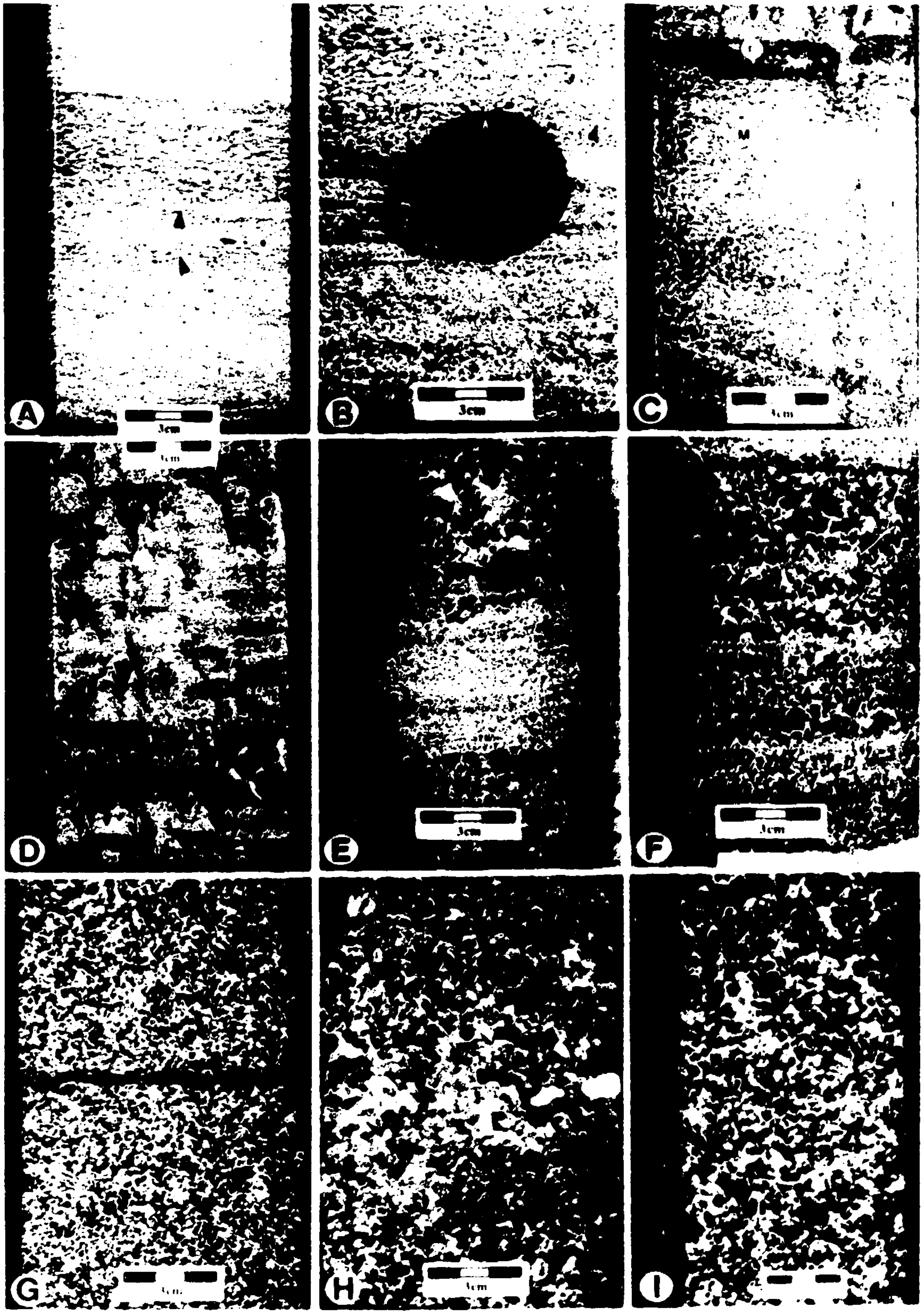
Figure VI-11. FA3: Low Angle Planar Laminated Sandstones, Pebbly Sandstones and Conglomerates of the Foreshore (Cadotte Member). (A) Low angle planar stratified sandstone with *Macaronichnus segregatis* (arrows). Well 10-16-69-11W6, depth 1982.1 m. **(B)** Low angle planar stratified sandstone with well-developed *Macaronichnus segregatis* (arrows). Well 07-26-68-09W6, depth 1888.2 m. **(C)** Trough cross-stratified sandstone of the upper shoreface, passing into low angle planar laminated sandstone of the foreshore. Note the well-developed *Macaronichnus segregatis* (M) which persists across the contact. Some deeply penetrating root structures (r) and *Skolithos* (S) subtend from the overlying backshore deposits. Well 07-10-63-01W6, depth 2168.4 m. **(D)** Upper portion of foreshore sandstone, displaying abundant rooting (arrows) and eluviation. Well 07-10-63-01W6, depth 2168.0 m. **(E)** Pebbly sandstone overlain by sandstone and conglomerate, displaying low angle planar stratification. Well 10-26-66-11W6, depth 2371.0 m. **(F)** Low angle planar stratified, pebbly sandstone of the foreshore. Note the well-segregated nature of the pebbles. Well 10-26-66-11W6, depth 2363.0 m. **(G)** Largely structureless granule conglomerate. Note the well-sorted nature of the grains. Well 10-23-72-11W6, depth 1583.1 m. **(H)** Crudely (low angle planar) stratified, granule to pebble conglomerate of the foreshore. Note the well-segregated nature of the clasts, and the generally well-sorted character of the facies. Well 10-23-72-11W6, depth 1587.5 m. **(I)** Largely structureless granule to pebble conglomerate. The intervals lacks a matrix (open framework). Note the well-sorted nature of the interval. Well 10-23-72-11W6, depth 1583.8 m.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The sandstones (Figure VI-10 A-F) are typically bedded on a scale of 2-40 cm in thickness, though 5-20 cm thick beds are more common. The sand is moderately-sorted with grain size variations from fU-cU (2.5-0.0ø); individual beds typically range across only 2-3 grain size divisions (*i.e.* fU-mU; 2.5-1.0ø). Carbonaceous detritus is locally common, but generally less abundant than in FA2. Pebbles and granules of chert, argillite or lithified sandstone are locally dispersed or present as 1-2 clast thick stringers within the sandstone beds. Intraformationally-derived siderite-cemented clasts and mudstone rip-up clasts are present as rare additions to the coarse fraction.

Sandstones are generally trough cross-bedded with stratification fanning upward from inclinations of 2° to a maximum of 26° reflecting bottomsets and foresets. Current ripple lamination is locally intercalated, typically in beds from 2-5 cm thick. Trough and current ripple stratification displays highly variable dip orientations in core, suggesting a multidirectional character of sediment transport. Stratification is demarcated by grain size segregations and, to a lesser degree, by finely comminuted plant debris. Bedsets are ubiquitously truncation bound.

The pebbly sandstones (Figure VI-10 G, H) comprise a continuum from the sandstone subfacies to the conglomerate subfacies. Consequently, pebble content is highly variable. Clasts, similar to those of the sandstone subfacies, are present in abundant amounts, dispersed throughout the sandstone. Pebbles and granules may also occur as 1-5 clast thick stringers, and as clast-supported conglomeratic beds up to 20 cm thick. These stringers and beds are commonly intercalated within the subfacies. Granules are generally rounded and show high degrees of sphericity. Pebbles tend to be more variable in shape, ranging from subrounded to rounded, and flat to moderately spherical. Thicker clast beds tend to contain some imbricated pebbles. Coalified wood clasts, siderite-cemented mudstone clasts and mudstone rip-up clasts are locally present, but rare overall.

The pebbly sandstones are dominated by multidirectional trough cross-stratification in beds 5-50 cm in thickness, though typically 10-25 cm thick. Beds are truncation bound. Less common planar tabular cross-stratification and current ripple lamination may be locally present in both the pebbly sandstones and the intercalated conglomeratic beds. Most thin conglomeratic beds appear massive.

The conglomeratic subfacies (Figure VI-10 G, I) ranges from granule- to pebble-sized clasts, with maximum (long axis) clast diameters reaching 2 cm. Most clasts range from 0.2-1.0 cm (long axis) in diameter. Clasts are subrounded to rounded, with a small proportion reaching well rounded. Clast shapes range from moderately spherical to highly flattened (disk-shaped). Clasts are predominantly grey, green, black or brown coloured cherts, with subordinate amounts of lithified sandstone and argillite. Intraformationally-derived clasts, consisting of siderite-cemented mudstone, sideritic nodules and mudstone rip-up clasts are virtually absent.

The conglomerate beds are predominantly clast-supported, although thin beds of pebbly sandstone may be intercalated. Clast sizes, though variable overall, are fairly uniform within each bed. Beds range from 5-25 cm in thickness. Most beds contain moderately well-sorted mL-cU (2.0-0.0ø) grained sand matrix, although some beds, particularly those with granule-sized clasts, are open framework and appear to lack matrix (*cf.* Bourgeois and Leithold, 1984).

The bulk of conglomerate beds appear massive or low angle planar stratified. Elongate, typically disk-shaped pebbles may be imbricated. Interstratified pebbly sandstone or rarer sandstone beds are typically trough cross-stratified.

Overall, this trough cross-stratified sandstone, pebbly sandstone and conglomerate facies shows a progressive upward increase in grain size, except where the entire succession is characterised by the sandstone subfacies, such as in the southeast portion of the study area. Within the conglomerates, sand size in the matrix generally stays approximately the same, but maximum clast size commonly increases towards the top of the facies.

The second facies within FA3 is characterised by low angle planar stratified sandstones, pebbly sandstones and conglomerates (Figure VI-11) and is interpreted to reflect foreshore deposition. As in the previous facies, this facies is highly variable with respect to grain size, although it is generally less variable in any one well location. Grain sizes tend to be diminished compared with the underlying facies, and sorting is improved. Clast compositions remain the same.

The sandstone subfacies (Figure VI-11 A-D) is well-laminated and dominated by low angle (<15°) planar stratification. Truncation surfaces are common, with overlying laminae parallel to set contacts. Sandstone beds are typically 10-20 cm thick, amalgamated into intervals reaching 3 m in thickness. Most intervals are in the range of 1-2 m thick. Upwards, the sandstone becomes more massive in appearance and mottled. Some intervals become dark and carbonaceous upwards, while others become lighter in colour and posses a "leached" appearance (Figure VI-11 D). In many cases, root traces are visible. Sand size is generally fU-mU (2.5-1.0ø), with rarer intervals of cL (1.0-0.5ø). Thin pebble or granule stringers and interbeds, typically well segregated and showing fairly uniform clast size, are locally present. Elongate or disk-shaped clasts are locally imbricated.

The pebbly sandstone subfacies (Figure VI-11 F) is very similar to the sandstones, except that stratification is generally highlighted by clast segregations. Granule and pebble conglomerate beds up to 20 cm in thickness are locally intercalated. Elongate clasts may show imbrication. Sand sizes are commonly coarser than the sandstone subfacies, ranging from mL-cU (2.0-0.0ø), but remain well-sorted in any one bed. The presence of rooting is less apparent in this subfacies, but is locally observed.

The conglomerate subfacies (Figure VI-11 F-I) is typically very well-sorted within each bed, although stacked beds may range from pebble conglomerates with clasts up to 2 cm in diameter (long axis), to upper very coarse sand- and granule-sized particles. Clasts may range from moderately spherical to highly disk-shaped, are subrounded to rounded and may show imbrication. All conglomerates are clast-supported, with many lacking a matrix (open framework; Figure VI-11 G, I), especially the granule conglomerates. Matrix grain size is predominantly mL-cU (2.0-0.0ø).

Stratification is commonly cryptic, with most beds appearing internally massive. Most pebbly sandstone interbeds, some granule conglomerate beds, and rarer pebble-conglomerate beds display crude, low angle (<15°) planar stratification, marked principally by grain segregations.

The general character of the low angle parallel stratified sandstone, pebbly sandstone and conglomerate facies is one of subtle upward fining, and is generally finer-grained than the underlying trough cross-stratified facies of FA3. This is especially apparent in intervals dominated by sandstone and pebbly sandstone subfacies; intervals dominated by conglomeratic subfacies show little obvious upward fining.

Ichnology

Burrowing is generally an uncommon component to FA3 successions. In general, the coarser-grained the succession is, the fewer biogenic structures are visible. Burrowing intensities are generally low, and traces are sporadically distributed, with the exception of the ichnogenera *Macaronichnus*, and in particular *M. segregatis*.

In the trough cross-stratified facies, particularly where sandstones and pebbly sandstones are the dominant subfacies, rare fugichnia, *Skolithos*, *Diplocraterion*, *Ophiomorpha* and *Palaeophycus* may be present, commonly truncated by overlying sandstone or pebbly sandstone beds (Figure VI-10 B, C). Migration of subaqueous dunes poses a highly stressful setting for infauna, since minimal deposited food is generally available, precluding deposit feeders, and persistent avalanching of sediment down the slip faces of the bedform constantly buries the entrances to domiciles (Howard and Frey, 1984; Saunders, 1989; MacEachern and Pemberton, 1992; MacEachern and Pemberton, in press). Further, erosional amalgamation of beds tends to remove much of the record of biogenic activity, with the exception of fugichnia and deeply penetrating dwelling structures. Very rare shale interbeds locally contain *Planolites* and *Lockeia*. Towards the top of the trough cross-stratified facies and the base of the low angle parallel stratified facies, moderate to intense degrees of burrowing with a monospecific assemblage of *Macaronichnus segregatis* may be present, particularly where the interval is dominated by sandstones and pebbly sandstones (Figure VI-10 D-F). In many cases, despite high degrees of burrowing, the primary physical stratification is still preserved. Such burrowed intervals may range up to 2.3 m in thickness, although more commonly, the intervals ranges from 0.8-1.5 m.

The low angle parallel stratified facies is typically devoid of all biogenic structures, with the exception of *Macaronichnus segregatis* near the base (Figure VI-11 A-C), and root traces towards the top (Figure VI-11 D). In general, as in the underlying facies of FA3, the coarser the sediment is, the fewer the biogenic structures observed. A similar situation was described by Saunders (1989) from the Appaloosa Sandstone of the Bearpaw-Horseshoe Canyon transition near Drumheller, Alberta.

Intervals dominated by sandstone, and to a lesser degree pebbly sandstone, locally contain rare, isolated *Skolithos*, *Arenicolites* and *Diplocraterion*. The most common biogenic structure is *M. segregatis*, commonly passing upwards out of the underlying trough cross-stratified facies. The zone is typically intensely burrowed and has an abrupt upper contact where burrowing becomes absent. Rooting is a common component to the facies, where the upper portion is preserved and has not been scoured away by FA4 of the overlying Walton Creek Member or Paddy Member. Rooting is more common in the sandier subfacies than in the conglomeratic subfacies. Roots may reach 0.2 cm in diameter and lengths greater than 10 cm. Rooting is probably genetically related to facies of the overlying FA4 succession.

Interpretation of FA3

FA3 is interpreted as a coarse clastic upper shoreface to foreshore succession, sharply overlying the lower to middle shoreface deposits of FA2. The strongest arguments for this interpretation are associated with the character of the conglomerates, the presence of intensely burrowed *Macaronichnus segregatis* zones, and the extensive distribution of the facies association along strike.

Alluvial *vs.* Marine Conglomerates:

Bourgeois and Leithold (1984) outlined a number of parameters to aid in the differentiation between alluvial conglomerates and marine-worked conglomerates. Differences are not always clear-cut. A close association tends to exist between fluvial conglomerates and shallow marine conglomerates, since the river systems act as the principal transporting agents for the coarse detritus to the shoreline, particularly in non-glacial systems. The prospect of both components occurring in a single section must not be dismissed (Cant, 1983), in differentiating fluvial from beach conglomerates. Physical parameters commonly employed include lateral persistence of bedding, pebble shape, degree of clast segregation, relative preservation of resistant clasts, clast imbrication and the presence of heavy mineral zones (*cf.* Clifton, 1969, 1973, 1981, 1988; McLean and Kirk, 1969; Straaten, 1974; Leckie and Walker, 1982; Cant, 1983; Bourgeois and Leithold, 1984; Carter and Orford, 1984; Dupré, 1984; Massari and Parea, 1988; Nadon, 1988). Unfortunately, there is not always a consensus between various researchers.

Upper shoreface and foreshore conglomerates tend to display good lateral continuity of bedding, reflecting the widespread distribution of waves, compared with the localised nature of channelised currents within fluvial systems. The extent of longshore dispersal of gravels from the fluvial point source will ultimately depend on wave energy and the nature of longshore transport mechanisms acting in the receiving basin. Grain shape is by far one of the most contentious parameters employed. Some hold that grain shape is fundamentally modified by wave processes and that wave-worked conglomerates (particularly beach conglomerates) are typified by high degrees of pebble flatness and reduced sphericity, unlike fluvial conglomerates (*e.g.* Straaten, 1974). Others contest this, citing that original pebble shape, transportation history, and clast composition impart a major control on the ultimate clast shape (*e.g* Clifton, 1973). In the case of foreshore settings, observed textural zonations are commonly attributed more to the segregation ability of the wave processes, which distribute the available clast shapes into a zonation with spherical clasts dominating the lower beach and upper shoreface, and disk-shaped clasts dominating the upper beach (Bourgeois and Leithold, 1984).

Virtually all authors agree that wave-sorted conglomerates tend to show much superior pebble segregation within each bed, and imbrication of elongate clasts, when compared to fluvial counterparts. The greater degree of reworking of clasts in beach conglomerates also favours the destruction of non-resistant clasts. Siderite-cemented mudstone clasts, sideritic nodules, and mudstone rip-up clasts are rare or absent from beach and upper shoreface gravels, but commonly form significant constituents in alluvial conglomerates (Bourgeois and Leithold, 1984).

The presence of heavy mineral zones is also used as a diagnostic criterion of beach deposition (Clifton, 1969), and has locally been employed in the recognition of ancient examples (*e.g.* Nadon, 1988). No heavy mineral zones were observed from cored intervals of the Cadotte Member. The conglomerate intervals within FA3 do, however, display many of the primary physical features considered typical of wave-worked gravels. The most significant parameters include a well-sorted and segregated character, imbrication of elongate clasts, and a paucity of non-resistant clast types.

In addition to the physical characteristics, Bourgeois and Leithold (1984) stress the significance of body fossils and biogenic structures in the recognition of wave-worked marine conglomerate and pebbly sandstone deposits. The presence of *Skolithos, Diplocraterion, Ophiomorpha,* *Arenicolites*, *Palaeophycus*, fugichnia and in particular, *Macaronichnus segregatis*, demonstrates a marine affinity to the sandstones, pebbly sandstones and conglomerates of FA3.

The presence of discrete zones of *Macaronichnus segregatis* is highly significant to the interpretation of FA3 as upper shoreface and foreshore deposits (Saunders and Pemberton, 1986; Saunders, 1989; Pemberton and Saunders, 1990). Clifton and Thompson (1978) originally described and defined *Macaronichnus segregatis*, and attributed it to the deposit feeding behaviour of the *opheliid* polychaete *Ophelia limicina*. In addition, the modern polychaete *Euzonus mucronata*, also of the family *Ophelidae*, makes similar structures (Saunders, pers. comm., 1994). Both modern tracemakers ingest sand as a means of exploiting an epigranular food source of bacteria and other grain-attached substances, and subsequently excrete the "cleansed" sand to form the fill of the structure. The polychaetes preferentially ingest quartz and feldspar sand and habitually avoid mica flakes and mafic grains; consequently, the fill of the structure tends to be lighter in colour than the surrounding host sediment. The organisms are capable of feeding well below the sediment-water interface. This factor accounts for the preservation of their burrows in high energy, nearshore sand and sandy conglomerates (Clifton and Thompson, 1978; Clifton, 1988; Saunders, 1989).

In their general description of *Macaronichnus*, Clifton and Thompson (1978) designated a single ichnospecies - *M. segregatis*. Saunders (1989) considered this inadequate, recognising the existence of three distinct forms, differentiated on the basis of foraging pathway configurations (Figure VI-12). *M. simplicatus* is characterised by randomly interpenetrating burrows. *M. segregatis*, the type species, is restricted to forms exhibiting an equally random pattern, but in which there is a marked tendency (despite the randomness of the burrows) towards the avoidance of interpenetration. Finally, *M. spiralis* was designated to account for the locally observed developments of distinct planispiral configurations. The respective species reflect fundamentally different patterns of resource utilisation (namely space and food), and also appear to be strongly density dependent; *M. simplicatus* and *M. segregatis* manifesting under conditions of high population density, and *M. spiralis* representing more of a low-density response (Saunders, pers. comm., 1994). The upper shoreface *Macaronichnus* zone of the Cadotte appears to be

Macaronichnus

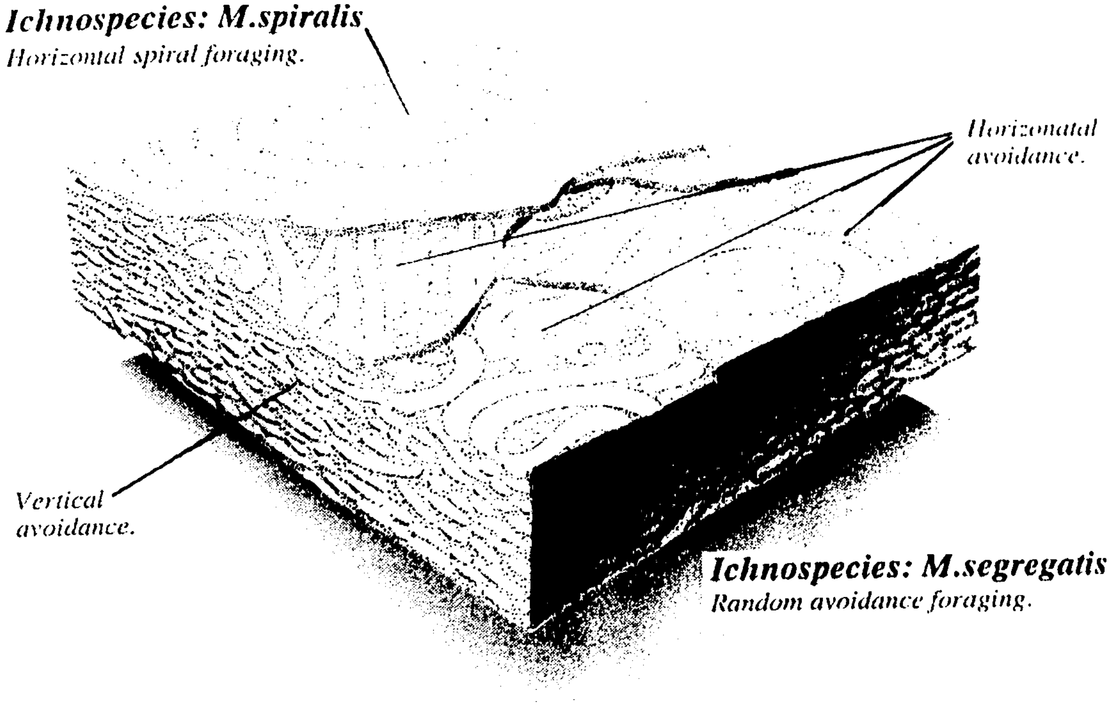


Figure VI-12. Schematic diagram of the trace fossil *Macaronichnus*, showing two of the most common species *M. segregatis* and *M. spiralis*. Both forms show foraging avoidance. Diagram courtesy of T.D.A. Saunders.

dominantly represented by *M. segregatis*, although the general absence of bedding plane exposures largely precludes the identification of *M. spiralis*.

The trough cross-stratified sandstone, pebbly sandstone and conglomerate facies is interpreted to reflect coarse sediment accumulation in an upper shoreface setting. Such depositional regimes correspond to the "Outer Rough" and "Outer Planar" zones of Clifton *et al.* (1971), where the bulk of sediment transport is related to multidirectional current flow in the build-up and surf zones (Carter, 1978; Davis, 1978). Shore-normal currents are generated by plunging waves, whereas storm waves produce shore-parallel currents (Reinson, 1984). These currents are further modified by the existence of a barred shoreline configuration, containing longshore troughs, ridge and runnel systems, rip channels and/or nearshore bars (*e.g.* Davidson-Arnott and Greenwood, 1976; Greenwood and Davidson-Arnott, 1979; Hunter *et al.*, 1979; Thom *et al.*, 1986). Under barred situations, wave- and storm-induced currents flow obliquely shoreward over the bar, turn shore-parallel along the longshore troughs, and ultimately return seaward through the rip channels. Box cores from the modern (*e.g.* Clifton *et al.*, 1971; Davidson-Arnott and Greenwood, 1976; Hunter *et al.*, 1979; Roy *et al.*, 1980; Howard and Reineck, 1981; Thom *et al.*, 1986) show that virtually all subenvironments in the upper shoreface are characterised by trough and current ripple cross-bedding, whether corresponding to a barred or unbarred configuration. Observations of the ancient in outcrop (*e.g.* Clifton, 1981, 1988; Leckie and Walker, 1982; Bourgeois and Leithold, 1984; Dupré, 1984; Leithold and Bourgeois, 1984; Massari and Parea, 1988; Nadon, 1988; Rahmani and Smith, 1988) serve to confirm this, making it difficult to assess the character of the build-up and surf zones on the basis of core alone. It appears unfruitful to attempt to discern which of the myriad of subenvironments within the upper shoreface are responsible for deposits within the basal facies of FA3. Greenwood and Mittler (1985), in their study of the barred Kouchibouguac Bay, New Brunswick, showed that most deposits of a barred system have a low preservational potential; most preserved intervals represent the seaward margin of the bar slope, and the longshore trough deposits. They concluded that in most cases, the preserved sediments would be very difficult to recognise as part of a barred deposit.

Despite this inherent problem in subdividing the facies into barred system subenvironments, it is useful to speculate as to whether the Cadotte shoreline was barred or not. Rahmani and Smith (1988) interpreted the Cadotte as a barred system, mainly on the basis of the sharp erosional surface separating FA2 from FA3, with a corresponding abrupt increase in sediment grain size. This surface corresponds to the scoured base of the deepest rip channel, or to the longshore trough, which progressively shifts seaward during progradation of the shoreline, and alongshore due to channel migration (*cf.* Hunter *et al.*, 1979). Initial deposition on the scour surface would therefore correspond to rip channel deposits, capped by bar, longshore trough and various other upper shoreface-generated subaqueous dunes.

The low angle parallel laminated sandstone, pebbly sandstone and conglomerate facies of FA3 is interpreted to reflect foreshore deposition. The interpretation is strengthened by its stratigraphic position in the depositional succession, directly overlying trough cross-stratified sandstones, interpreted as upper shoreface deposits. Abundantly burrowed zones, consisting of *Macaronichnus segregatis*, commonly occurs near the base of the facies. A number of environmental tendencies can be recognised with respect to *Macaronichnus*. In the Appaloosa Sandstone, reflecting the Bearpaw-Horseshoe Canyon transition, *Macaronichnus* is found preferentially concentrated within a narrow zone situated in the upper foreshore (Saunders, 1989). The burrows persist in low densities down to, but never below, the foreshore-upper shoreface transition. A similar foreshore-restricted pattern occurs in the Tertiary of Japan (Kikuchi, 1972; Tokuhashi and Kondo, 1989; Yokokawa and Masuda, 1991; Okazaki and Masuda, 1992). In the Cadotte, as well as virtually all other shoreline cycles of the boreal Lower Cretaceous, *Macaronichnus* shows the opposite zonal relationship. Here, the burrows tend more towards a "toe-of-the-beach" position. Only in isolated examples does the zone ever actually transcend into overlying swash-laminated foreshore sandstones. This same pattern of recurrence has also been recognised from Cretaceous to Tertiary deposits of the Pacific west coast (Hunter, 1980; Clifton, 1981, 1988; Hunter *et al.*, 1984; Clifton and Hunter, 1987; Leithold and Bourgeois, 1989; Saunders, 1989; Okazaki and Masuda, 1992).

The well segregated and imbricated nature of clasts supports a wave-worked marine origin for the conglomerates, whereas the predominance of low angle planar stratification in sandstones, pebbly sandstones and some conglomerates are reminicent of swash zone cross-stratification, features all considered characteristic of foreshore deposits (Bluck, 1967; Clifton, 1969, 1973, 1988; Davis, 1978; Bourgeois and Leithold, 1984; Leithold and Bourgeois, 1984; Massari and Parea, 1988). The rooted tops to some of these intervals support ultimate subaerial exposure of the beach during continued progradation.

Several authors have suggested that clast shape is also diagnostic of foreshore settings (Bluck, 1967; Straaten, 1974). A predominance of disk-shaped pebbles in the upper part of the beach is believed to reflect the greater suspendability of such clasts during the swash stage of beach run-up, whereas the greater pivotability of spherical clasts favours their accumulation in the lower beachface during wave backwash (Bourgeois and Leithold, 1984). A rigorous textural analysis was not performed on the Cadotte Member conglomerates, but a visual inspection showed little evidence of this type of clast distribution within this facies.

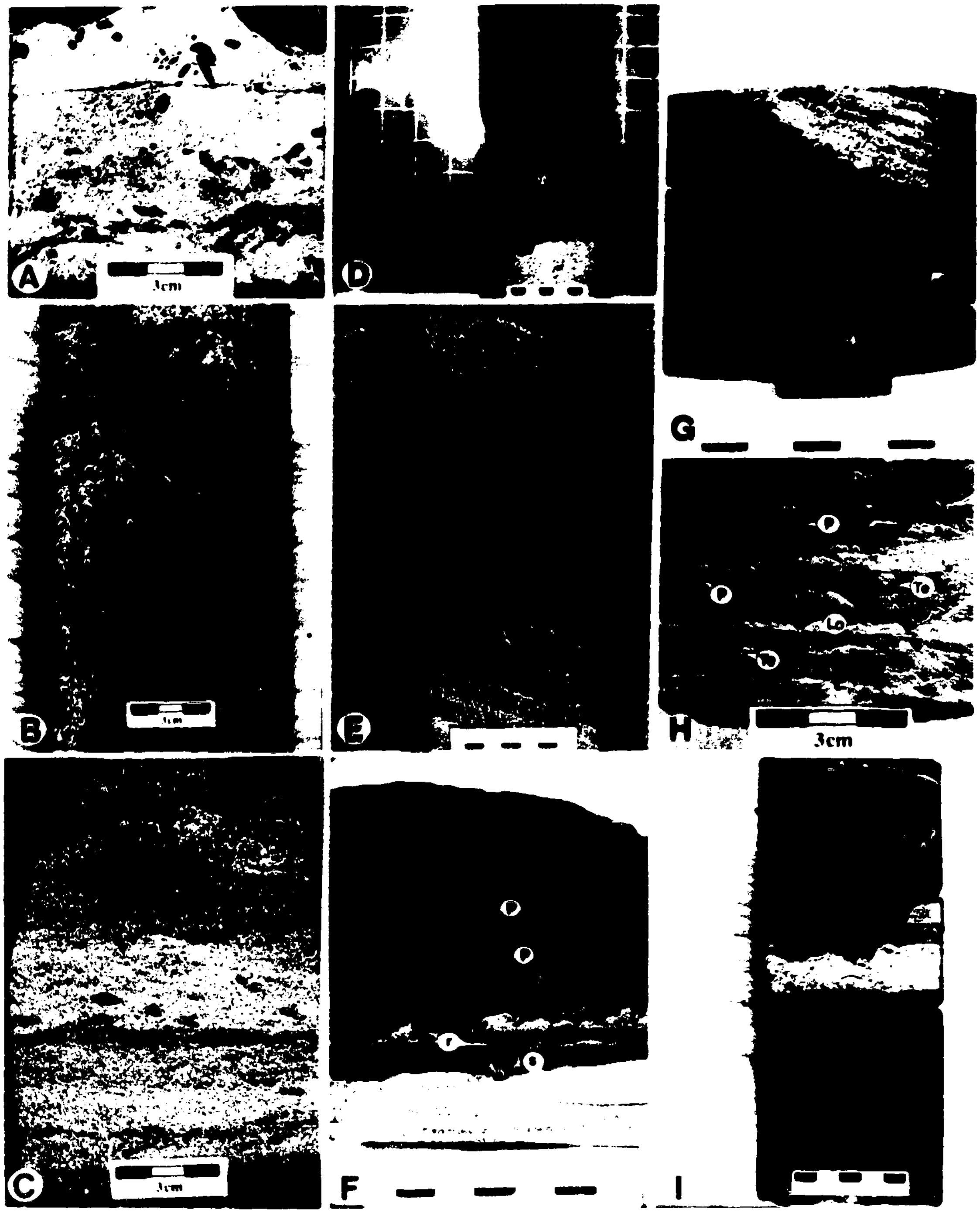
PADDY/WALTON CREEK MEMBERS

The Paddy Member has been described from outcrop in the Peace River town area (Leckie, 1988, 1990; Leckie and Singh, 1991), as well as from the subsurface (Leckie *et al.*, 1990; Stelck and Leckie, 1990; Leckie and Reinson, in press). The upper part of the Boulder Creek Formation, termed recently the Walton Creek Member, has been described in the subsurface by Leckie *et al.*, (1989), Stelck and Leckie (1988), and by Gibson (1992) from outcrop in northeastern British Columbia. The Paddy/Walton Creek members consist of a number of facies associations, but only the basal facies association is considered to be genetically related to the Harmon-Cadotte shoreline system. Discussion is restricted to this basal facies association.

Backshore Deposits: Facies Association 4 (FA4)

FA4 is made up of a complex association of 7 facies, and ranges from gradationally to sharply overlying FA3 (Figure VI-13). Locally, FA4 has incised through much of FA3, removing the foreshore deposits and lying directly on upper shoreface deposits. FA4 is poorly-developed in the thesis area, ranging from an erosional remnant in the south and eastern portions of the study area to a thin development, subaerially exposed and strongly modified by later Paddy/Walton Creek deposition in the southwest. FA4 is

Figure VI-13. FA4: Backshore Deposits (Paddy Member /Walton Creek Member). **(A)** Facies 1: Mottled to massive argillaceous sandstone. The sandstone is silica-cemented, rooted and probably eluviated, interpreted as the top of the foreshore. Well 10-16-69-11W6, depth 1980.0 m. **(B)** Facies 1: Mottled to massive argillaceous sandstone. Interval is intensely rooted, and reflects the backshore rooting of the upper portion of the foreshore. Well 08-02-66-09W6, depth 2358.7 m. **(C)** Facies 2: Moderately-sorted, low angle planar laminated sandstone. Interval contains abundant organic detritus and rip-up clasts, and is interpreted as washover deposits. Well 10-23-72-11W6, depth 1580.9 m. **(D)** Facies 3: Dark, carbonaceous sandstone. The interval sharply overlies foreshore sandstones. No primary stratification is visible. The facies is interpreted to reflect infill of swales in the back-beach area during flood events. Well 06-18-71-12W6, depth 1890.7 m. **(E)** Moderately-sorted, trough cross-stratified sandstone, with mudstone rip-up clasts and organic detritus. The facies is interpreted to reflect backshore/coastal plain tidal creek deposits or, more rarely, distributary channel deposits. Well 08-35-62-03W6, depth 2330.7 m. **(F & G)** Facies 4: Inclined heterolithic stratification (IHS). The facies is closely associated with trough cross-stratified channel sandstones and is interpreted to represent point bar deposits associated with tidal creek or distributary channels. Note the root traces (r), syneresis crack (s) and *Planolites* (P) in photo F. Photo G shows the inclined character of the bedding. Well 06-06-64-25W5, depths 1904.0 m and 1903.6 m, respectively. **(H)** Facies 5: Interbedded sandstone and mudstone. The facies contains *Planolites* (P), *Lockeia* (Lo) and *Teichichnus* (Te). The facies is interpreted as backshore ephemeral pond deposits, probably associated with washover events. Well 10-23-62-26W5, depth 2082.4 m. **(I)** Facies 6: Dark, carbonaceous mudstone. The mudstone overlies a pebbly sandstone, truncating Facies 7 (Coal). Facies 6 contains sandstone stringers and organic detritus, and is interpreted as backshore, shallow pond deposits. The underlying coal of Facies 7 reflects a backshore swamp deposit. Well 10-23-62-26W6, depth 2083.2 m.


A
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rarely thicker than 3 m in the study area and displays little lateral correlatability of individual facies. No single location displays all 7 facies.

Facies 1: Mottled to Massive Argillaceous Sandstones

Facies 1 is the most common facies of FA4, and passes gradationally out of the foreshore sandstones of FA3 (Figure VI-13 A, B). The sandstone is typically mL-mU (2.0-1.0ø) in grain size, moderately well-sorted and commonly appears silica- or clay-cemented. Primary sedimentary structures are either entirely absent or are present as cryptic deformation structures, displayed as indistinct mottles. Organic detritus is commonly present and locally abundant. Coal fragments may also be intercalated. Most intervals are less than one meter thick and typically less than 50 cm in thickness. Intervals are commonly pale in colour and appear leached. Trace fossils are exceedingly rare, except as root structures, which dominate the facies.

Facies 2: Moderately-Sorted Low Angle Planar Laminated Sandstone

Facies 2 consists of fU-cU (2.5-0.0ø) grained, moderately- to poorly-sorted sandstone (Figure VI-13 C). Organic detritus is typically present and locally abundant, occurring as coaly interlaminae. Granules and small pebbles of chert may be present, particularly where the facies overlies conglomeratic FA3. Individual beds are sharp-based, erosive, and 10-60 cm in thickness, locally amalgamated into sets 0.5-1.5 m thick. Some intervals may appear to coarsen upwards.

Primary stratification is dominated by low angle (<15°) planar to horizontal planar stratification, with intercalated current and oscillation ripple lamination. Stratification is typically cryptic in coarser intervals. Less commonly, the facies dominantly consists of oscillation and current ripple laminated sandstone with allochthonous coaly interlaminae in bedsets 10-60 cm thick. Trace fossils are very rare, and characterised by sporadic occurrences of *Skolithos*, *Arenicolites*, and fugichnia. Root structures are locally present, typically restricted to the top of the facies interval. Facies 2 rarely directly overlies FA3 and is more closely associated with Facies 5 and Facies 6.

Facies 3: Dark, Carbonaceous Sandstones

Facies 3 is very rare, observed in only two intervals in the study area. The facies is black in colour and extremely carbonaceous, with leaf fragments on bedding planes (Figure VI-13 D). Grain sizes of sands range from fU-cL (2.5-0.5ø). The facies is sharp-based and typically less than 50 cm in thickness. Primary physical structure was not observed. In both cases, Facies 3 directly overlies foreshore sandstones of FA3. No burrowing or rooting was visible in the facies.

Facies 4: Moderately-Sorted, Trough Cross-Stratified Sandstone

Facies 4 consists of fU-mU (2.5-1.0ø), and typically mL (2.0-1.5ø) grained sandstones, with abundant mudstone rip-up clasts and allochthonous coal spar (wood fragments probably coalified *in situ*) (Figure VI-13 E). Finely comminuted plant debris is also intercalated. The facies is exclusively sharp-based and may overlie any facies within FA4, or directly overlie FA3. The facies may display a cryptic fining upward succession. The sandstone is dominated by trough cross-stratified beds 10-20 cm in thickness, with intercalated current ripple lamination. Most intervals are less than 1.5 m in thickness.

In a few exceptional cases, the facies may reach thicknesses of 6.7 m and fine upward into inclined heterolithic stratification (IHS; *cf.* Thomas *et al.*, 1987; Wood, 1989). IHS is characterised by 2-7° inclined beds of dark organic detritus or carbonaceous mudstone, interstratified with current rippled to structureless, medium-grained sandstone (Figure VI-13 F, G). Deformation structures, such as gravity faults, dewatering structures and convolute bedding are locally present. Syneresis cracks may also be present in some intervals (Figure VI-13 F). Rooting is typically abundant in the IHS intervals. Facies 4 rarely contains burrows, although locally, *Planolites*, *Palaeophycus* and fugichnia may be present.

Facies 5: Interbedded Sandstone and Mudstone

Facies 5 is physically quite similar to FA1, being characterised by 1.0-10.0 cm thick beds of vfU-fU (3.5-2.0ø) grained sandstones, interstratified with 0.5-5.0 cm thick beds of moderately to weakly organic, medium to light grey coloured silty mudstone (Figure VI-13 H). This interstratification locally produces wavy bedding or pinstripe bedding. Sandstones are oscillation ripple laminated and wavy parallel laminated. Mudstone beds typically drape the sandstone beds and may also contain thin interlaminae of fine-grained sand. Facies intervals range from 0.5-1.5 m in thickness and may either be sharp- or gradationally-based. Facies 5 commonly grades out of Facies 6.

In contrast to FA1 of the Harmon Member, Facies 5 locally contains syneresis cracks, a sporadic distribution of root structures, and a very low diversity and low abundance of ichnogenera. Burrows are characterised by rare *Planolites, Teichichnus, Cylindrichnus* and fugichnia, with very rare *Skolithos, Arenicolites* and *Palaeophycus*.

Facies 6: Dark, Carbonaceous Mudstone

Facies 6 consists of black to dark grey, generally silt-poor, highly organic-rich mudstone (Figure VI-13 I). Locally, organic detritus is so abundant, the facies acquires a coal-like appearance. Facies 6 commonly grades into and out of Facies 7. The facies interval is typically sharp-based and less than 1.0 m in thickness. Plant fragments and leaf impressions are locally preserved on bedding planes. Root structures, commonly pyritised, are also present. Thin (0.2-1.0 cm), vfU-fU (3.5-2.0ø) grained sandstone stringers are sporadically intercalated. The sandstone stringers are horizontally laminated or massive (apparently structureless).

Although rooting is present, other ichnofossils are generally not. *Planolites* and very rare *Cylindrichnus* are present, but exceedingly subordinate elements of the facies.

Facies 7: Coal

Facies 7 consists of dense, black, locally vitrain-rich, but predominantly clarain coal (Figure VI-13 I). Vitrain coals tend to be vitreous and displays conchoidal fracture, banding of bright coal with dull coal and inorganics, and well-developed cleating. The more common clarain coals show a semi-bright, silky lustre, lack of concoidal fracture and display less well-developed banding. Bands occur on a scale of 0.2-0.5 cm in thickness and consists of durain (dull grey-brown coal) and clarain, fusain (fibrous, sooty coal), and lesser vitrain. Interbeds of clastics, both carbonaceous mudstone and fL-mL (3.0-1.5ø) grained sandstone are common constituents. Dispersed sand grains and mudstone rip-up clasts also occur intercalated in the coals. Pyrite is present both as displacive nodules and as replacements of root structures. Coal beds are generally 10-30 cm in thickness.

The coals locally occur either sharply overlying foreshore deposits of FA3 or gradationally interstratified with Facies 6. With the exception of root traces, biogenic structures are absent.

Interpretation of FA4

FA4 is interpreted to have been deposited in a backshore setting, associated with the progradation of the Harmon-Cadotte shoreline system. The backshore interpretation is largely based on the close association with the upper shoreface and foreshore deposits of FA3, in addition to the occurrence of terrestrial deposits (*e.g.* paleosols) overlying but never underlying FA4. Further support derives from a low diversity and low abundance of trace fossils in many of the facies, supporting a salinity-stressed marginal marine environment (Wightman *et al.*, 1987; Beynon *et al.*, 1988; Pemberton *et al.*, 1992a), the presence of root traces which suggests shallow water and/or subaerial exposure, and the presence of syneresis cracks, suggesting possible salinity fluctuations (Burst, 1965; Plummer and Gostin, 1981).

The mottled to massive argillaceous sandstone (Facies 1) is interpreted as the leached or eluviated portion of the foreshore sandstones of FA3. The eluviation is a function of subaerial exposure and extensive rooting following shoreline progradation. Several intervals show *M. segregatis* in the foreshore sandstones, cross-cut by root traces penetrating from the backshore (Figure VI-11 C, D). Such foreshore sandstones grade upward into Facies 1 of FA4.

The moderately-sorted, low angle planar laminated sandstones (Facies 2) are interpreted to represent washover deposits from the foreshore during storm events and associated wave run-up. Low angle planar laminae reflect upper flow regime conditions (UFR), generated by the shallow, sheet-like flows over the beach and into the backshore area. Intercalated current ripple laminae probably correspond to waning flow conditions. Thick intervals of current and oscillation ripple laminae suggest some washover flows may have debouched into ponded bodies of water in the back-beach area, probably related to initial washover events. Escape traces correspond to disturbances made by organisms entrained in, or buried by, the washover event bed. Rare *Arenicolites* and *Skolithos* may correspond to initial colonisation of the bed by transported organisms, where the event bed was deposited into ponded marine water. Rooting may correspond to the ephemeral nature of these back-beach ponds.

The dark, carbonaceous sandstones (Facies 3) are enigmatic. They are tentatively interpreted as swale fills in the back-beach area, where flood- and storm-deposited marine organics, terrestrial organics and clastic material accumulate. The close association with the foreshore sandstones of FA3 and the sharp-based character of the facies suggest a topographic low or swale, developed on former beach deposits, relegated to a back-beach position as a result of shoreline progradation.

The moderately-sorted, trough cross-stratified sandstones (Facies 4) are interpreted as coastal plain/backshore tidal creek deposits. Thicker Facies 4 intervals with associated IHS beds are interpreted either as larger tidal creeks, or as distributary channels. The fining upward character and local presence of IHS corresponds to the upper point bar of the respective laterally migrating channel systems. The occurrence of rooting suggests shallow water and/or subaerial exposure, whereas the sporadic distribution of *Planolites*, *Palaeophycus* and fugichnia are regarded to suggest that marginal marine waters at least periodically drained through the channels.

The interbedded sandstones and mudstones (Facies 5) are interpreted as lagoonal or backshore pond deposition. Of all the facies in FA4, Facies 5 shows the strongest marine influence, demonstrated by the marginal-marine trace fossil suite and the presence of syneresis cracks. Periodic wave reworking and incremental sediment supply, largely attributable to storm-related washover events in the case of ephemeral ponds or direct wave access in the case of lagoons, produces the wavy bedded character of the silty muds and oscillation ripples. The thin intervals of Facies 5 (<1.5 m) suggests that in the study area, these settings were largely shallow, ephemeral ponds rather than lagoons.

The dark, carbonaceous mudstone facies (Facies 6) is interpreted as deposition in shallow ponded water environments, either as abandoned channel fills associated with Facies 4 intervals, or as broad, water-filled shallow depressions in the backshore environment where associated with the coals of Facies 7. Organic detritus and clastic material may have been derived from washover events at the foreshore, or from channel systems on the coastal/delta plain. The presence of rare *Planolites* and *Cylindrichnus* suggests some periodic input of marginal marine waters into the setting.

The coals indicate accumulation of vegetation, either as a backshore swamp, particularly where associated with Facies 6, or as back-beach coals, where subsidence and dewatering/compaction landward of the shoreline favoured peat accumulation directly on the foreshore sandstones (*cf.* Kalkreuth and Leckie, 1989). As such, the zone of peat accumulation was probably well removed from the active zone of foreshore accretion. In virtually all occurrences of Facies 7, overlying deposits lack any evidence of marine influence, supporting deposition removed from the active shoreline. Most of these coal intervals, therefore, act as a transition between the other facies of FA4 and the overlying terrestrial facies association of the Walton Creek and Paddy members, which dominate in the southwest and west-central portions of the study area.

DEPOSITIONAL DYNAMICS OF THE HARMON-CADOTTE SHOREFACE COMPLEX: DISCUSSION AND OVERVIEW

The Harmon/Cadotte members of the Peace River Formation reflects a complete offshore to foreshore succession capped by a thin, laterally variable backshore interval (Figures VI-14 and VI-15). The integration of sedimentology with the ichnology provides considerable refinement in the interpretation of the strandline system. In the study area, the succession is interpreted as a high energy, wave- and storm-dominated delta system.

FA1, constituting the offshore transition deposits, reflects pronounced storm-domination. The abundance of thin, largely unburrowed sandstones, mantled by weakly burrowed silty mudstones and organic detritus supports distal tempestites generated by high frequency storms with suspension fallout of fine material, probably genetically related to the tempestites (Aigner and Reineck, 1982). Associated flood discharge of distributaries as well as fine detritus put into suspension by the storm waves themselves accounts for the dark, fissile mud beds mantling the tempestites (*cf.* Allen, 1982; Massari and Parea, 1988; Leithold, 1989). The trace fossils observed from FA1 are sporadic in distribution and low in abundance, supporting episodic event deposition and high sedimentation rates. The absence of structures generated by suspension feeding organisms may suggest either rapid burial of sandy substrates by post-storm fines, generally high water turbidity, or both. Such

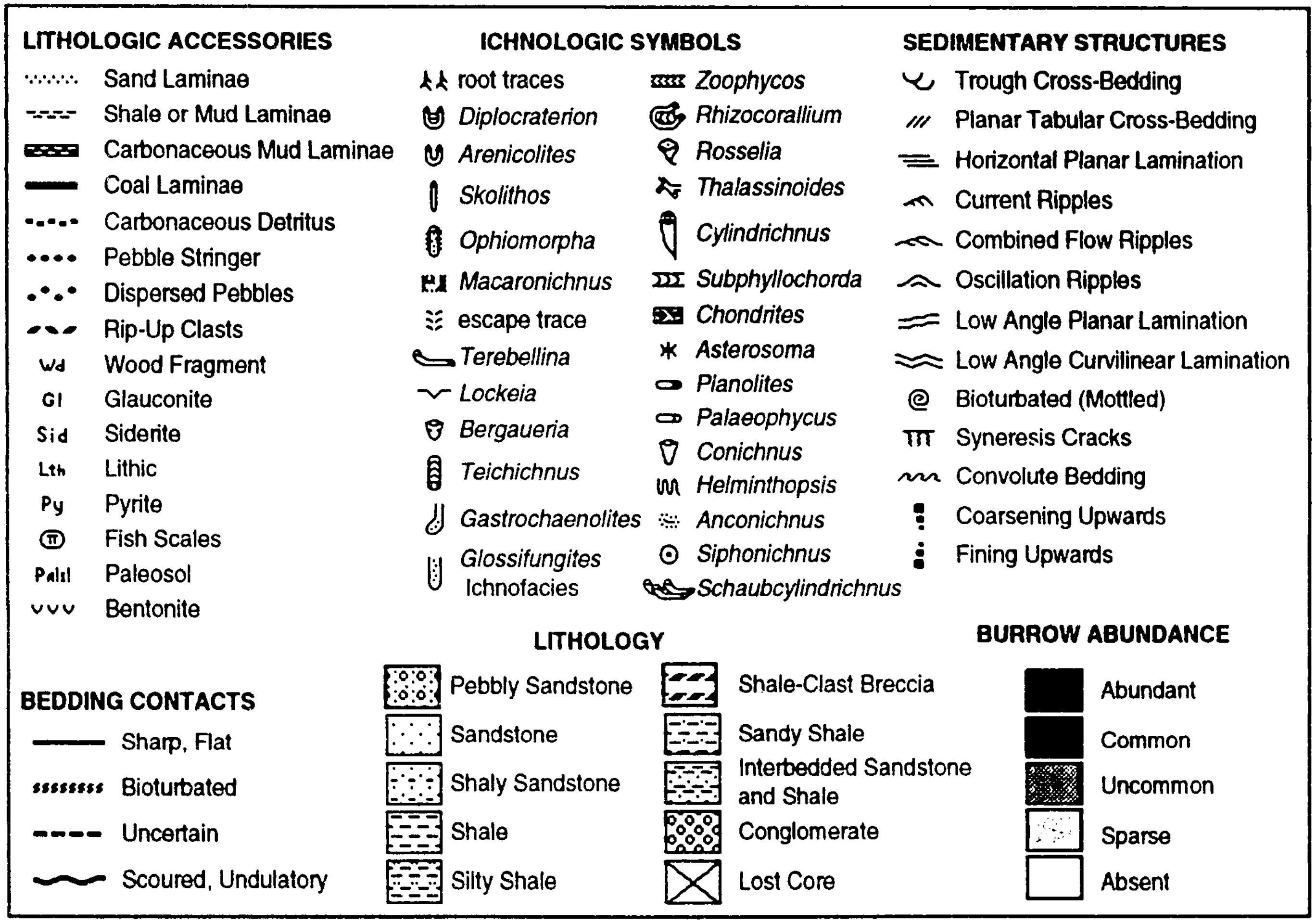

Figure VI-14. Legend of Symbols used in Lithologs.

Figure VI-15. Litholog of the Harmon-Cadotte Member shoreface, showing weakly burrowed, storm-dominated offshore transition (FA1) passing into amalgamated tempestites of the storm-dominated lower-middle shoreface (FA2). Note the abrupt increase in grain size of the overlying nearshore complex (FA3). Note also the preserved burrowed horizon in FA2, underlying the nearshore complex. Deposits of FA4 overlie an autocyclic(?) erosion surface, which has removed the foreshore succession and sits on a remnant of the *Macaronichnus segregatis* zone within the upper shoreface-foreshore transition. The legend of the symbols used in the litholog is given in Figure VI-14.

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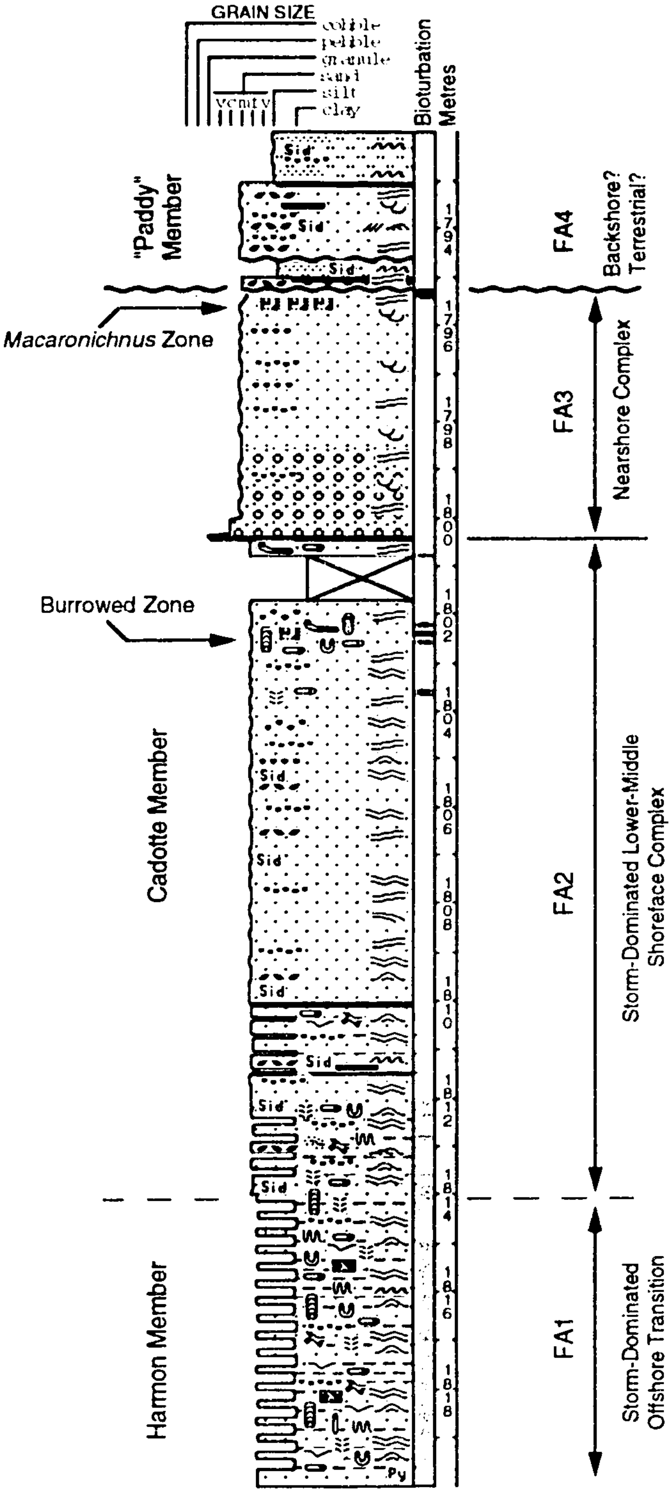


conditions are afforded by prodelta to distal delta front settings in storm-dominated deltas (*cf.* Moslow and Pemberton, 1988).

FA2, reflecting the lower to middle shoreface positions of the delta front provide little evidence in support or refutation of a deltaic origin. Repeated, higher energy storm events favoured erosional amalgamation of the tempestites with virtual elimination of any evidence of initial storm bed colonisation or fairweather burrowing. Increased proximity favours enhanced erosional amalgamation to the point of becoming "cannibalistic" (Aigner and Reineck, 1982). Understanding the character of the fairweather suite of trace fossils is essential in order to interpret the nature of the paleoenvironmental conditions dominating the setting. The few burrowed horizons preserved in FA2 support colonisation by opportunistic forms under fully marine conditions, but with a surprisingly low abundance of suspension feeding structures such as *Cylindrichnus, Skolithos, Arenicolites, Conichnus, Bergaueria* and *Diplocraterion*. Although the available database is small, it is speculated that higher than normal water turbidity, such as is common in deltaic settings, may have been partly to blame (Rhoads and Young, 1971. Interdeltaic or non-deltaic lower to middle shoreface settings tend to be characterised by well oxygenated, shifting sandy substrates as well as clear, non-turbid water columns, favouring colonisation by suspension-feeding organisms (Seilacher, 1967; Pemberton and Frey, 1984; Pemberton *et al.*, 1992a).

FA1 and FA2 constitute the basal portion of the shoreface succession which prograded basinward over the deeper water marine mudstones of the Harmon Member (*cf.* Bloch, 1990). These two facies associations provided the stable depositional platform, across which the overlying upper shoreface/foreshore complex prograded. This dynamic interplay between the lower-middle shoreface/offshore transition and the upper shoreface/foreshore has been commented on by numerous researchers (*e.g.* Cook and Gorsline, 1972; Fox and Davis, 1978; Wright *et al.*, 1979; Niedoroda *et al.*, 1984; Aigner, 1985; Swift, *et al.*, 1985).

Virtually all preserved sediments in the lower-middle shoreface consist of storm-generated deposits (Figure VI-15), with almost no evidence of fairweather conditions remaining (Kumar and Sanders, 1976; Niedoroda *et al.*, 1984; Aigner, 1985; Greenwood and Mittler, 1985). The storm-dominated character of the lower-middle shoreface deposits departs markedly from the hypothetical "vertical succession" models based on modern studies, because these models are primarily based on oscillatory-flow theory, predicted under "ideal" or fairweather conditions (*e.g.* Clifton *et al.*, 1971; Hunter *et al.*, 1979; *etc.*). This has also been remarked upon by Van den Berg (1977), who pointed out that researchers working on modern examples should be more concerned with those processes that produce deposits most preservable in the rock record, particularly when presenting facies models for the ancient. These are seldom the average (fairweather) depositional conditions expressed by flow regime theory (*cf.* Dott, 1983; 1988). The concept of "uniformitarianist catastrophism", employed by Kumar and Sanders (1976) is an actualistic approach that has obvious applications to the study of shoreface morphodynamics in the ancient record.

Most of the sediment in the lower-middle shoreface is derived at the expense of the upper shoreface/foreshore complex, where the record of storm events is manifest by pronounced erosion. Basinward transport of sand occurs due to a combination of high energy, short-period waves and strong, onshore-directed winds. These conditions produce wave set-up and strong offshore surges, typically directed through rip channels and longshore troughs (Aigner and Reineck, 1982; Hunter *et al.*, 1979; Field and Roy, 1984; Swift *et al.*, 1985). Much of this sediment may be returned to the beach in the form of longshore bars, which migrate landward in response to the fairweather long-period waves which generate very weak rip currents (Cook and Gorsline, 1972; Davidson-Arnott and Greenwood, 1976). Not all the sediment may be returned, however, and the sand stranded in the offshore and shelf remains relatively undisturbed until it is mobilised and fashioned into tempestites following a storm event (Kumar and Sanders, 1976; Aigner and Reineck, 1982; Swift *et al.*, 1985). In this sense, the more sediment acquired permanently from the foreshore, the more rapidly the lower-middle shoreface can prograde (Niedoroda *et al.*, 1984). Despite the permanent loss of sediment, this situation actually facilitates more rapid progradation of the upper shoreface/foreshore complex. The bulk of the accommodation space to be filled is that lying between the maximum storm weather wave base and the surf zone, and must be filled first, before the upper shoreface/foreshore can shift basinward. If the profile seaward of the upper shoreface is too steep, then the zone becomes one of sediment bypass alongshore, until the gradient favours basinward progradation again (Chapman, 1981). The Cadotte

Member depositional edge to the north corresponds to a rapid deepening into the south flank of the Fort St. John Graben (Barclay *et al.*, 1990; O'Connell *et al.*, 1990; Leckie *et al.*, 1990; Figure VI-3), and demonstrates such a relationship.

The overlying FA3 succession corresponds to the upper shoreface/foreshore setting and is generally much coarser than the underlying lower-middle shoreface tempestites of FA2 (Figures VI-15 and VI-16). This abrupt diminishment of grain size basinward corresponds to the rapid decline in transport competence of offshore surges as they leave the surf zone and/or the rip channel, and enter the nearshore (*cf.* Clifton *et al.*, 1971; Hunter *et al.*, 1979; Clifton, 1981; Reinson, 1984). The facies of the upper shoreface reflect a variety of subenvironments which are characteristic of the build-up and surf zones, whether barred or non-barred (*cf.* Clifton *et al.*, 1971; Davidson-Arnott and Greenwood, 1976; Hunter *et al.*, 1979; Greenwood and Mittler, 1985). Virtually all subenvironments consist mainly of trough and current ripple stratification with lesser low angle planar stratification, whether part of the outer rough megaripple field of an unbarred configuration (Clifton *et al.*, 1971), or the bar/longshore trough/rip channel system of a barred system (Davidson-Arnott and Greenwood, 1976; Hunter *et al.*, 1979). In their study of a barred complex in Kouchibouguac Bay, New Brunswick, Greenwood and Mittler (1985) pointed out that generally, only the slope of the bar and the longshore trough deposits are commonly preserved during shoreline progradation, making it very difficult to recognise a succession as having been barred.

Perhaps the most compelling argument in favour of a barred configuration for the Cadotte shoreface is the widespread presence of an erosional discontinuity separating the lower-middle shoreface platform (FA2) from the overlying upper shoreface/foreshore complex (FA3) (*cf.* Hunter *et al.*, 1979; Shipp, 1984; Greenwood and Mittler, 1985), a model proposed for the Cadotte Member by Rahmani and Smith (1988). The widespread distribution of the erosional discontinuity corresponds to the alongshore migration, and progradation-induced basinward shift of the deepest of the longshore troughs and rip channels. In this sense, although each cored interval may display a single discontinuity, regionally it actually reflects a multitude of discrete erosional breaks. The discontinuity is therefore not a surface of sequence stratigraphic significance. Overlying facies are clearly genetically related to

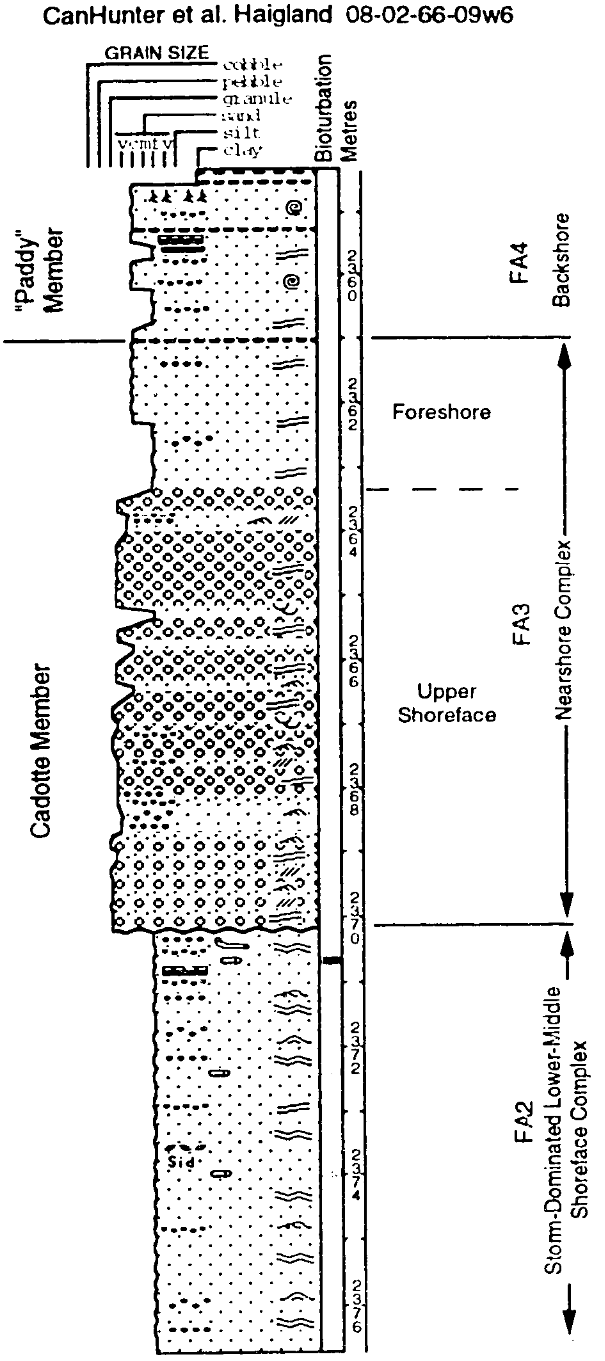


Figure VI-16. Litholog of Cadotte Member shoreface showing a conglomeratic nearshore complex. Note the abrupt increase in grain size from the lower-middle shoreface complex into the overlying nearshore complex. The backshore deposits of FA4 consist of Facies 3, which is rooted towards the top. The legend of the symbols used in the litholog is given in Figure VI-14.

those underlying the break, and the existence of the surface is easily explained autocyclically as a natural and expected phenomenon within an intermediate (barred) state of shoreface morphodynamics (*cf.* Hunter *et al.*, 1979; Wright *et al.*, 1979; Short, 1984; Thom *et al.*, 1986).

The existence of an intensely burrowed zone underlying the erosional break separating the upper shoreface from the lower-middle shoreface deposits has been observed in sediments of Kouchibouguac Bay (Greenwood and Mittler, 1985), as well as in the Cadotte Member. This probably reflects the dynamic interplay between fairweather wave base which largely controls the distribution of burrowing, and storm-enhanced scouring depth of the rip channel which occurs below modal (fairweather) wave base (Hunter *et al.*, 1979). Consequently, the rip channel commonly scours down to, or below, the top of the fairweather burrowed zone. Intensely burrowed zones tend to be mucous-bound and may therefore inhibit rip channel incision. In most cases, the erosional discontinuity lies on at least a veneer of fairweather burrowed sandstone.

The foreshore deposits overlying the upper shoreface probably record steep, highly accretionary systems. In general, coarse-grained beaches, typical of most of the Cadotte successions in the study area, are characterised by steep profiles (Bascom, 1951; McLean and Kirk, 1969; Davis, 1978; Kirk, 1980; Carter and Orford, 1984), tending towards the reflective end member of shoreline morphodynamics (*cf.* Wright *et al.*, 1979; Short, 1984; Thom *et al.*, 1986). Steep beaches are typical of highly accretionary shorelines. Most reflective systems lack a persistent barred configuration, however, sandy, non-rocky shorelines are rarely entirely unbarred, because the beach and surf zones are generally in processes of adjustment between the morphodynamic extremes of purely reflective and purely dissipative states (Sonu, 1973; Guza and Inman, 1975; Short, 1979; Thom *et al.*, 1986). In the case of the Cadotte Member, the system appears to have fluctuated from high energy reflective states to a more intermediate barred system. Although the Cadotte Member contains a low relief, broad lower-middle shoreface platform, the strong storm-domination resulted in the bulk of the platform lying near or below fairweather wave base. As a result, deep water swells were not dissipated significantly across this depositional zone, and the upper shoreface/foreshore complex was permitted to acquire a reflective profile. During storms, particularly during extended periods of storm activity, effective wave base was lowered and the those underlying the break, and the existence of the surface is easily explained autocyclically as a natural and expected phenomenon within an intermediate (barred) state of shoreface morphodynamics (*cf.* Hunter *et al.*, 1979; Wright *et al.*, 1979; Short, 1984; Thom *et al.*, 1986).

The existence of an intensely burrowed zone underlying the erosional break separating the upper shoreface from the lower-middle shoreface deposits has been observed in sediments of Kouchibouguac Bay (Greenwood and Mittler, 1985), as well as in the Cadotte Member. This probably reflects the dynamic interplay between fairweather wave base which largely controls the distribution of burrowing, and storm-enhanced scouring depth of the rip channel which occurs below modal (fairweather) wave base (Hunter *et al.*, 1979). Consequently, the rip channel commonly scours down to, or below, the top of the fairweather burrowed zone. Intensely burrowed zones tend to be mucous-bound and may therefore inhibit rip channel incision. In most cases, the erosional discontinuity lies on at least a veneer of fairweather burrowed sandstone.

The foreshore deposits overlying the upper shoreface probably record steep, highly accretionary systems. In general, coarse-grained beaches, typical of most of the Cadotte successions in the study area, are characterised by steep profiles (Bascom, 1951; McLean and Kirk, 1969; Davis, 1978; Kirk, 1980; Carter and Orford, 1984), tending towards the reflective end member of shoreline morphodynamics (*cf.* Wright *et al.*, 1979; Short, 1984; Thom *et al.*, 1986). Steep beaches are typical of highly accretionary shorelines. Most reflective systems lack a persistent barred configuration, however, sandy, non-rocky shorelines are rarely entirely unbarred, because the beach and surf zones are generally in processes of adjustment between the morphodynamic extremes of purely reflective and purely dissipative states (Sonu, 1973; Guza and Inman, 1975; Short, 1979; Thom *et al.*, 1986). In the case of the Cadotte Member, the system appears to have fluctuated from high energy reflective states to a more intermediate barred system. Although the Cadotte Member contains a low relief, broad lower-middle shoreface platform, the strong storm-domination resulted in the bulk of the platform lying near or below fairweather wave base. As a result, deep water swells were not dissipated significantly across this depositional zone, and the upper shoreface/foreshore complex was permitted to acquire a reflective profile. During storms, particularly during extended periods of storm activity, effective wave base was lowered and the development of a barred intermediate configuration was favoured. Many coarse-grained storm-dominated shoreline systems appear to be reflective during fairweather conditions, but with pronounced deepening of effective wave base during storms or storm seasons, acquires a barred configuration until persistent fairweather conditions allows a return to a reflective condition (*cf.* Hunter *et al.*, 1979; Massari and Parea, 1988). Regular alternations between sandstone and conglomerate beds in the upper shoreface/foreshore complex, as is apparent locally in the Cadotte Member (Figure VI-16), is interpreted to reflect repeated alternations between storm-induced barred states, and fairweather recovery reflective states.

The position of the zones of abundant *Macaronichnus segregatis* within upper shoreface deposits of FA3 may support the reflective, high energy character of the system. In many foreshore successions within Alberta, such as the Appaloosa sandstone in the Bearpaw-Horseshoe Canyon transition (Saunders and Pemberton, 1986; Saunders, 1989), as well as the Blood Reserve Sandstone (Nadon, 1988), the *M. segregatis* zone occurs at the base of the foreshore and persists upward into the beach deposits. In the modern, *M. segregatis* accumulates within foreshore deposits at Long Beach, Vancouver Island, British Columbia (Saunders, pers. comm., 1993). These examples are characterised by much finer-grained, lower gradient foreshores, reflecting more intermediate or dissipative shoreface states compared to the Cadotte Member. The coarser and steeper beaches of the Cadotte and their fairweather reflective states may have favoured wave run-up on the beach with associated greater rates of infiltration of O_2-rich water through the foreshore and into the upper shoreface deposits. This may have permitted the *M. segregatis* trace-makers to burrow deeper into the substrate, and/or to occupy a more basinward position than possible under a finer-grained and more dissipative shoreface state (Saunders, pers. comm., 1993).

In general, the upper shoreface/foreshore complex is characterised by accretion during persistent fairweather conditions, and by pronounced erosion with basinward transport of clastic detritus, during storm conditions. As a result, the upper shoreface-foreshore deposits agree well with hypothetical models based on modern studies, in marked contrast to the lower-middle shoreface successions. Based upon regional study of the Cadotte Member, particularly to the north, T.D.A. Saunders (pers. comm., 1993) has proposed a model of deposition which effectively accounts for many of the features observed (Figure VI-17). It appears reasonable that the Cadotte shoreline was characterised by a marked temporal variation in storm activity, such as a winter storm/summer fairweather seasonality, typical of many high latitude systems (Owens, 1977; Cook and Gorsline, 1978; Fox and Davis, 1978; Hunter *et al.*, 1979; Marsaglia and Klein, 1983; Carter and Orford, 1984; Duke, 1985; Swift *et al.*, 1985).

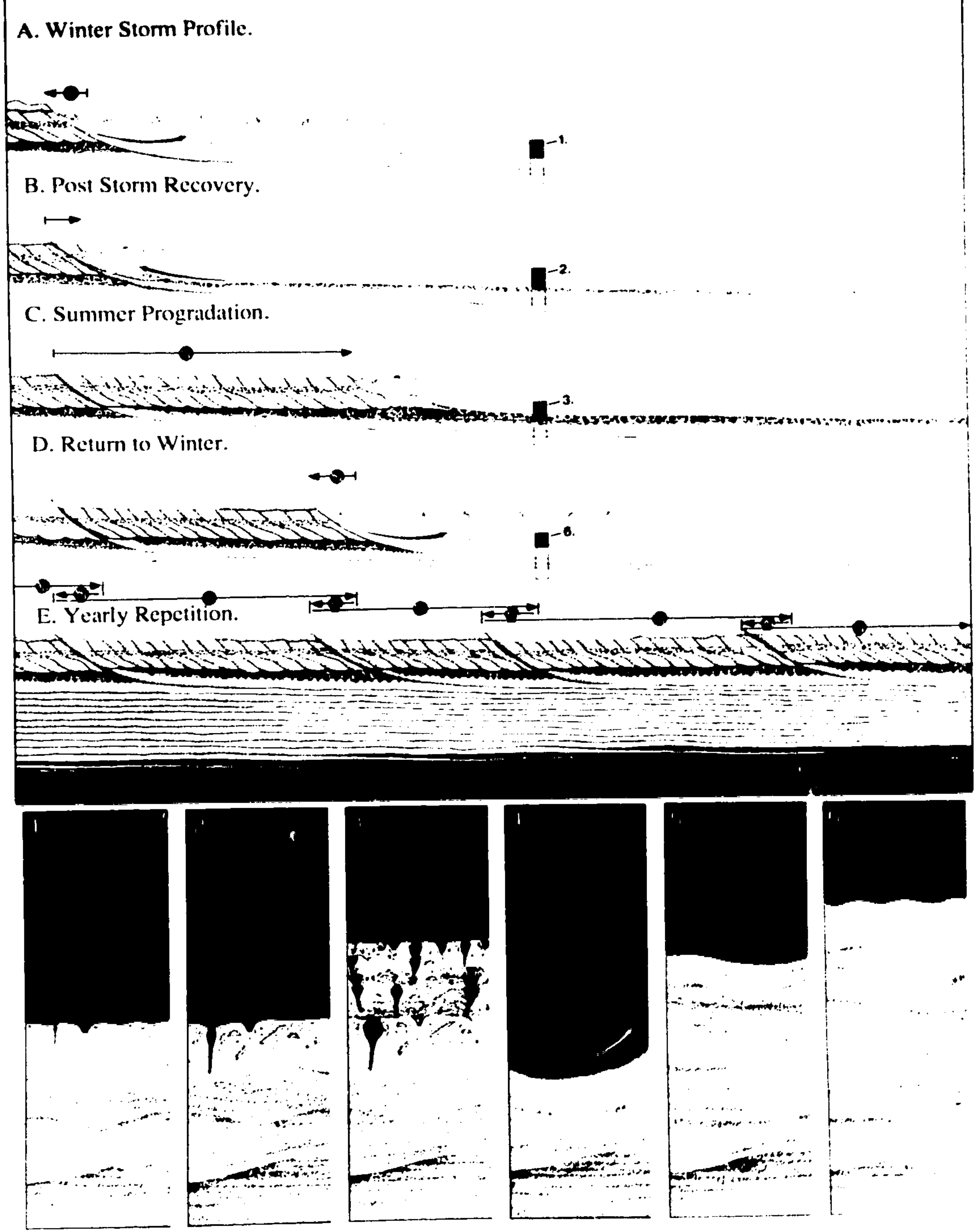
In the winter, high frequency and high intensity storm sets are concentrated, resulting in pronounced erosion on the beachface (Figure VI-17 A). Storm-induced basinward transport of sediment is generally at least one order of magnitude greater than fairweather accumulation (Swift *et al.*, 1985), resulting in rapid modification of the shoreface profile and addition of large volumes of sediment to the lower-middle shoreface platform. Most erosion occurs on the initial accretionary profile of the beach, and on any longshore bars which are in the process of migrating onshore to weld with the foreshore (Fox and Davis, 1978). Once a lower relief, convex profile is achieved, much less erosion occurs on the beachface during storms. In the winter months, the short periods of fairweather conditions permit rapid, though generally incomplete, return of sediment to the beach, in the form of large bars (Figure VI-17 B). It is during this winter storm season that most sediment accumulates in the lower-middle shoreface setting. Erosional amalgamation of storm beds and consequent removal of any fairweather burrowing of the tempestites dominate during this period, permitting basinward progradation of the lower-middle shoreface platform.

During the summer months, fairweather conditions, punctuated by less frequent and lower intensity storms, are ineffective in generating significant erosion on the beachface. The beach receives much of its sediment in the form of landward-migrating longshore bars from the middle shoreface, which ultimately weld to the foreshore, as well as from fluvial or distributary channels draining to the coast and coastal eolian dunes. The summer season is characterised by the return of the accretionary profile of the beachface and the basinward progradation of the upper shoreface/foreshore complex (Figure VI-17 C).

During this summer season, extended fairweather conditions allow organisms to colonise the tempestites which accumulated in the lower-middle shoreface during the preceding winter season, generating an extensive burrowed horizon. The burrowed zone possesses little preservation potential

Figure VI-17. Depositional Model for the Cadotte Shoreface. The model proposes that the Cadotte shoreface was subjected to intense and high-frequency storms reflecting a seasonal cyclicity (winter-summer cycles), typical of high latitude settings. The winter storm season (A) is characterised by a temporal concentration of storm events, resulting in pronounced erosion of the beachface profile. During this period, considerable volumes of sediment are removed from the beach and transported to the lower and middle shoreface. Post-storm periods (B) see the return of a portion of this sediment to the nearshore complex by the landward migration of longshore bars. In the summer months (C), the nearshore complex receives sediment from longshore drift and from terrestrial sources, permitting relatively rapid progradation over the lower-middle shoreface platform. The beachface returns to its depositional profile. The summer, because it is an extended period of reduced storm activity, favours the extensive colonisation of the lower and middle shoreface by infaunal organisms. This colonisation period results in the development of a widespread burrowed horizon in front of the prograding nearshore complex. With the return of the winter storm period (D), progradation of the nearshore complex largely ceases and the beachface returns to its winter erosional profile. The lower and middle shoreface setting is subjected to erosional amalgamation of tempestites. Seaward of the nearshore complex, the burrowed horizon has a low preservation potential (*i.e.* stage 4 of the schematic section). Sections seaward of the nearshore complex may show no preserved evidence of a colonisation period. In contrast, this burrowed zone possesses a highly favourable preservation potential where summer cycle progradation of the nearshore complex buries it (E). Note that the burrowed horizon is actually a composite of a number of autocyclically-generated surfaces, and has no sequence stratigraphic significance. Diagram courtesy of T.D.A. Saunders, upon whose model this interpretation is based.

CADOTTE PROGRADATION: MODEL # 1.



if exposed to storm-wave reworking during the succeeding winter season (Figure VI-17 D), but may be preserved if buried by summer season progradation of the upper shoreface/foreshore complex (Figure VI-17 E). Partial removal of this summer "fairweather" zone may occur where rip channels or longshore troughs scour below fairweather wave base.

The return of the winter storm season results in the planing back of the beachface to the winter erosional profile, and a return of sediment supply to the lower-middle shoreface platform. Rip channels widen the zone of scour into the previous summer burrowed zone alongshore. The succeeding summer season results in a new burrowed horizon and a new basinward shift of the rip channel erosional scour. Consequently, the erosional breaks and burrowed horizons observed in core are not a single stratigraphic entity, but constitute a composite of many fairweather burrowed surfaces and storm season rip channel scour surfaces (Figure VI-17 E). The model illustrates that the progradation of the upper shoreface/foreshore complex and the lower-middle shoreface platform are largely independent of one another, despite the dynamic interplay of sediment exchange between the two.

Deltaic *vs.* Non-Deltaic

The arguments surrounding determination of deltaic *versus* non-deltaic influence in deposition of the Cadotte Member are largely indirect; most of the principal data are absent or obscured due to the strongly storm-dominated and wave-dominated character of the succession. In the Holocene, many wave-dominated coasts possess wave-dominated deltas, flanked by extensive sandy strandline systems (*e.g.* Tabasco Coast, eastern Mexico - Psuty, 1967; the São Francisco Delta, Brazil - Coleman and Wright, 1975; the Nile Delta - Fisher *et al.*, 1969). Clearly, several depositional settings may exist along a wave-dominated shoreline (Palmer and Scott, 1984). During deposition of the Cadotte Member, the bulk of the sediment was derived from the west and distributed eastward by longshore processes (Ethier, 1982; Hayes, 1988; Smith and Rahmani, 1988; Leckie *et al.*, 1990). This geographically limited source area favours at least local development of point source supplies of sediment to the coast and development of deltaic systems, flanked westward by largely interdeltaic strandlines.

With regard to the actual facies within the Harmon/Cadotte system, there is little evidence that unequivocally points to a deltaic character. The high rates of deposition suggested by the sporadic, low degrees of burrowing, and the mud drapes on tempestites, possibly derived from distributary/fluvial flood discharge associated with storms, supports deposition in a wave-dominated delta system (*cf.* Moslow and Pemberton, 1988). The paucity of suspension feeding structures within parts of the study area may reflect high water turbidity (Rhoads and Young, 1971), supports a deltaic interpretation, although erosional removal of these structures is at least as likely as their absence due unfavourable environmental conditions.

In the backshore (FA4) successions, thick channel systems, though rare, may correspond to distributary systems, supporting a deltaic interpretation. Hayes (1988) described a thick (>10 m) channel/valley system from the Noel, British Columbia area, west of the present study area, which he interpreted as an equivalent to the Cadotte Member. The channel system is coarse-grained, containing pebbles, granules and coarse sand similar in size and composition to the conglomerate and pebbly sandstone upper shoreface/foreshore (FA3) deposits of the Cadotte Member in the thesis area. The presence of contemporaneous channel complexes in the west indicates a point source for much of the sediment delivered to the Cadotte shoreline, favouring the development of a wave-dominated delta system.

Studies of other tectonically active foreland settings, such as the Cope Basin along the southeast coast of Spain (Dabrio, 1990; Bardaji *et al.*, 1990), the Apulian Foreland Basin on the Gulf of Taranto, southern Italy (Massari and Parea, 1990), and a Messinian-aged Venetian foreland basin along the southern Alps of Italy (Massari and Parea, 1988) show that non-glacial, coarse conglomeratic beach and strandline systems are typically closely associated with coarse-grained deltas or fan delta systems. In the Cope Basin, much of the coarse-grained sediment of the fan delta front is captured in highly accretionary, steep, reflective beaches (Dabrio, 1990). It is likely that most non-glacial conglomeratic beaches are part of wave-dominated, coarse-grained delta or fan delta systems, which supply large volumes of sediment to the coast, to be distributed alongshore by longshore drift (Massari and Parea, 1988). In general, accretion rates of these systems are highest during relative highstands of sea level, or slowly rising relative sea level, while lowstand conditions favour subaerial exposure and erosion of the delta front (Dabrio, 1990).

The regional paleogeography (Figure VI-18) suggests that the early stage of Cadotte deposition, which characterises much of the southern part of the study area, occurred in an embayment, and therefore under conditions favouring deltaic accumulation. As the shoreline prograded to the north, and acquired a straighter northwest-southeast trend, deltaic characteristics were probably largely restricted to the west, nearer the point sources of sediment, while more typical strandline systems dominated in the central and eastern portions of the study area. Study of the Cadotte and upper Harmon members north of the study area (Saunders, pers. comm., 1993) show far less evidence of deltaic influences on the shoreface, except insofar as coarse-grained sediment continued to be supplied to some beaches.

The Harmon/Cadotte succession, capped by the Walton Creek/Paddy backshore and terrestrial deposits, suggests that the entire system accumulated under conditions of slowly rising sea level, or slow subsidence of the depocentre. These conditions account for the preservation of foreshore and backshore deposits within this thick succession (*cf.* Davis and Clifton, 1987; Dabrio, 1990). The lowstand conditions, responsible for the unconformity between the Paddy and Cadotte members on the Peace River Arch (Leckie, 1988; Leckie *et al.*, 1990), and the diastems within the paleosols of the Walton Creek Member to the south and west (Leckie *et al.*, 1989; Gibson, 1992; Leckie and Reinson, in press) probably post-date much of the progradation of the Harmon-Cadotte storm-dominated/wave-dominated delta system.

Progradational Straightening of Cadotte Shoreline.

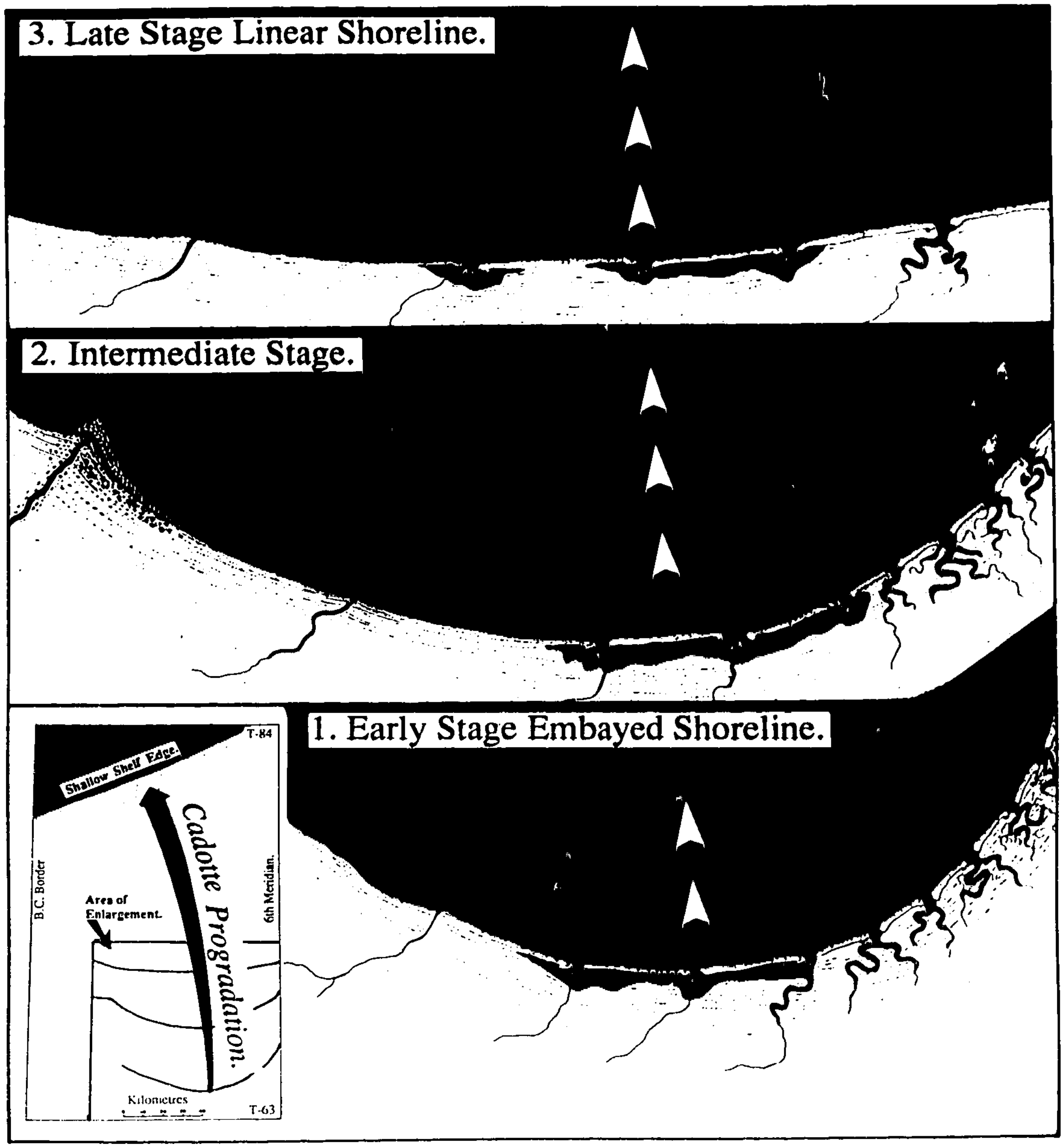


Figure VI-18. Proposed regional paleogeography of the Cadotte shoreface. Note that early in the progradational history of the Cadotte, the system was dominated by a embayed setting. With progressive progradation, the shoreface acquired a straighter orientation, partly related to the filling of the embayment and partly to the tectonic control of the Fort St. John Graben. Diagram courtesy of T.D.A. Saunders.

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CHAPTER VII

THE VIKING FORMATION OF THE KAYBOB FIELD: A CASE STUDY OF AN INTERMEDIATE STORM-ENERGY FORCED REGRESSION SHOREFACE

INTRODUCTION

The Viking Formation in the Kaybob Field area is ideally suited to illustrate two relatively new models associated with shoreface deposition. The first is the characterisation of a shoreface intermediate between strongly storm-dominated ones, such as the Cadotte Member of the Peace River Formation (Chapter VI) and weakly storm-influenced ones, such as the Viking Formation at Giroux Lake (Chapter VIII). The moderately storm-dominated (intermediate storm-energy) shoreface is typified by tempestite deposition alternating with post-storm and fairweather burrowing (MacEachern and Pemberton, 1992), and typifies several intervals in the rock record. The Kaybob area possesses a data base which facilitates the integration of ichnology and sedimentology, in order to characterise these shoreface types.

Secondly, the succession displays an erosional discontinuity separating underlying, regionally extensive, shallowing-upward parasequences in the lower part of the Viking Formation from the main hydrocarbon-producing sand body of the Kaybob area. This discontinuity is demarcated by a *Glossifungites* ichnofacies (*cf.* MacEachern *et al.*, 1992b; Chapter II) and has regional sequence stratigraphic significance. The overlying sand body reflects rapid shoreface progradation induced by relative lowering of sea level, and corresponds to a "forced regression" shoreface (Plint, 1988; Posamentier and Vail, 1988; Posamentier *et al.*, 1992). These lowstand shorefaces are sedimentologically and stratigraphically discrete from highstand shorefaces and high energy parasequences, which prograde basinward purely under the impetus of sedimentation. The Kaybob area, therefore, also facilitates the integration of ichnology and sedimentology in order to characterise the nature of forced regression shorefaces.

STUDY AREA

The Kaybob Viking field is situated in Tp 62, R 20W5 and produces gas from the Viking A pool along the eastern margin of the township (Figure VII-1). The main Viking sand body, however, extends across the entire township, eastward into Tp 62, R 19W5. The Kaybob sand body possesses a NW-SE trend, traceable southward at least as far as Tp 59, R18W5. To the north, the sand body extends only as far as Tp 63, R21W5, where it appears to have been erosionally removed by a late-stage intra-Viking discontinuity (*cf.* Chapter VIII).

A total of 13 cored intervals within the Joli Fou and Viking formations were logged in detail with respect to both the ichnology and the sedimentology. These were compared and contrasted with a total of 9 Viking Formation cores within the adjacent Fox Creek field, in order to establish the local absence of the Kaybob forced regression shoreface to the east.

REGIONAL STRATIGRAPHY

The Viking Formation is upper Albian (Lower Cretaceous) in age, passes upwards out of the marine shales of the Joli Fou Formation, and is overlain by Lower Colorado marine shales. Slipper (1918) informally gave the name "Viking" to gas-producing sandstones of the Viking-Kinsella field near Viking, Alberta. Wickenden (1949) first referred to the black shales at the base of the Colorado Group, overlying the Mannville Group, as the "Joli Fou" shale. Stelck (1958) later formally raised both the Viking and the Joli Fou to formation status.

The general stratigraphic equivalents of the Viking and Joli Fou are given in Figure VII-2. The Joli Fou Formation unconformably overlies the Mannville Group. Rough equivalents of the Joli Fou Formation include the Skull Creek shale in Montana and the Thermopolis shale in Wyoming (McGookey *et al.*, 1972; Weimer, 1984). The Viking Formation is roughly equivalent to the Paddy Member of the Peace River Formation (Koke and Stelck, 1985; Stelck and Leckie, 1990; Leckie and Singh, 1991), the upper part of the Bow Island Formation (Glaister, 1959; Cox, 1991; Raychaudhuri and Pemberton, 1992), as well as the Muddy Sandstone, Newcastle Formation and

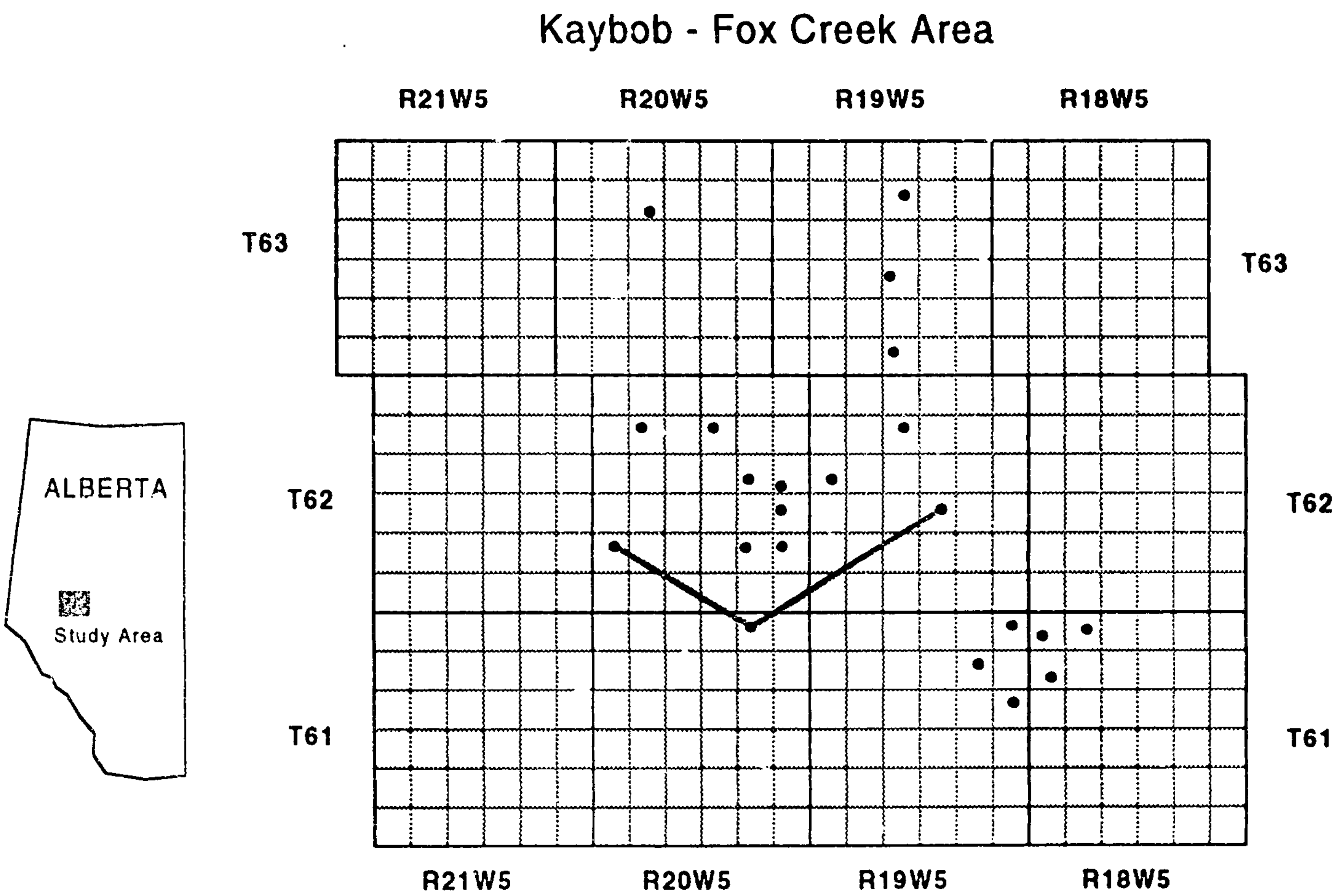


Figure VII-1. Kaybob study area, showing the cored well locations and the line of cross-section in Figure VII-13.

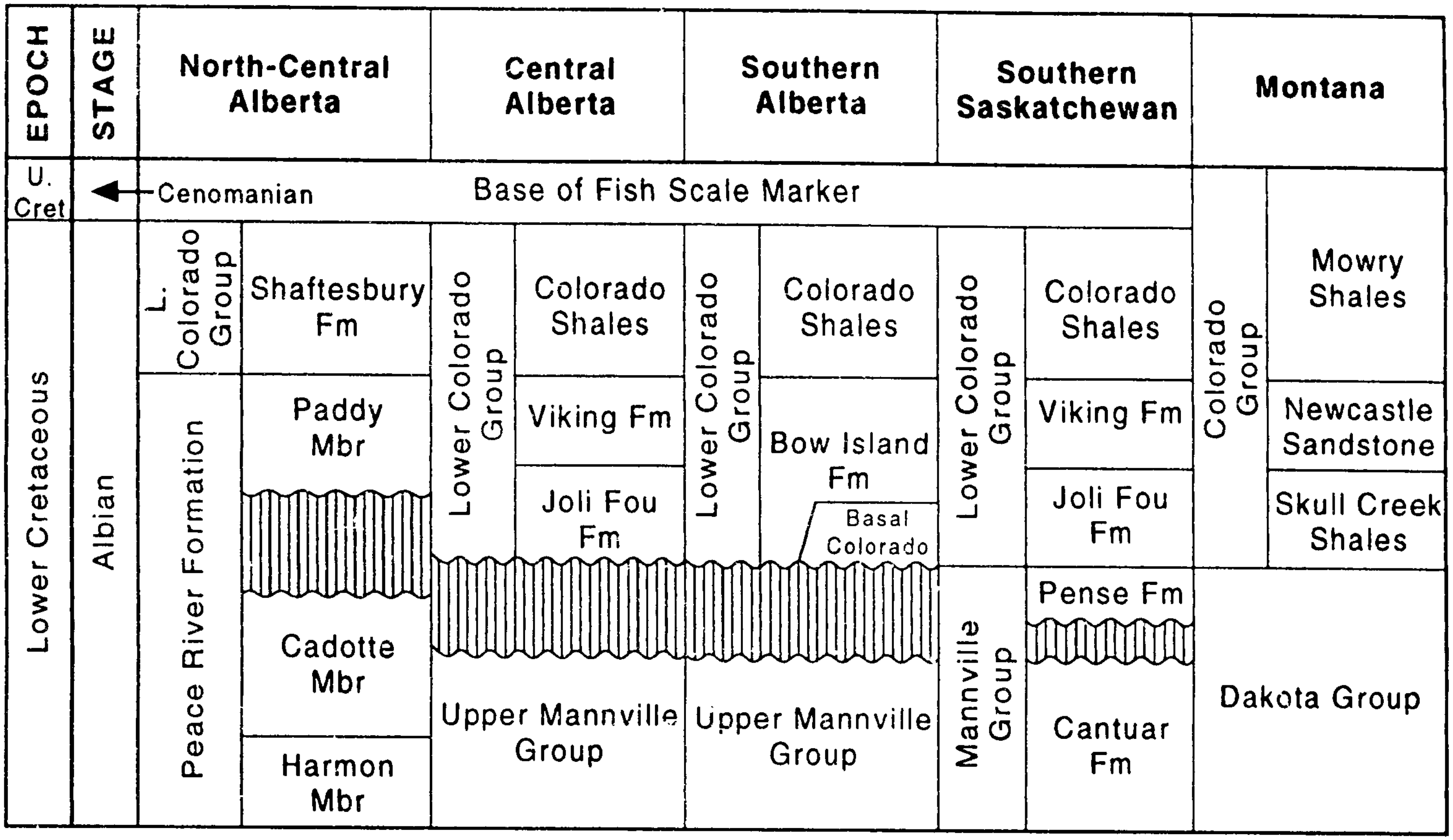


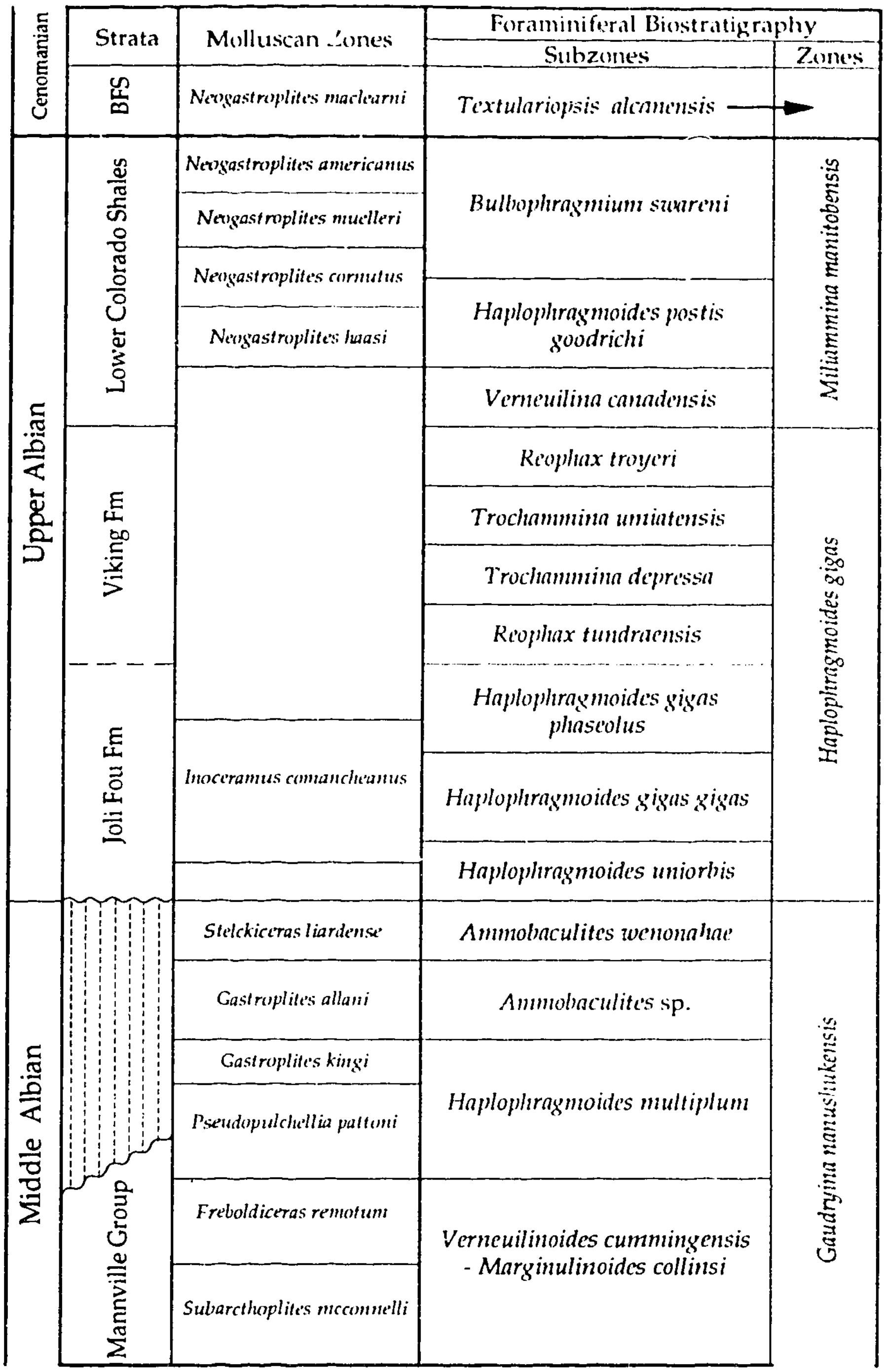
Figure VII-2. Stratigraphic correlation chart for the Viking Formation and equivalents.

J-Sandstone in Montana, Wyoming and Colorado, respectively (McGookey *et al.*, 1972; Beaumont, 1984; Weimer, 1984).

The overlying marine shales are typically referred to as the Lower Colorado shales (Stelck, 1958), the Lloydminster shale (Tizzard and Lerbekmo, 1975) or the unnamed shale member of the Colorado Group (Evans, 1970; Downing and Walker, 1988). More recently, Bloch *et al.*, (1993) have proposed that the Colorado Group, from the top of the Viking Formation to the Second White Speckled Shale, be subdivided and assigned formal units. They are, in ascending order, the Westgate Formation, the Base of Fish Scale Formation, the Belle Fourche Formation and the Second White Speckled Shale Formation. As such, the shales overlying the Viking Formation are equivalent to the proposed Westgate Formation. The shales of the Westgate Formation are stratigraphically equivalent to the lower part of the Shaftesbury Formation, overlying the Peace River Formation (Stelck and Leckie, 1990; Leckie *et al.*, 1990; Bloch *et al.*, 1993), and to part of the Hasler Formation, Goodrich and lower part of the Cruiser Formation in N.E. British Columbia (Stelck and Koke, 1987; Stelck and Leckie, 1990). In the United States, the shales are equivalent to the Mowry shale in Montana and North Dakota (McGookey *et al.*, 1972).

A formal biostratigraphy using arenaceous foraminiferal assemblages has been established for the upper Albian Hasler Formation in N.E. British Columbia and its equivalents (Figure VII-3), based largely on the work of Stelck (1975), Caldwell *et al.* (1978), Stelck and Hedinger (1983), Koke and Stelck (1985), Stelck and Koke (1987), Stelck and Leckie (1990) and Stelck (1991). The Joli Fou and Viking formations occupy the *Haplophragmoides gigas* Zone, overlying the *Ammobaculites wenonahae* subzone of the *Gaudryina nanushukensis* Zone. The zone is, in turn, overlain by the *Verneuilina canadensis* subzone of the *Miliammina manitobensis* Zone. Detailed studies of the Hasler Formation shales have led to the subdivision of the *H. gigas* Zone into seven discrete subzones. Unfortunately, this subdivision h yet successfully been carried south into central Alberta.

Several authors have suggested that there exists a disconformity of both local and regional extent between the Joli Fou and Viking formations (*e.g.* Jones, 1961; Evans, 1970; *cf.* Beaumont, 1984), although there does not appear to be an absence of any molluscan or foraminiferal zones. Stelck (1958) recognised a general thinning of the Viking to the north and west. The Joli



	Strata	Molluscan Zones	Foraminiferal Biostratigraphy	
			Subzones	Zones
Cenomanian	BFS	*Neogastroplites maclearni*	*Textulariopsis alcanensis* →	
Upper Albian	Lower Colorado Shales	*Neogastroplites americanus*	*Bulbophragmium swareni*	*Miliammina manitobensis*
		Neogastroplites muelleri		
		Neogastroplites cornutus	*Haplophragmoides postis goodrichi*	
		Neogastroplites haasi		
			Verneuilina canadensis	
	Viking Fm		*Reophax troyeri*	*Haplophragmoides gigas*
			Trochammina umiatensis	
			Trochammina depressa	
			Reophax tundraensis	
	Joli Fou Fm		*Haplophragmoides gigas phaseolus*	
		Inoceramus comancheanus	*Haplophragmoides gigas gigas*	
			Haplophragmoides uniorbis	
Middle Albian	Mannville Group	*Stelckiceras liardense*	*Ammobaculites wenonahae*	*Gaudryina nanushukensis*
		Gastroplites allani	*Ammobaculites* sp.	
		Gastroplites kingi	*Haplophragmoides multiplum*	
		Pseudopulchellia pattoni		
		Freboldiceras remotum	*Verneuilinoides cummingensis* - *Marginulinoides collinsi*	
		Subarcthoplites mcconnelli		

Figure VII-3. Correlation of Molluscan Zones and Foraminiferal Zones/ Subzones within the Albian, and its relationship to the Joli Fou and Viking formations. BFS refers to the Base of Fish Scales Marker [modified from Stelck (1991) and Stelck (pers. comm., 1993)].

Fou does not appear to be preserved north of the Kaybob field, having been removed by one of a number of intra-Viking discontinuities. Boreen and Walker (1991) described a veneer of scattered granules separating black shales of the Joli Fou Formation from the siltier shales of the basal Viking Formation in the Willesden Green area, although they could not demonstrate erosion on the surface. In the Kaybob area, the Joli Fou-Viking contact does not appear to be disconformable, and reflects a downlap surface.

The Viking Formation is internally complex, and contains numerous discontinuities which have led to several attempts to subdivide the interval into regionally correlative units (Figures VII-4 and VII-5). Downing and Walker (1988), Raddysh (1988), Raychaudhuri (1989), Davies (1990), Boreen and Walker (1991) and Pattison (1991a,b, 1992) have sought to establish a formal allostratigraphic framework for the Viking, according to the rules of the North American Code of Stratigraphic Nomenclature (NACSN, 1983). Of these attempts, the most notable and effective have been Boreen and Walker (1991; Figure VII-4) and Pattison (1991a,b; Figure VII-5). Others have taken a sequence stratigraphic approach to the subdivision of the interval (*e.g.* Posamentier and Chamberlain, 1991, 1993; Leckie and Reinson, in press). To date, a paucity of good internal markers and lack of a precise biostratigraphic framework for the interval in central Alberta have limited the ability of researchers to carry their correlations reliably across the area.

JOLI FOU FORMATION TRANSGRESSION

In the Kaybob area, the base of the Joli Fou Formation consists of a pronounced transgressive lag of chert and intraformationally-derived pebbles overlying the Mannville Group (Figures VII-6 and VII-7), corresponding to transgressive modification of a subaerially exposed unconformity (*i.e.* an FS/SB; Van Wagoner *et al.*, 1990; Pemberton and MacEachern, in press). Locally, a *Glossifungites* assemblage of *Thalassinoides*/*Spongeliomorpha* demarcates the FS/SB, overlain by sandy shales containing intraformationally-derived siderite-cemented mudstone clasts, chert pebbles and coarse granules of sand and chert (*cf.* MacEachern *et al.*, 1992b; Chapter II).

The lag grades up through a finer-grained sandy shale and into dark, locally fissile silt-poor shale, which characterises the Joli Fou Formation.

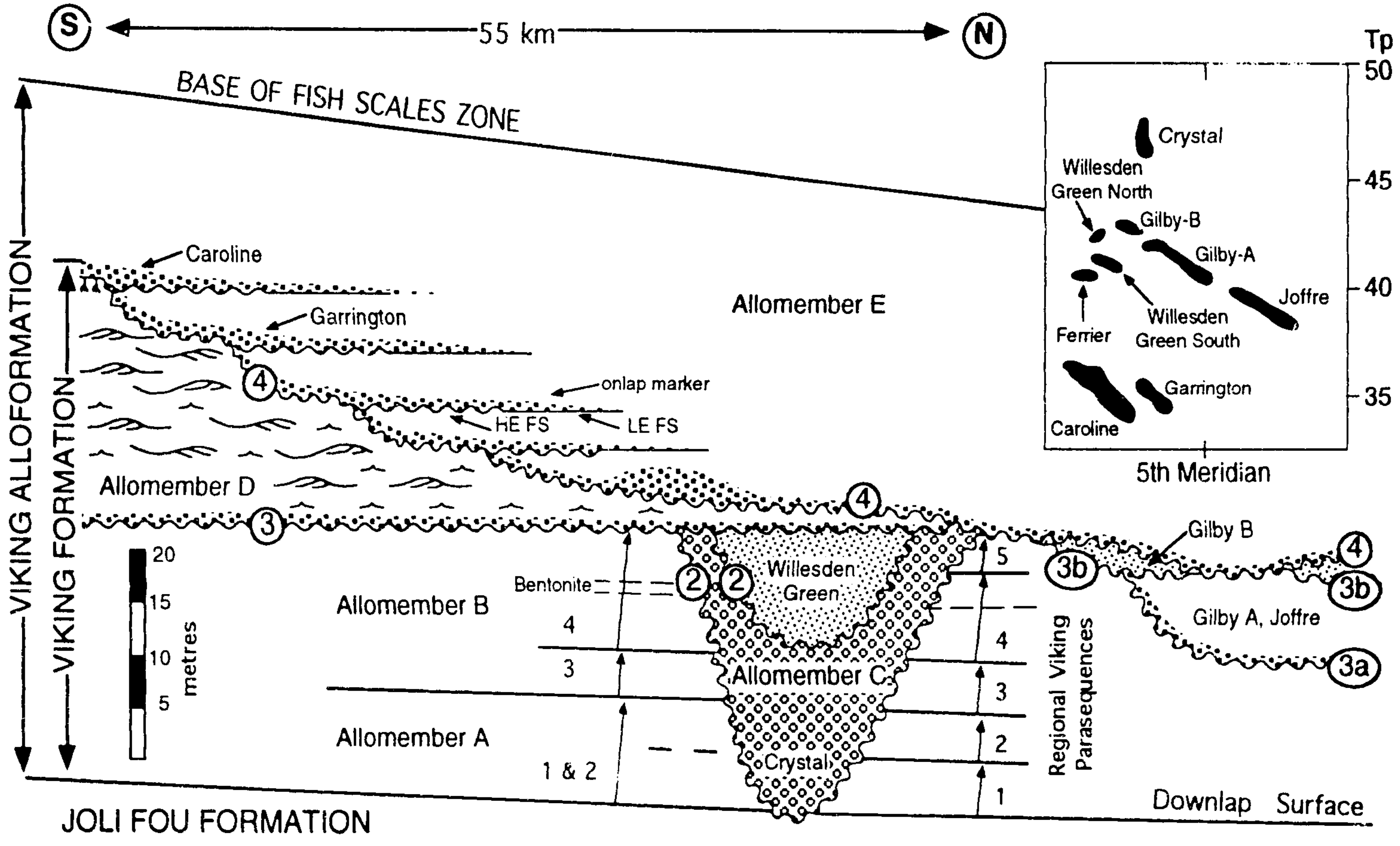


Figure VII-4. Allostratigraphic framework proposed for the Viking Formation. The Viking Alloformation contains 5 Allomembers (A-E), separated from one another by regional discontinuities. The main discontinuities are VE2 (2), VE3 (3) and VE4 (4), with secondary erosion surfaces present as well. Figure modified after Boreen and Walker (1991).

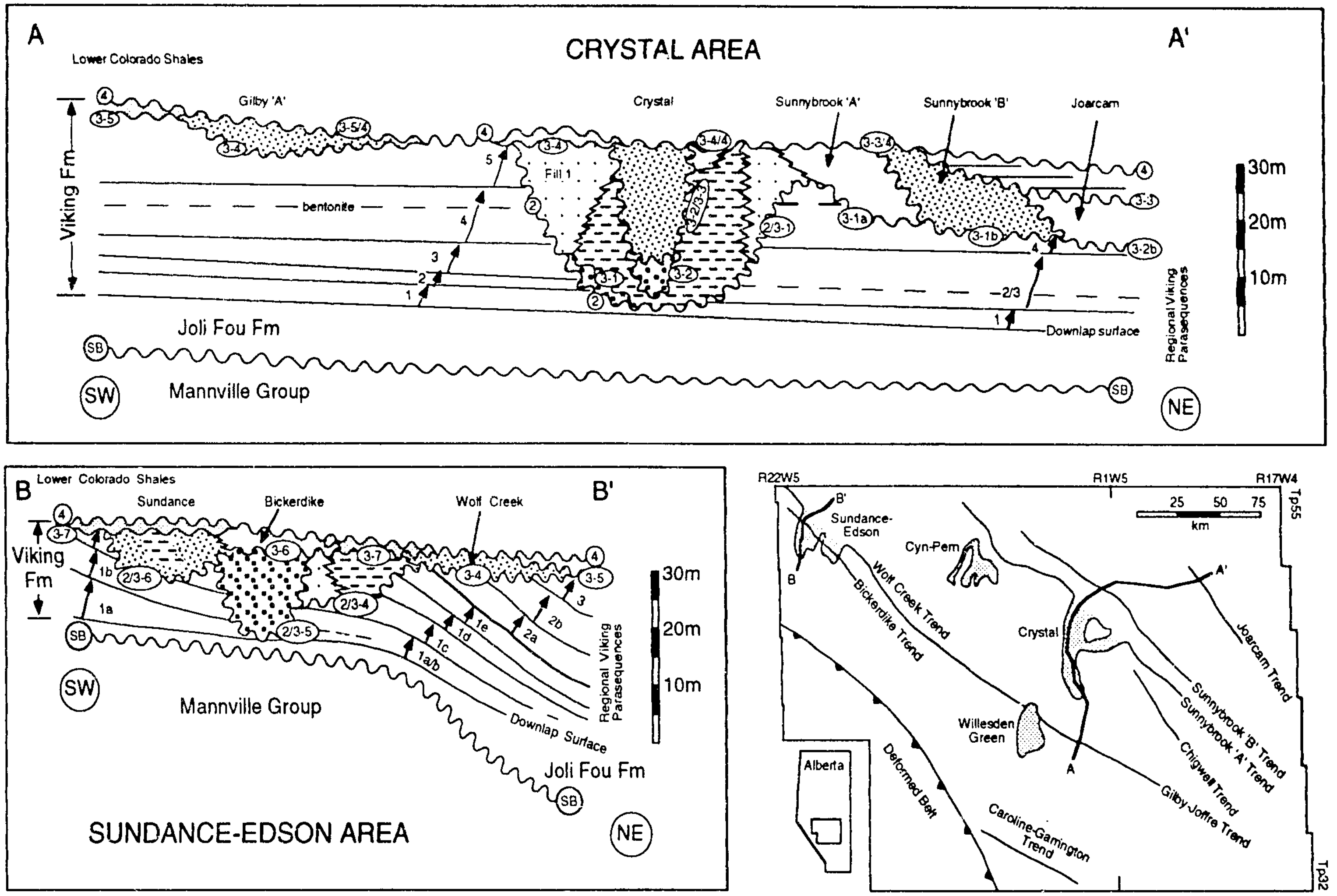


Figure VII-5. Revised allostratigraphic framework for the Viking Formation by Pattison (1991a). The VE3 surface has been subdivided into 7 discrete surfaces (3-1 to 3-7). In addition, surfaces are locally amalgamated, designated by a backslash (*i.e.* 2/3-5). This second generation allostratigraphy highlights the complexity of the VE3 transgression in central Alberta. Figure modified after Pattison (1991a).

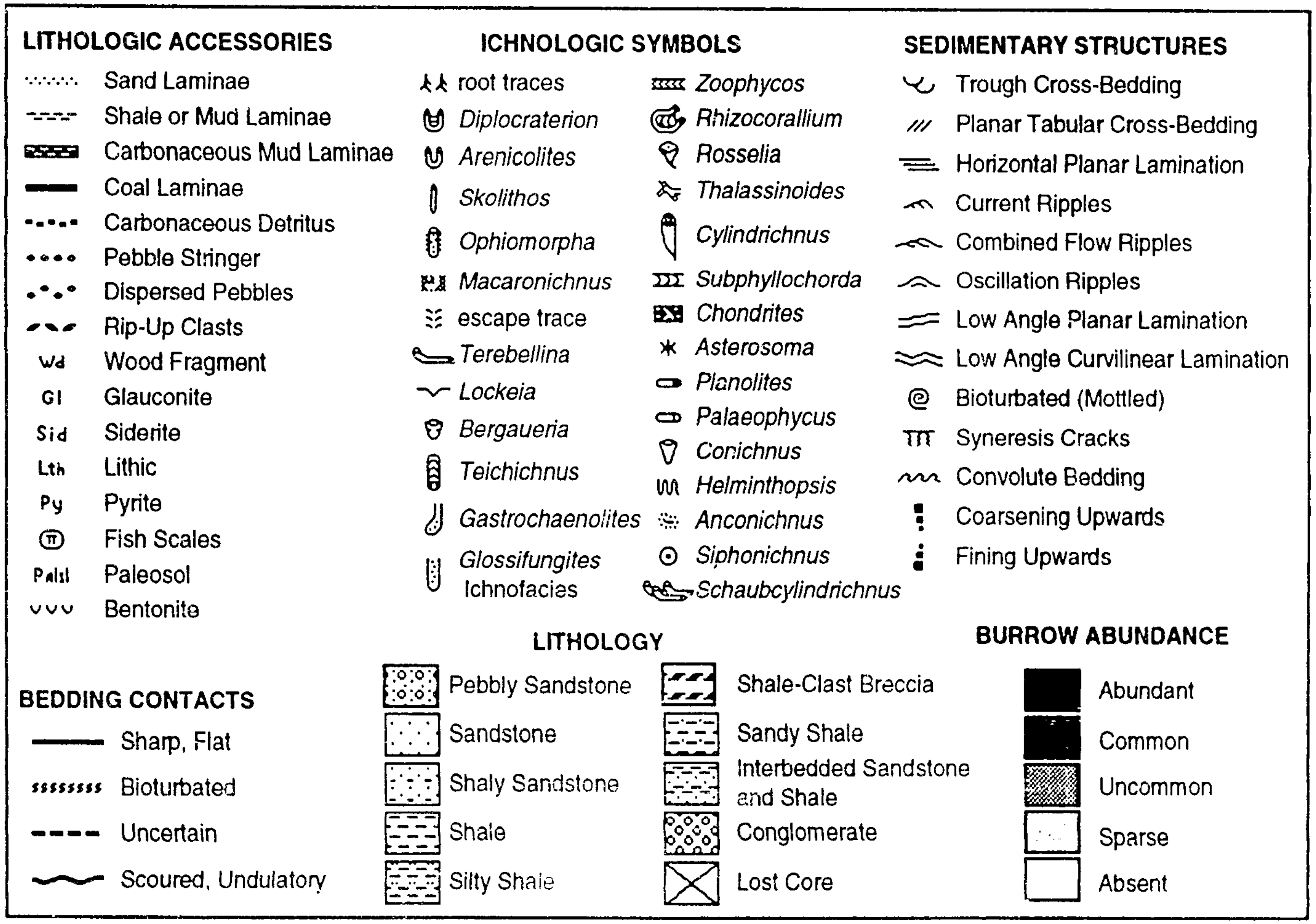


Figure VII-6. Legend of Symbols used in Lithologs and Cross-section.

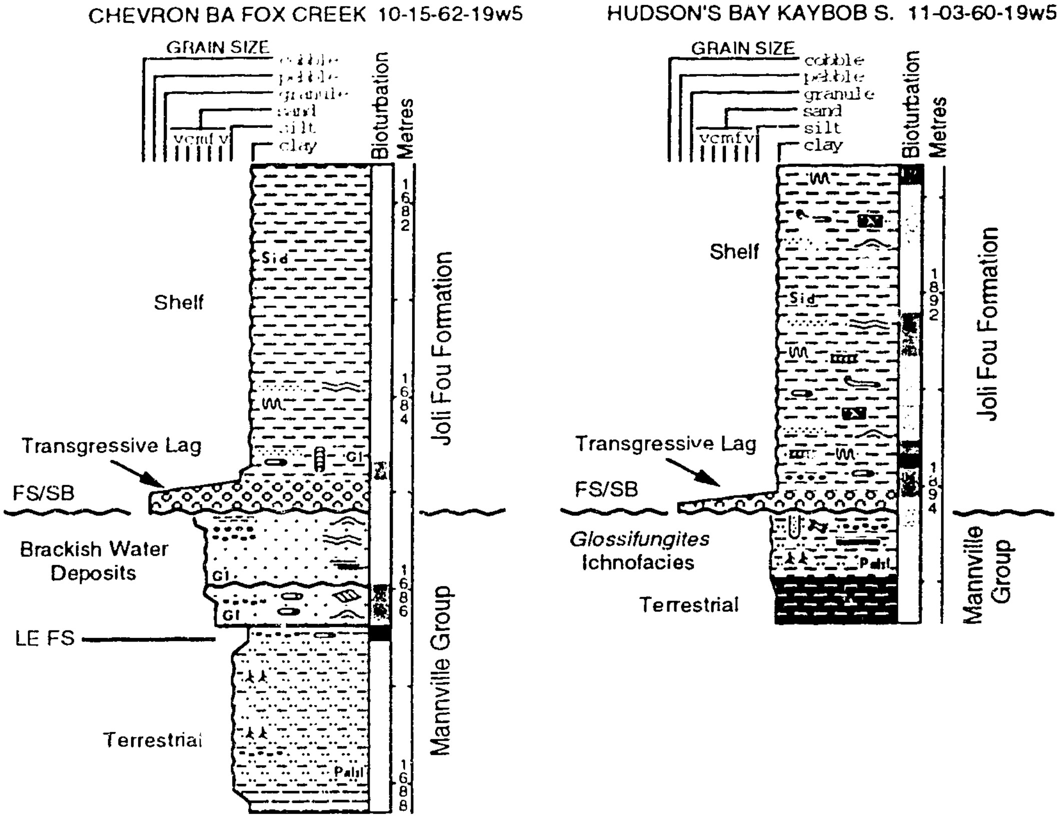
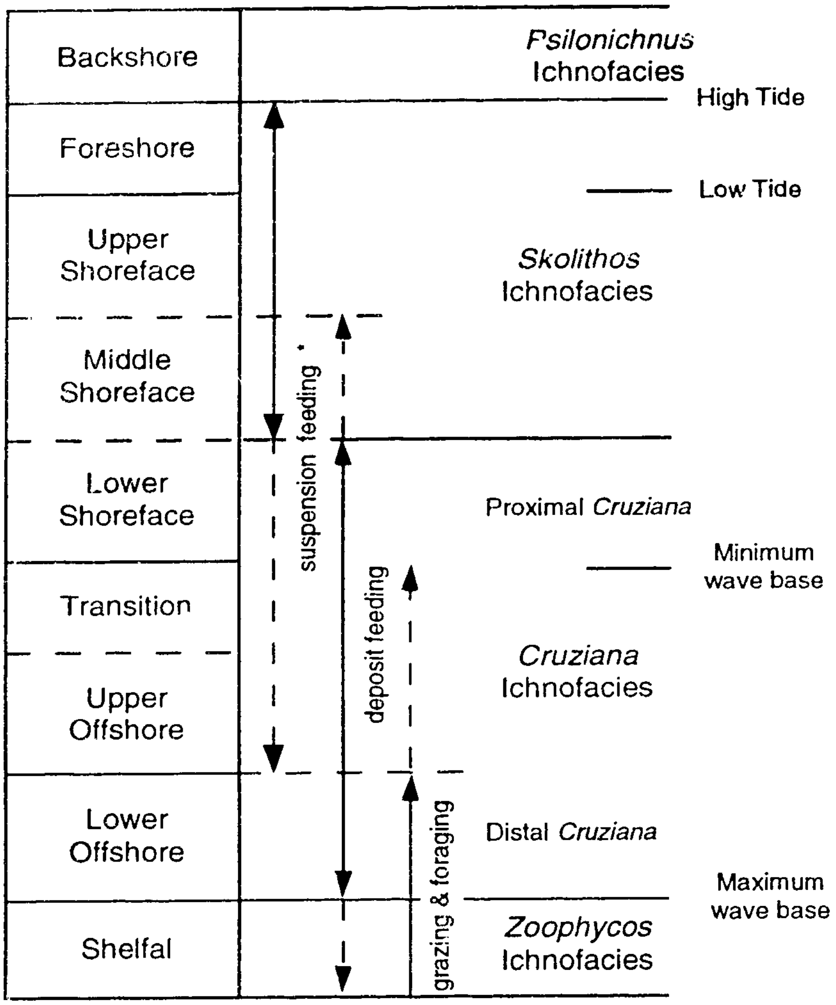


Figure VII-7. Lithologs showing the contact between the Mannville Group and the overlying Joli Fou Formation. The Mannville Group is largely terrestrial in the area, with evidence of brackish water deposits highlighting the onset of transgression. The main transgressive event is manifest by a high energy marine flooding surface across a subaerial exposure surface, producing an FS/SB. The 11-03-60-19W5 well contains a *Glossifungites* assemblage demarcating the erosional discontinuity. The Joli Fou Formation contains a transgressive lag directly overlying the FS/SB, and passes upwards into dark marine shales reflecting shelfal conditions. The legend of the symbols used in the lithologs is given in Figure VII-6.

Rare, thin (<1 cm) sandstone layers, containing low angle parallel lamination, are interpreted as distal storm beds. Pyrite and carbonaceous detritus are locally present. Trace fossils are not commonly visible, but this may reflect a taphonomic rather than environmental control (*cf.* MacEachern *et al.*, 1992a). Samples collected for microfossil analysis show relatively large numbers of arenaceous foraminifera with a high diversity of species. Trace fossils are mainly *Helminthopsis, Planolites, Terebellina,* rare *Chondrites, Anconichnus,* and very rare *Thalassinoides*. *Zoophycos* has been observed in only a few intervals. The character of the facies, coupled with the presence of diminutive traces of grazing and surface deposit feeding organisms supports a *Zoophycos* to distal *Cruziana* ichnofacies, characteristic of shelfal to lower offshore environments (Figure VII-8; MacEachern and Pemberton, 1992).

REGIONAL VIKING PARASEQUENCES: BASAL VIKING DEPOSITION

There does not appear to be a disconformity between the Joli Fou shales and the silty shales of the lower Viking Formation parasequences in the Kaybob area. Instead, the regional Viking parasequences downlap onto the Joli Fou shales. Each parasequence is bounded above and below by low energy (non-erosional) marine flooding surfaces, and form coarsening upward successions of regional extent. Pattison (1991a) mapped five main cycles (fourth-order parasequences), the lower two of which contain numerous minor cycles (fifth-order parasequences) in the lower Viking Formation, which he interpreted to reflect changes in relative sea level attributable to a combination of eustasy, local or regional tectonics, and variations in sediment supply. The fourth-order parasequences are capped by more regionally extensive flooding surfaces and are capped by thicker marine shales than the fifth-order parasequences. The parasequences reflect shelfal to distal lower shoreface progradation from the northwest to the southeast, with a NNE-SSW oriented strike. The parasequences occur as a regionally extensive progradational parasequence set, indicating accumulation within a highstand systems tract, downlapping onto the Joli Fou Formation marine shales of the underlying transgressive systems tract (Figure VII-9; *cf.* Pattison, 1991a; Pemberton and MacEachern, in press).



ICHNOLOGICAL-SEDIMENTOLOGICAL SHOREFACE MODEL

* Many tube dwellers are passive carnivores rather than suspension feeders.

Figure VII-8. Idealised shoreface model of ichnofacies successions, based on observation of Cretaceous strata of the Western Interior Seaway of North America (modified after Pemberton *et al.*, 1992a).

FOURTH- AND FIFTH-ORDER PARASEQUENCES IN THE REGIONAL VIKING FORMATION

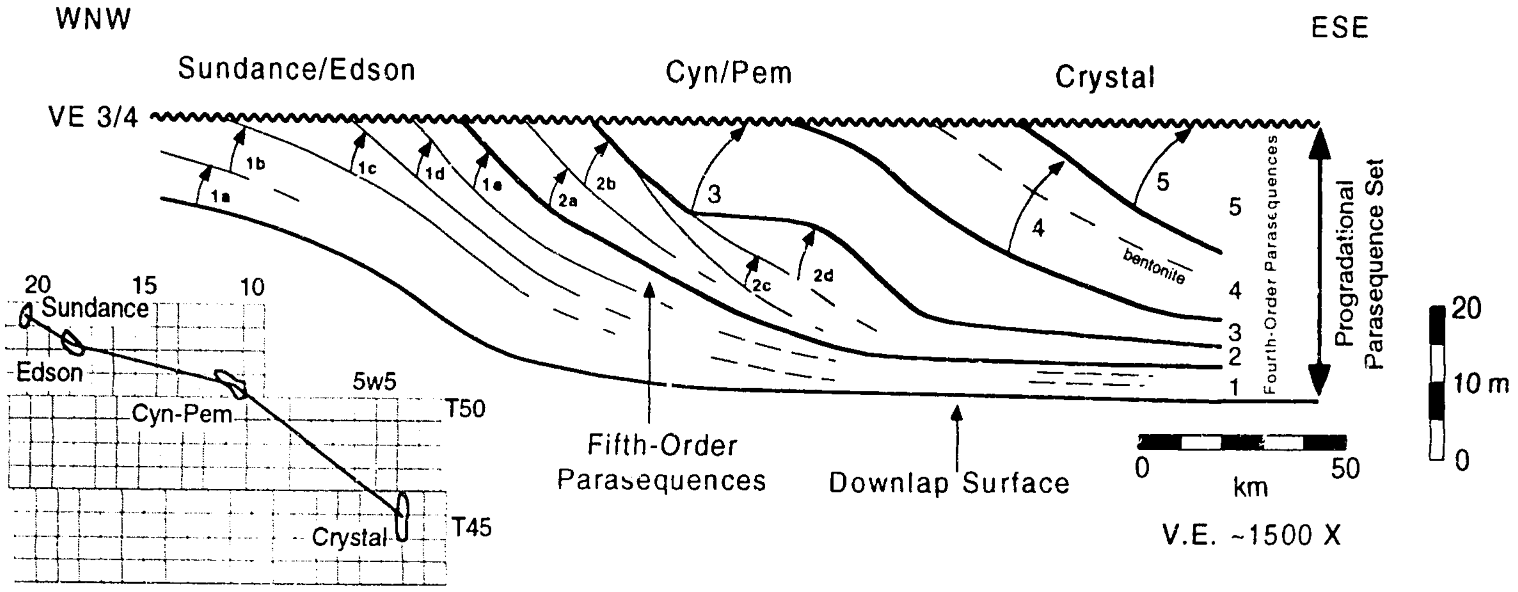


Figure VII-9. Regionally Extensive Parasequences of the Viking Formation. This schematic cross-section shows the character of a number of coarsening upward successions in the basal portion of the Viking Formation. The main successions (1-5) correspond to fourth-order parasequences, consisting of shelfal/lower offshore to lower shoreface deposition. The lower two fourth-order parasequences consist of a number of fifth-order parasequences. All parasequences are generally bounded by low energy flooding surfaces. The overall stacking pattern corresponds to a progradational parasequence set, reflecting a highstand systems tract. The succession is truncated by a high energy flooding surface (VE3/4). The map to the lower left indicates the approximate line of section. Figure modified after Pattison (1991a).

Three facies make up a complete coarsening cycle within the parasequences. The basal facies consists of silty shale, typically showing intense bioturbation (Figure VII-10 A). Silt is dispersed biogenically throughout the facies, and may locally be present as discontinuous remnants or stringers. Very rare, vfL-vfU grained sand interbeds (<2 cm thick) may be intercalated, and possess low angle wavy parallel lamination or combined flow ripple lamination, interpreted as distal tempestites.

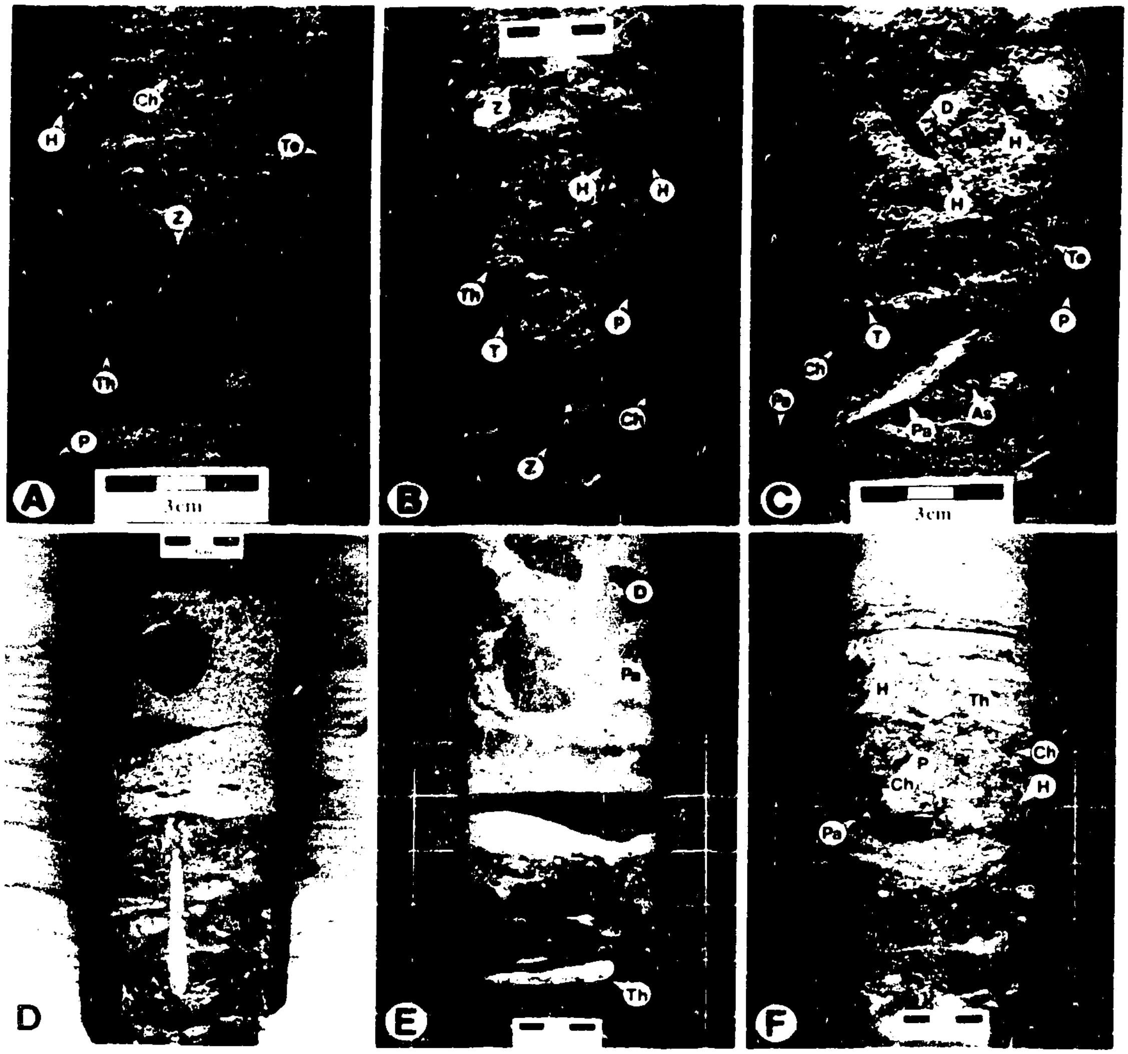
The observed trace fossils of the silty shale facies are uniformly distributed and present in most intervals studied, with the exception of the accessory traces. *Helminthopsis*, *Chondrites*, *Planolites* and *Terebellina* comprise the dominant elements of the suite, occurring in moderate to abundant numbers. *Zoophycos* and *Thalassinoides* constitute the secondary elements, with *Asterosoma*, *Teichichnus*, *Rhizocorallium*, *Palaeophycus*, *Rosselia* and fugichnia exceedingly uncommon.

Grading from the silty shale facies is the sandy shale facies (Figure VII-10 B, C). Sand is typically vfL-fU in grain size and is present both as biogenically dispersed grains and as remnant wavy parallel laminated or combined flow ripple laminated tempestite beds. Burrowing is generally uniform and intense, although a few parasequences (*e.g.* cycle 3 of the Cyn-Pem field area; *cf.* Pattison, 1991a) show reduced degrees of burrowing.

The trace fossil suite of the sandy shale facies is more diverse than that of the silty shale underlying it, and is dominated by *Helminthopsis*, *Chondrites*, *Planolites*, *Terebellina*, *Teichichnus* and *Asterosoma*, with moderate numbers of *Zoophycos*, *Palaeophycus*, *Thalassinoides*, *Skolithos* and *Diplocraterion* constituting the secondary elements. Accessory elements are rare in numbers and are represented by *Rosselia*, *Arenicolites*, *Cylindrichnus*, *Rhizocorallium*, *Ophiomorpha*, *Siphonichnus*, *Lockeia* and fugichnia (escape traces).

Grading upward from the sandy shale facies is the muddy sandstone facies. The muddy sandstone facies is not commonly preserved in the Kaybob area, although it is well-developed in parasequences to the south and east. The sand remains vfL-fU in grain size, though typically fL; mud is generally dispersed throughout the facies and present as partings and discontinuous stringers. Discrete sandstone beds are rare, but show remnant wavy parallel lamination where present, and are interpreted as tempestites. The general absence of discrete sandstone beds is a reflection of the high degree of

Figure VII-10. Underlying Facies and Erosional Discontinuity. (A) Silty shale facies underlying the erosional discontinuity, with a distal *Cruziana* ichnofacies consisting of *Zoophycos* (Z), *Thalassinoides* (Th), *Planolites* (P), *Teichichnus* (Te), *Helminthopsis* (H) and *Chondrites* (Ch). The facies occurs at the base of regional Viking Formation parasequences, and reflects shelfal to lower offshore deposition. Well 11-29-62-20W5, depth 1707.0 m. **(B)** Sandy shale facies underlying the erosional discontinuity, intensely burrowed with a *Cruziana* ichnofacies consisting of *Zoophycos* (Z), *Thalassinoides* (Th), *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch) and *Terebellina* (T). The facies occurs in the regional Viking Formation parasequences, and reflects upper offshore deposition. Well 12-11-62-20W5, depth 1704.3 m. **(C)** Sandy shale facies underlying the erosional discontinuity, intensely burrowed with a *Cruziana* ichnofacies consisting of *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch), *Diplocraterion* (D), *Palaeophycus* (Pa) *Terebellina* (T), *Asterosoma* (As) and *Teichichnus* (Te). The facies occurs in the regional Viking Formation parasequences, and reflects upper offshore deposition. Well 11-29-62-20W5, depth 1705.9 m. **(D)** Erosional discontinuity at the base of the Kaybob sand body, truncating bioturbated sandy shales of an underlying regional Viking Formation parasequence. A *Glossifungites* assemblage, consisting of *Skolithos* (arrow) subtends from the discontinuity. The discontinuity, interpreted as a sequence boundary, is overlain by trough cross-stratified sandstone with intraformationally-derived siderite-cemented rip-up clasts. Well 11-35-61-20W5, depth 1759.1 m. **(E)** Erosional discontinuity (sequence boundary) at the base of the Kaybob sand body, truncating bioturbated silty shales of a regional Viking parasequence. A *Glossifungites* assemblage, consisting of *Thalassinoides/?Spongeliomorpha* (Th) demarcates the break. Bioturbated muddy sandstones of the lower shoreface overlie the break, and contain *Palaeophycus* (Pa) and *Diplocraterion* (D). Well 10-15-62-19W5, depth 1672.0 m. **(F)** Discontinuity at the base of the Kaybob sand body. In this location, a *Glossifungites* suite is not developed, but the underlying sandy shales of a regional Viking parasequence pass abruptly upwards into bioturbated muddy sandstones and laminated sandstones of the Kaybob sand body. The discontinuity has been biogenically modified, and hence, is cryptic. The overlying sandstones reflect lower to middle shoreface deposition, and contain *Planolites* (P), *Palaeophycus* (Pa), *Chondrites* (Ch), *Thalassinoides* (Th) and *Helminthopsis* (H). Well 12-11-62-20W5, depth 1704.2 m.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bioturbation and the penetrative action of more robust infauna than in the previously described facies (*cf.* Chapters IV and V).

The dominant trace fossil elements of the muddy sandstone facies are *Planolites, Terebellina, Chondrites, Helminthopsis, Asterosoma, Palaeophycus, Skolithos, Teichichnus, Rosselia* and *Diplocraterion*. Secondary elements occur in rare to moderate numbers and include *Ophiomorpha, Arenicolites, Zoophycos* and *Cylindrichnus*. Accessory elements are rare in numbers, and include *Thalassinoides, Rhizocorallium, Schaubcylindrichnus, Lockeia, Siphonichnus* and fugichnia.

The regionally extensive Viking Formation cycles reflect both coarsening upward of facies and an increase in diversity of ichnogenera, under fully marine conditions. Each major cycle is interpreted as lower offshore to distal lower shoreface progradation (Figure VII-8). The silty shale facies reflects a dominance of grazing and surface deposit feeding structures of the distal *Cruziana* ichnofacies and is interpreted as lower offshore deposition. Rare, thin sand beds reflect the distal deposits of exceptionally strong storms. The sandy shale facies shows a more diverse suite of trace fossils and a dominance of deposit feeding over grazing behaviour. The introduction of suspension feeding and passive carnivore structures within the fairweather assemblage is also distinctive, and is interpreted to indicate shallowing. This facies is interpreted as upper offshore deposition at and above storm weather wave base. Remnant laminated sandstone beds record preservation of tempestites whose thicknesses exceeded the infauna's ability to completely obliterate it (*cf.* Wheatcroft, 1990; Chapter IV). The muddy sandstone facies shows an increase in diversity of behaviour, with a decrease in the dominance by individual forms. Deposit feeding structures dominate, with diminishing influence of grazing behaviour and enhanced influence of suspension feeding, reflecting a proximal *Cruziana* suite. This facies is interpreted as distal lower shoreface deposition. All facies of the regional parasequences display trace fossil suites consistent with a fully marine, equilibrium or K-selected strategy of population kinematics (*cf.* Pianka, 1970; Jumars, 1993), typical of unstressed settings. The lack of dominance by individual ichnogenera, as well as the presence of elaborate or specialised behaviours supports an equilibrium community. The thorough bioturbation which characterises the succession suggests that sedimentation was relatively slow and continuous (Howard, 1975).

INTRA-VIKING FORMATION EROSIONAL DISCONTINUITY

The regional Viking parasequences are abruptly truncated by an erosional discontinuity in several wells in the Kaybob area, defining the base of the main sand body in the field (Figure VII-10 D-F). The discontinuity is interpreted to reflect a sequence boundary (lowstand surface; *cf.* Van Wagoner *et al.*, 1990; Posamentier and Vail, 1988; Posamentier *et al.*, 1992), based upon the rapid shallowing indicated by the character of the facies above the contact, as well as the erosional nature of the break. The sequence boundary is biogenically churned in several locations at Kaybob. In contrast to other forced regression shoreface successions (*e.g.* the Viking Fm of the Chigwell field, Raychaudhuri, 1989; Raychaudhuri *et al.*, 1992; the Viking Fm of the Joarcam field, Posamentier and Chamberlain, 1991, 1993; and outcrops of the Campanian Shannon Sandstone near Casper, Wyoming, Walker and Bergman, 1993) the Kaybob example lacks visible chert or phosphatic pebbles along the erosion surface. It is, however, locally demarcated by a *Glossifungites* suite of *Skolithos*, *Thalassinoides* and rare *Diplocraterion*, passively filled with medium- to coarse-grained sand from the overlying sand body (Figure VII-10 D, E).

The *Glossifungites* Ichnofacies

The *Glossifungites* ichnofacies (redefined by Frey and Seilacher, 1980) encompasses trace fossils associated with semilithified or firm substrates. The substrates typically consist of dewatered, cohesive muds, due either to subaerial exposure, or burial and subsequent exhumation (Figure VII-11; *cf.* Pemberton and Frey, 1985). Less commonly, *Glossifungites* suites may be developed in incipiently-cemented sandstone substrates (Saunders and Pemberton, 1986; Saunders, 1989). The *Glossifungites* ichnofacies is one of three substrate-controlled assemblages; the other two constituting the *Trypanites* and *Teredolites* ichnofacies. In contrast to the latter two, the *Glossifungites* assemblage is the most common substrate-controlled suite in siliciclastic intervals.

The characteristics and general applications of the *Glossifungites* ichnofacies are dealt with in detail in MacEachern *et al.* (1992b) and Chapter II. In summary, trace fossils of the *Glossifungites* ichnofacies are dominated by

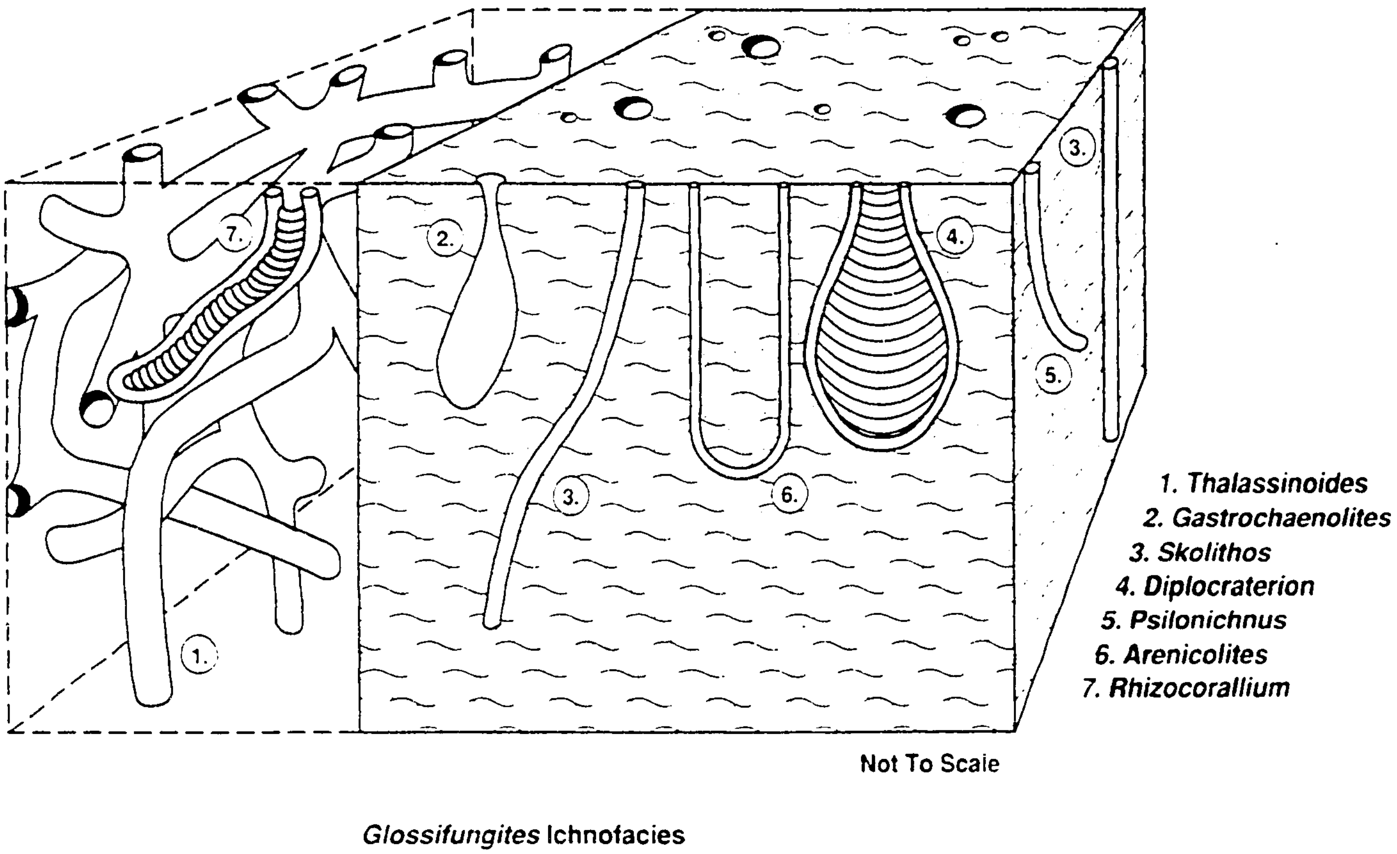


Figure VII-11. Trace fossil association characteristic of the *Glossifungites* ichnofacies (modified from Frey and Pemberton, 1984).

vertical to subvertical dwelling structures of suspension feeding organisms (Figure VII-11). In the Viking Formation, the most common structures correspond to the ichnogenera *Diplocraterion, Skolithos, Psilonichnus, Arenicolites,* and firmground *Gastrochaenolites.* Dwelling structures of deposit feeding organisms are also constituents of the ichnofacies, and include firmground *Thalassinoides/Spongeliomorpha* and *Rhizocorallium.* The presence of vertical shafts within shaly intervals is anomalous, as such structures are not capable of being maintained in soft muddy substrates. Their presence suggests the substrate was not soft, but rather, stiff. Ichnogenera of the *Glossifungites* ichnofacies are typically robust, commonly penetrating 20-100 cm below the bed junction. Many shafts tend to be 0.5-1.0 cm in diameter, particularly *Diplocraterion habichi* and *Arenicolites.* This scale of burrowing is in sharp contrast to the predominantly horizontal, diminutive trace fossils common to shaly intervals. The firmground traces are generally very sharp-walled and unlined, reflecting the stable, cohesive nature of the substrate at the time of colonisation and burrow excavation (see Chapter II, Figure II-3 A, D, E). Large structures are exceedingly difficult to maintain in soft muddy substrates, and burrow linings are therefore employed by the tracemaker in an attempt to stabilise the burrow in such material. The absence of linings on *Glossifungites* burrows demonstrates that the substrate was not, in fact, soft, but firm. Many structures, particularly in outcrop, show preserved sculptings or scratch marks on the burrow wall, confirming that construction of the dwelling burrow occurred in a firm substrate (see Chapter II, Figure II-3 C). Further evidence of substrate stability, atypical of soft muddy beds, is the passive nature of burrow fill. This demonstrates that the biogenic structure remained open after the tracemaker vacated the burrow, thus allowing material from the succeeding depositional event to passively fill the open structure. If the burrow had been excavated in soft mud, the domicile would have collapsed upon burrow vacation, unless lined. The post-depositional origin of the *Glossifungites* suite, in relation to the original softground assemblage, is clearly demonstrated by the ubiquitous cross-cutting relationships observed in the rock record. The final characteristic of the *Glossifungites* suite is the tendency to demonstrate colonisation in large numbers. In several examples, seven to fifteen firmground traces, commonly *Diplocraterion habichi,* have been observed on the bedding plane of a 9 cm (3.5 inch) diameter core; this corresponds to between 1100 to 2300 shafts per m^2 (see Chapter II, Figure II-3 B). Comparable populations were observed from *Glossifungites* suites on the modern coast of Georgia (Pemberton and Frey, 1985). Dense populations are typical of many opportunistic assemblages (Levinton, 1970; Pemberton and Frey, 1984).

Stratigraphic Applications of the *Glossifungites* Ichnofacies

In siliciclastic settings, most firmground assemblages are associated with erosionally exhumed (dewatered and compacted) substrates and, hence, demarcate erosional discontinuities. Depositional breaks, in particular condensed sections, may also be semilithified or lithified (*e.g.* Loutit *et al.*, 1988), presumably at the upper contact (or downlap surface; *cf.* Van Wagoner *et al.*, 1990) and may be colonised without associated erosion. In general, however, the recognition of substrate-controlled ichnofacies may be regarded as equivalent to the recognition of erosional discontinuities in the stratigraphic record.

Although certain insect and animal burrows in the terrestrial realm may be properly regarded as firmground (*e.g.* Fürsich and Mayr, 1981) or, more rarely, hardground suites, they have a low preservation potential and constitute a relatively minor element in the preserved record of these associations. The overwhelming majority of *Glossifungites* assemblages originate in marine or marginal marine settings. Consequently, a discontinuity may be generated in either subaerial or submarine settings, but the colonisation of the surface may be regarded to be marine-influenced, particularly in pre-Tertiary intervals. This has important implications regarding the genetic interpretation of the discontinuity in question.

Finally, the substrate-controlled ichnocoenose, which cross-cuts the pre-existing softground suite, reflects conditions *post-dating* both initial deposition of the underlying unit and its subsequent erosional exhumation following burial (Figure VII-12). The *Glossifungites* suite therefore corresponds to a depositional hiatus between the erosional event and deposition of the overlying unit; significant depositional cover precludes firmground colonisation. By observing (1) the softground ichnofossil assemblage (contemporaneous with deposition of the unit), (2) the ichnofacies of the exhumed substrate, and (3) the ichnofossil assemblage of

Schematic development of a *Glossifungites* Ichnofacies

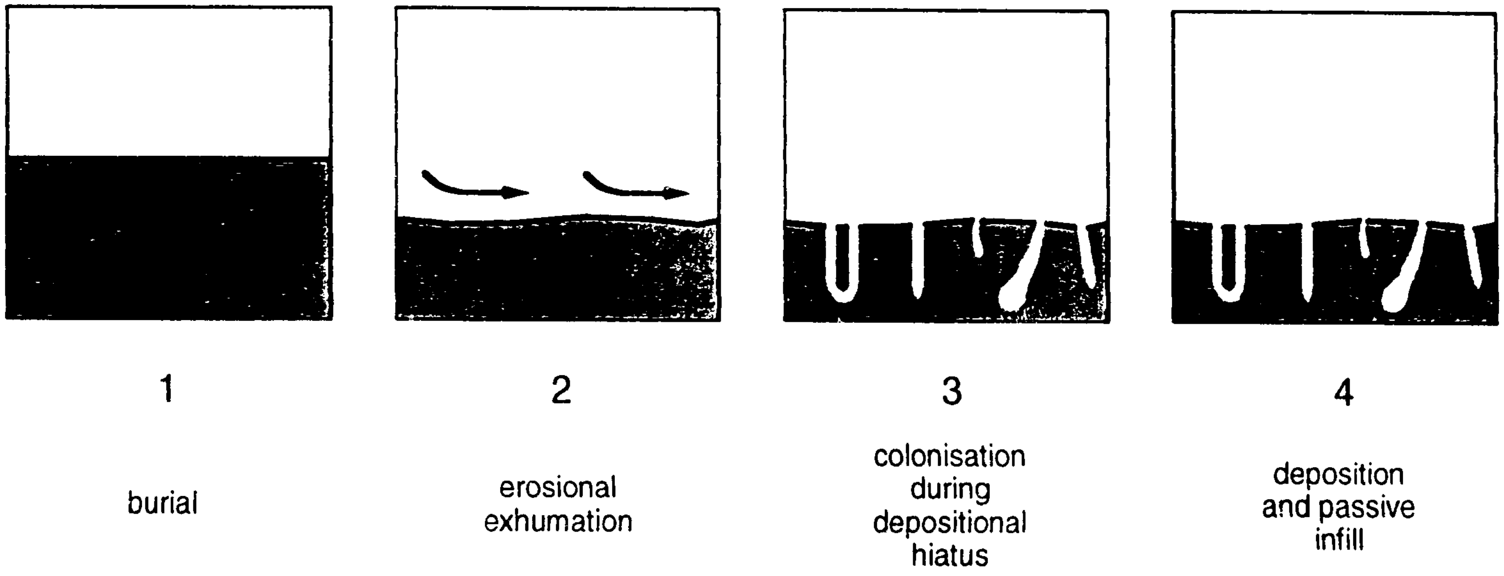


Figure VII-12. Schematic development of a *Glossifungites*-demarcated erosional discontinuity. 1) The muddy substrate is buried and dewatered, resulting in a compacted, stiff character. 2) The shaly bed is erosionally exhumed, exposing a firm substrate. 3) Colonisation of the discontinuity surface by tracemakers of the *Glossifungites* ichnofacies proceeds under marine conditions during a depositional hiatus. 4) The structures are passively filled during a succeeding depositional episode.

the overlying unit, it is possible to provide considerable insight into the origin of the surface and the allocyclic or autocyclic mechanisms responsible.

THE KAYBOB SAND BODY

The main sand body at Kaybob consists of four facies. Thoroughly burrowed sandy shales pass progressively into thoroughly burrowed muddy sandstones, interstratified parallel laminated and burrowed sandstones, to trough cross-stratified sandstones, both in ascending order in vertical succession above the sequence boundary, as well as in a distal (east) to proximal (west) trend. The entire sand body possesses a roughly NW-SE orientation, and thins rapidly to the east. This thinning is compounded by apparent truncation of the deposit by sandstones in the Fox Creek field (Figure VII-13).

Thoroughly Burrowed Sandy Shale Facies

The sandy shale facies is virtually identical to those of the regional Viking parasequences. Where the sequence boundary is not clearly preserved, discrimination between the two is virtually impossible, except for a slight coarsening of grain size from lower fine in the underlying regional parasequences, to upper fine with rare dispersed lower medium grains in the Kaybob sand body. In many of these locations, the succession may reflect deposition across a correlative conformity (*cf.* Van Wagoner *et al.*, 1990). The sandy shales are thoroughly burrowed with a highly diverse *Cruziana* ichnofacies, consisting of *Helminthopsis, Chondrites, Planolites, Zoophycos, Terebellina, Teichichnus, Palaeophycus, Thalassinoides, Rosselia, Asterosoma, Cylindrichnus, Rhizocorallium* and *Siphonichnus*. The overall suite corresponds to deposition under upper offshore conditions (Figure VII-8).

Thoroughly Burrowed Muddy Sandstone Facies

Grading upwards out of the sandy shales are the muddy sandstone facies (Figure VII-14), similar in many regards to the equivalent facies of the regional Viking succession. In slightly more proximal positions, the facies

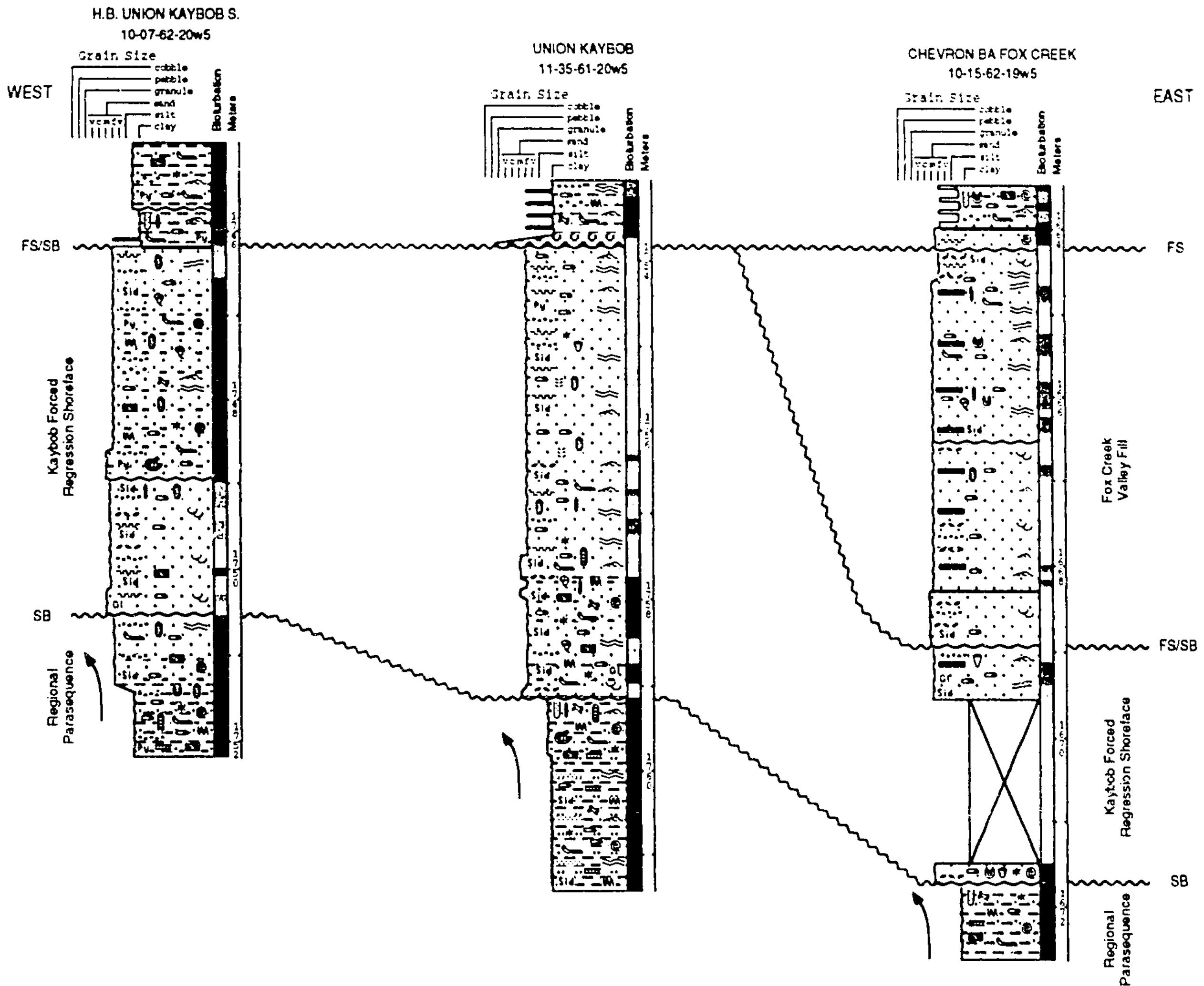
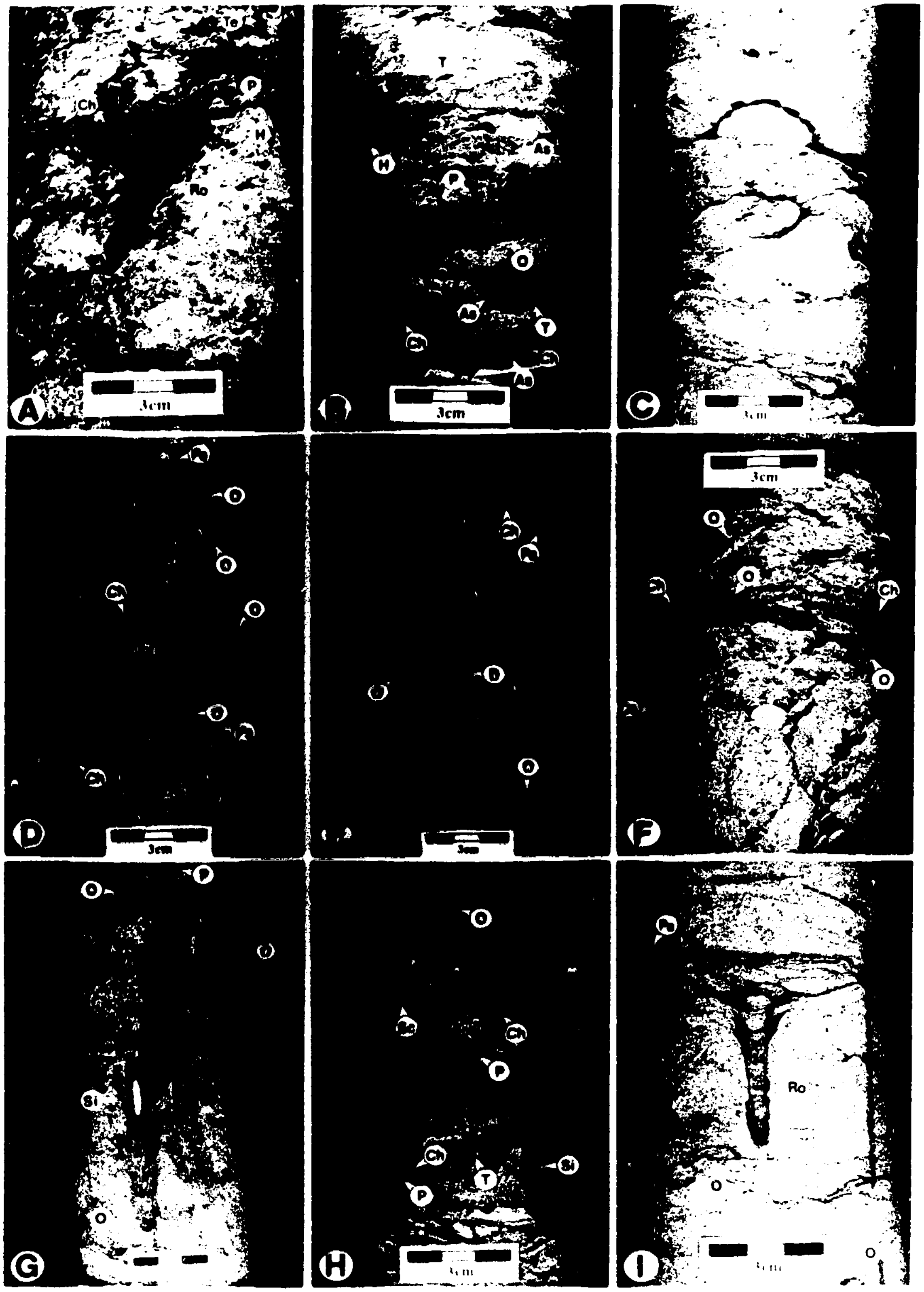


Figure VII-13. West-east (proximal-distal) litholog cross-section of the Kaybob forced regression shoreface. The forced regression shoreface overlies a sequence boundary incised into regionally extensive parasequences of the lower Viking Fm. The shoreface is erosionally removed to the east by an FS/SB, defining the base of a proposed incised valley at Fox Creek. Legend of the symbols used in the lithologs occur in Figure VII-6. The line of section is shown in Figure VII-1.

Figure VII-14. Kaybob Sand Body: Lower-Middle Shoreface Bioturbated Sandstone. **(A)** Highly muddy sandstone, with *Rosselia* (Ro), *Planolites* (P), *Helminthopsis* (H) and *Teichichnus* (Te). *Chondrites* (Ch) is also present, reburrowing the *Rosselia*. Well 04-24-62-20W5, depth 1717.9 m. **(B)** Bioturbated muddy sandstone, with well-developed *Ophiomorpha irregulaire* (O), *Terebellina* (T), *Helminthopsis* (H), *Planolites* (P), *Chondrites* (Ch) and *Asterosoma* (As). Well 06-23-62-20W5, depth 1710.8 m. **(C)** Thoroughly burrowed sandstone, with robust *Ophiomorpha irregulaire* (arrows). 11-27-62-20W5, depth 1664.5 m. **(D)** Bioturbated muddy sandstone, with vertical and inclined *Ophiomorpha irregulaire* (O), as well as *Palaeophycus* (Pa) and *Chondrites* (Ch). Well 11-29-62-20W5, depth 1702.2 m. **(E)** Thoroughly burrowed sandstone, with *Diplocraterion* (D), *Palaeophycus* (Pa), *Ophiomorpha irregulaire* (O) and *Chondrites* (Ch). Well 11-29-62-20W5, depth 1702.4 m. **(F)** Thoroughly burrowed muddy sandstone, with robust *Conichnus* (Co), as well as *Ophiomorpha irregulaire* (O) and *Chondrites* (Ch). Well 11-29-62-20W5, depth 1704.8 m. **(G)** Thoroughly burrowed sandstone, with elongate *Siphonichnus* (Si), *Ophiomorpha irregulaire* (O) and *Planolites* (P). Well 12-11-62-20W5, depth 1703.0 m. **(H)** Bioturbated muddy sandstone, with *Schaubcylindrichnus* (Sc), *Terebellina* (T), *Ophiomorpha irregulaire* (O), *Siphonichnus* (Si), *Chondrites* (Ch) and *Planolites* (P). Well 11-29-62-20W5, depth 1703.0 m. **(I)** Thoroughly burrowed sandstone, with *Ophiomorpha irregulaire* (O), *Palaeophycus* (Pa) and the basal shaft of *Rosselia* (Ro). Well 12-11-62-20W5, depth 1699.0 m.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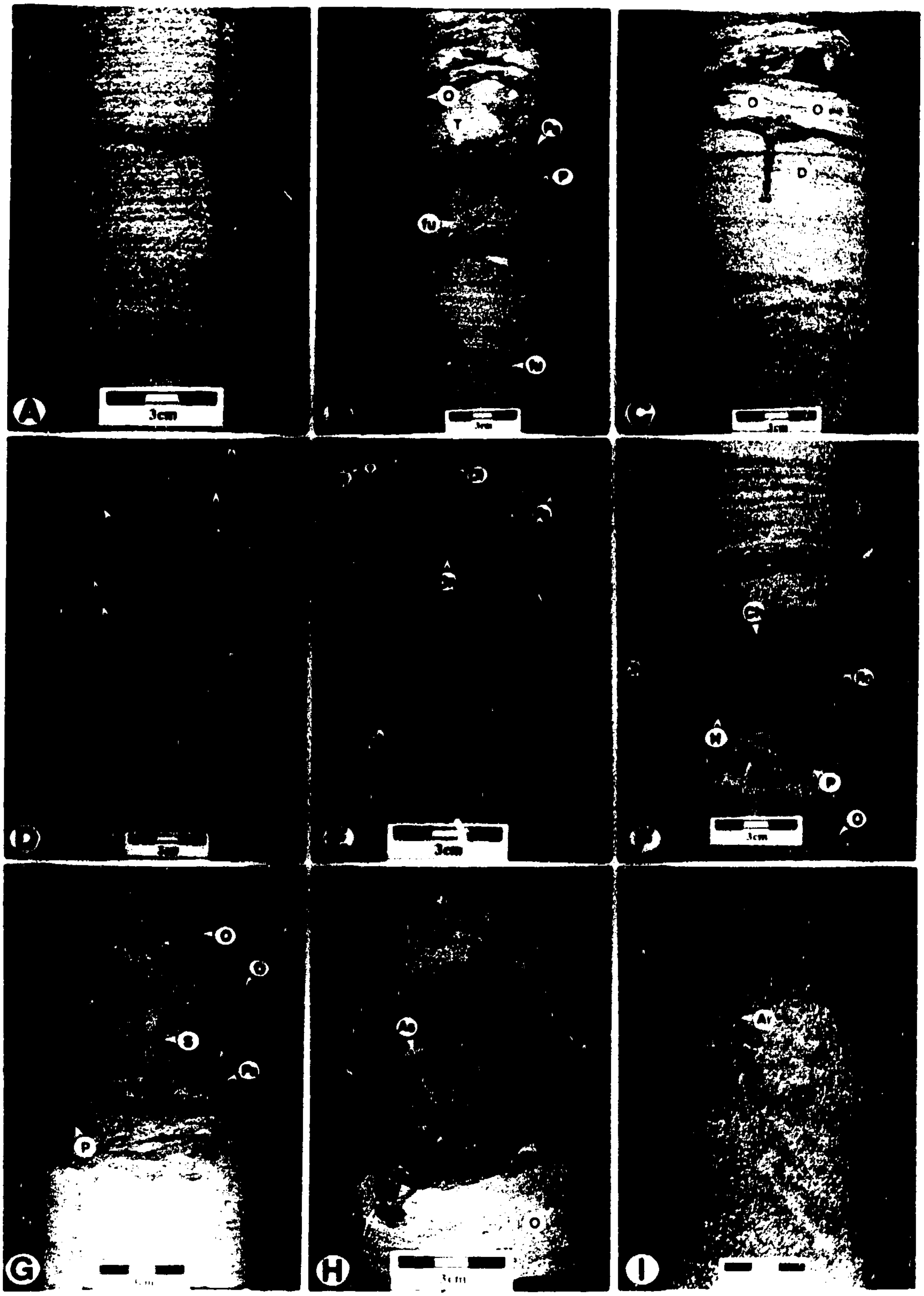
directly overlies the discontinuity (*cf.* Figure VII-10 E, F). The sandstone is somewhat coarser-grained than the regionally extensive parasequences, ranging from upper fine to lower medium, with intercalated wisps and lenses of dark, organic-rich mudstone. The facies is thoroughly burrowed and contains a proximal *Cruziana* trace fossil suite consisting of *Teichichnus, Asterosoma, Rosselia, Terebellina, Planolites, Chondrites, Rhizocorallium, Skolithos, Arenicolites, Diplocraterion, Ophiomorpha, Cylindrichnus, Palaeophycus*, and rarer *Helminthopsis, Zoophycos, Schaubcylindrichnus* and *Siphonichnus*. Remnant fugichnia may be locally observed.

The thorough degree of burrowing suggests relatively slow, continuous sedimentation (Howard, 1975), with few episodic depositional events preserved. A few tempestites are evident by the presence of remnant low angle parallel laminated sandstone lenses and associated fugichnia, but constitute minor components. The abundance of sandstone with intercalated mud lenses rather than discrete beds, suggests that the depositional zone lies within a zone of persistent wave shoaling (*i.e.* above fairweather wave base). The diverse and abundant proximal *Cruziana* ichnofacies is dominated by deposit feeding structures, with subordinate numbers of suspension feeding, passive carnivore and grazing structures, supporting an interpretation of weakly storm-influenced distal to proximal lower shoreface deposition under fully marine conditions (Figure VII-8; MacEachern and Pemberton, 1992).

Interstratified, Parallel Laminated Sandstone and Burrowed Sandstone Facies

Passing upwards out of the muddy sandstone facies is the interstratified, parallel laminated sandstone and burrowed sandstone facies (Figure VII-15). In intermediate positions, the facies may directly overlie the discontinuity. The sandstone consists of beds of low angle parallel lamination, interstratified with thoroughly burrowed beds. The laminated sandstone beds are upper fine to lower medium in grain size and typically 5-20 cm in thickness, although a few localities along the eastern margin of the field show laminated beds up to 35 cm thick, erosionally amalgamated into bedsets 1.5 m in thickness (Figure VII-15 A). All beds have low angle erosional bases truncating underlying units. Laminae possess low angle inclinations (<15°) and are parallel to subparallel to lower set contacts. In some zones, laminae decrease in inclination upwards, demonstrating the progressive draping of

Figure VII-15. Laminated to Burrowed Sandstones of the Lower-Middle Shoreface. (A) Well-sorted, low angle parallel laminated tempestites, erosionally amalgamated into bedsets up to 1.5 m thick. The thick amalgamated tempestites reflect a lower to middle shoreface environment. Well 12-12-62-20W5, depth 1730.2 m. **(B)** Well-laminated, fine-grained sandstone with fugichnia (fu), passing into thoroughly burrowed muddy sandstone. The muddy sandstone contains *Terebellina* (T), *Palaeophycus* (Pa), *Ophiomorpha irregulaire* (O) and *Planolites* (P). The interval reflects tempestite accumulation with post-storm colonisation. Well 12-12-62-20W5, depth 1730.3 m **(C)** Thoroughly burrowed sandstone, truncated by a laminated tempestite which grades into burrowed sandstone. The upper portion of the laminated bed displays remnant waning flow oscillation ripple laminae. An opportunistic suite of *Diplocraterion* (D) and *Ophiomorpha irregulaire* (O) penetrate the laminated bed. The interval reflects erosional removal of the original resident community during a storm, followed by event bed deposition and post-storm colonisation. Well 11-29-62-20W5, depth 1703.4 m. **(D)** Parallel laminated tempestite with an opportunistic suite of *Ophiomorpha irregulaire* (arrows). Cryptic disturbances in the laminae may correspond to the fugichnia of soft-bodied organisms. Well 12-23-62-20W5, depth 1719.8 m. **(E)** Laminated tempestite with an opportunistic suite of *Ophiomorpha nodosa* (O). This passes upwards into bioturbated sandstones containing *Ophiomorpha irregulaire* (Oi) and *Palaeophycus* (Pa). Well 11-35-61-20W5, depth 1756.8 m. **(F)** Bioturbated sandstone, containing a robust, siderite-cemented *Rosselia* (Ro), reburrowed with *Helminthopsis* (H), *Chondrites* (Ch) and *Planolites* (P), as well as *Ophiomorpha irregulaire* (O). The burrowed zone is truncated by a tempestite displaying well-developed parallel to subparallel lamination. Well 11-35-61-20W5, depth 1758.6 m. **(G)** Laminated sandstone near the base, grading upwards into bioturbated muddy sandstone with *Skolithos* (S), *Palaeophycus* (Pa), *Ophiomorpha irregulaire* (O) and *Planolites* (P). Well 11-29-62-20W5, depth 1701.8 m. **(H)** Laminated tempestite with opportunistic *Ophiomorpha irregulaire* (O), passing into bioturbated sandstone with a robust siderite-cemented *Asterosoma* (As). Well 11-35-61-20W5, depth 1757.3 m. **(I)** Trough cross-stratified, medium-grained sandstone of the ?basal upper shoreface, with rare, siderite-cemented mudstone rip-up clasts near the top. A robust *Arenicolites* (Ar) is also present. Well 06-23-62-20W5, depth 1710.9 m.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relief during deposition. The laminae locally show slight undulations. A few thicker laminated beds may contain oscillation ripple laminae towards the top, although these are typically biogenically mottled. Some beds contain siderite-cemented mudstone rip-up clasts and intraformationally-derived siderite-cemented nodules.

The laminated beds typically show minor degrees of burrowing, most of which are restricted towards the top of the units (Figure VII-15 B, C, E). The thicker the laminated bed, the less burrowing observed. Fugichnia are locally well-developed and may occur over the entire thickness of the laminated zone (Figure VII-15 B). *Skolithos, Ophiomorpha, Arenicolites, Diplocraterion* and rare *Conichnus* may penetrate through much of the laminated bed from above. *Palaeophycus* may be present. In general, the assemblage reflects a predominance of suspension feeding and passive carnivore structures typical of the *Skolithos* ichnofacies, and corresponds to initial, opportunistic colonisation of the substrate (*cf.* Pemberton *et al.*, 1992b; Chapter IV).

The intervening burrowed sandstone beds are upper fine to lower medium in grain size, and grade upwards out of the laminated beds (Figure VII-15 B, C, E, G). The tops of the burrowed sandstones are typically erosionally truncated by overlying laminated beds. The burrowed sandstones vary considerably in thickness, partly as a function of the degree of burrow penetration, the time available for fairweather sediment accumulation, and the degree of erosion by the overlying beds. The sandstones are moderately- to poorly-sorted, and locally quite argillaceous. Remnant low angle parallel laminae and oscillation ripple laminae may also be visible. Burrowing intensities range from moderate to fairly intense. The trace fossil suite consists of *Skolithos, Ophiomorpha, Arenicolites, Palaeophycus, Diplocraterion, Conichnus, Siphonichnus, Planolites, Teichichnus, Terebellina, Rosselia,* with lesser *Asterosoma, Helminthopsis, Chondrites, Cylindrichnus* and *Bergaueria*. Many of the ichnogenera are quite robust, in particular, *Rosselia, Asterosoma* and *Diplocraterion*, suggesting fully marine, optimum environmental conditions. Both *Asterosoma* and *Rosselia* are commonly siderite-cemented (Figure VII-15 F, H). This suite reflects a mixture of deposit feeding, suspension feeding and passive carnivore structures, with less abundant grazing structures, supportive of a proximal *Cruziana* ichnofacies. Upwards, the suite shows a diminishment of grazing and deposit feeding structures, leading to the establishment of a distal *Skolithos* ichnofacies.

The laminated beds are interpreted to represent deposition from storm events in a lower to middle shoreface setting. Much of the difficulty surrounding the recognition and interpretation of storm beds, or tempestites, is associated with our limited understanding of the mechanics of their deposition and the primary physical stratification which is ultimately produced (*cf.* Duke *et al.*, 1991; Chapter IV). Traditional paleontological control is rarely useful in resolving the above problems because most sandy clastic units are devoid of body fossils. These same units, however, locally display diverse and well-preserved trace fossil associations (Pemberton and Frey, 1984; Saunders and Pemberton, 1986; Vossler and Pemberton, 1988; Saunders, 1989; Dam, 1990; Frey, 1990; MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992a,b,c). Integrating physical sedimentary structures with these distinctive trace fossil suites greatly improves the recognition and interpretation of tempestites in the rock record.

The low angle parallel to subparallel laminated sandstone beds are interpreted to represent core expression of hummocky cross-stratification (HCS; *cf.* Dott and Bourgeois, 1982), swaley cross-stratification (SCS; *cf.* Leckie and Walker, 1982) or quasi-planar lamination (QPL; *cf.* Arnott, 1993a). All three bedding types appear to be related primarily to storm event deposition (Duke, 1985; Leckie and Krystinik, 1989; Cheel, 1991; Duke *et al.*, 1991; Pemberton *et al.*, 1992b; *cf.* Chapter IV). In general, however, it is unlikely that the three bedding types can be reliably differentiated from one another in core, and in the case of the Viking Formation at Kaybob, the laminated beds are simply regarded as tempestites.

The burrowed sandstones are interpreted to reflect post-storm conditions and the return to modal or "fairweather" sedimentation. The gradational base to the burrowed zones corresponds to the benthic colonisation of the tempestite and progressive disruption of the lamination. Detailed analysis of the ichnological suite preserved in this facies shows that it can be differentiated into discrete suites. One suite corresponds to initial colonisation of the event bed, whereas a second suite corresponds to a later establishment of the resident (original) benthic community. Fugichnia are associated with storm bed accumulation itself, and reflects the disruptions produced by infauna entrained within the flow or buried by the bed, as they attempt to reach the sediment-water interface. The development of these discrete suites is typical of virtually all tempestite successions (*cf.* Pemberton *et al.*, 1992b; Pemberton, in press; Chapter IV)

Initial colonisation of the tempestite is typically manifest by the development of a flourishing community of opportunistic organisms in an unstable, highly stressful, physically-controlled environment. This assemblage is characterised by the vertical to subvertical structures of suspension feeding and passive carnivore infauna, comprising elements of the *Skolithos* ichnofacies. The *Skolithos* suite developed typically displays a low diversity and variable, though locally high abundance of ichnogenera, characteristic of an opportunistic (r-selected) strategy in population dynamics (Levinton, 1970; Pianka, 1970; Jumars, 1993).

The resident "fairweather" assemblage (*i.e.* the elements of the *Cruziana* ichnofacies and some elements of the *Skolithos* ichnofacies) can be considered representative of a stable benthic community, within which individual populations are at, or near their carrying capacity (*i.e.* equilibrium suites). Such associations, which typically are regarded to be resource-limited, or K-selected (Levinton, 1970), occur in habitats having low physio-chemical stress. This resident suite progressively replaces the opportunistic assemblage, because under conditions of persistent ambient (fairweather) conditions they are more suited to the environment. The nature of the equilibrium suite is essential in determining the position along the depositional profile that tempestite accumulation took place. In the Viking Formation at Kaybob, the fairweather suite consists of a proximal *Cruziana* ichnofacies, passing upwards into a distal *Skolithos* ichnofacies, suggesting that such deposition took place in lower shoreface to middle shoreface settings. Figure VII-16 schematically demonstrates the progressive colonisation of a tempestite. Many intervals display repeated alternations of lower energy fairweather trace fossil suites with higher energy opportunistic tempestite suites (*cf.* Figure VII-15), constituting a high diversity, mixed *Skolithos-Cruziana* ichnofacies (Figure VII-17). Nonetheless, the alternation of two commonly depth-related ichnocoenoses, which has been attributed in the past to repeated rises and falls of sea level, is more likely to reflect the alternation of episodic deposition with fairweather sedimentation, caused by *in loco* hydrodynamic energy fluctuations. The two different ichnocoenoses

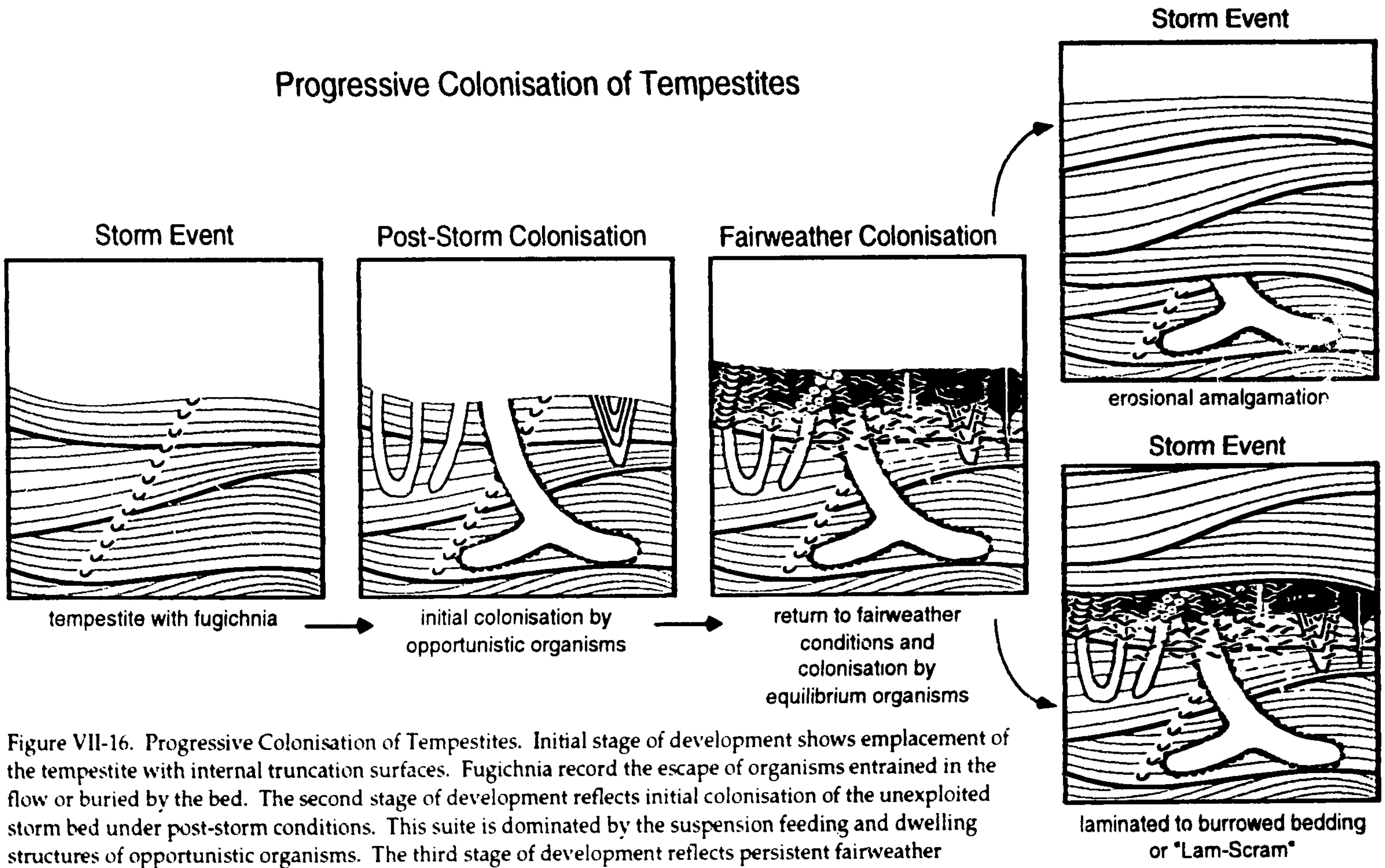


Figure VII-16. Progressive Colonisation of Tempestites. Initial stage of development shows emplacement of the tempestite with internal truncation surfaces. Fugichnia record the escape of organisms entrained in the flow or buried by the bed. The second stage of development reflects initial colonisation of the unexploited storm bed under post-storm conditions. This suite is dominated by the suspension feeding and dwelling structures of opportunistic organisms. The third stage of development reflects persistent fairweather conditions and re-establishment of the resident equilibrium community. Subsequent storm events may result in 1) complete or virtually complete removal of evidence of post-storm colonisation (some deeply penetrating structures and escape structures may survive) or 2) minimal erosional amalgamation of storm beds, preservation of the opportunistic storm suite, and locally, partial preservation of the fairweather suite, producing "laminated-to-burrowed" bedding.

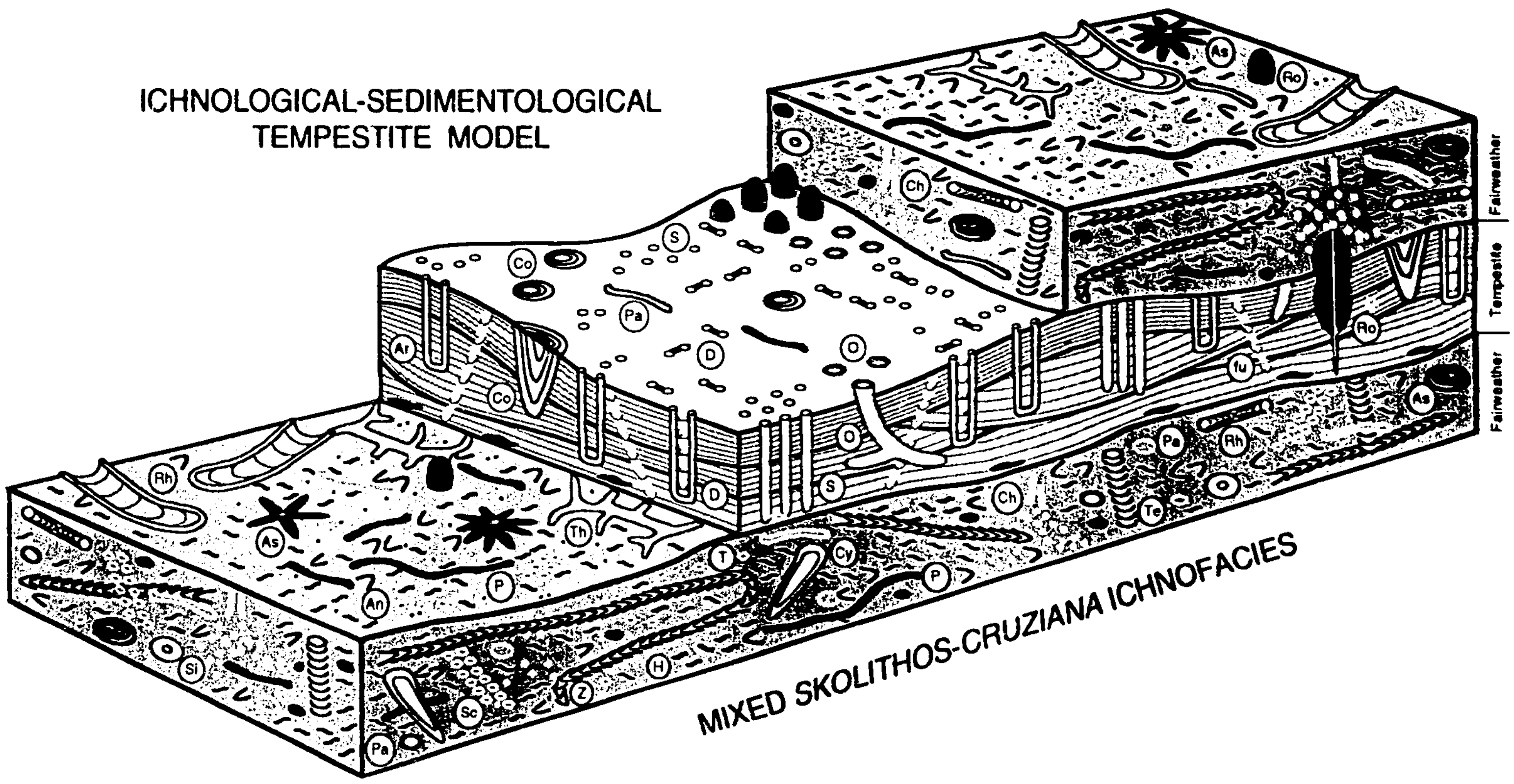


Figure VII-17. Idealised ichnological-sedimentological model of a high diversity mixed *Skolithos-Cruziana* ichnofacies, based on observations of Cretaceous strata of the Western Interior Seaway of North America. Fairweather deposits are characterised by thorough bioturbation with a high diversity of deposit feeding and grazing structures. The tempestite is burrowed with a lower diversity suite of mainly suspension feeding and dwelling structures. An: *Anconichnus*, Ar: *Arenicolites*, As: *Asterosoma*, Ch: *Chondrites*, Co: *Conichnus*, Cy: *Cylindrichnus*, D: *Diplocraterion*, fu: fugichnia, H: *Helminthopsis*, O: *Ophiomorpha*, P: *Planolites*, Pa: *Palaeophycus*, Rh: *Rhizocorallium*, Ro: *Rosselia*, Sc: *Schaubcylindrichnus*, Si: *Siphonichnus*, Sk: *Skolithos*, T: *Terebellina*, Te: *Teichichnus*, Th: *Thalassinoides*, Z: *Zoophycos*.

reflect the varying behavioural responses of the animals colonising two successive, individually distinct habitats.

Trough Cross-Stratified Sandstone Facies

Locally, trough cross-stratified sandstones sharply overlie the laminated to burrowed sandstone facies. In proximal positions, this facies may directly overlie the sequence boundary (Figure VII-13). The sandstone is typically moderately- to well-sorted and upper fine to upper medium in grain size, though locally, it may range up to lower coarse-grained. The stratification consists of thin (5-15 cm) beds of trough cross-stratification, stacked into bedsets 25-75 cm thick. Some intervals contain rip-up clasts of siderite-cemented mudstone and intraformationally-derived sideritic nodules. Rare, low angle parallel laminated sandstones are locally intercalated. Some mudstone interbeds are also present, though typically rare. Trace fossils within the trough cross-stratified sandstones consist of *Arenicolites* (Figure VII-15 I), *Skolithos, Diplocraterion, Palaeophycus, Cylindrichnus,* rare *Conichnus* and fugichnia. Mudstone interbeds locally contain rare numbers of *Chondrites* and *Planolites*. The facies is interpreted to reflect upper shoreface deposition, based largely on the dominance of small current-generated subaqueous dunes and the association with underlying lower and middle shoreface sandstones (*cf.* Clifton *et al.*, 1971; Davidson-Arnott and Greenwood, 1976; Hunter *et al.*, 1979; Greenwood and Mittler, 1985). The trace fossil suite displays a predominance of vertical and subvertical suspension feeding and dwelling structures of the *Skolithos* ichnofacies. Deeply penetrating and heavily-lined structures are consistent with animal response to physical stresses imposed by migrating subaqueous dunes (*cf.* Howard, 1972; 1975; Saunders, 1989; MacEachern and Pemberton, in press).

THE KAYBOB SHOREFACE SUCCESSION

The Kaybob shoreface shows both an upward transition from upper offshore to upper shoreface deposits and a proximal to distal (west to east) transition from initial upper shoreface sedimentation to initial upper offshore deposition on a major discontinuity (*cf.* Figure VII-13). Within the succession there appears to be an internal discontinuity reflecting a slight deepening event, evident by a return to lower shoreface deposition above upper shoreface or middle shoreface deposits (*e.g.* 10-07-62-20W5; *cf.* Figure VII-13). The regional significance of this secondary surface is not clear, due to a paucity of core and difficulty in resolving the change in character of the sandstone on geophysical well logs. The major discontinuity can be traced to the east as far as the 10-15-62-19W5 well (Figures VII-10 E and VII-13). It is progressively more difficult to identify eastward of the field due to the removal of the Kaybob shoreface by the Fox Creek deposit, coupled with the transition of the erosional sequence boundary into a correlative conformity. The transition from burrowed muddy sandstones to biogenically-modified tempestite sandstones corresponds to the shallowing from distal lower shoreface conditions to more proximal lower shoreface or middle shoreface conditions. Shallowing is accompanied by enhancement of effective storm erosion. Storm deposits are one of the most abundant event beds in shallow marine settings, and commonly constitute the bulk of the sediment supplied to the lower and middle shoreface environments (Kumar and Sanders, 1976; Niedoroda *et al.*, 1984). The thorough bioturbation of any tempestites in the distal lower shoreface indicates a relatively reduced storm energy setting (*cf.* MacEachern and Pemberton, 1992), compared to strongly storm-dominated successions such as the Cadotte Member of the Peace River Formation (*cf.* Chapter VI). This reduction may correspond to a combination of reduced storm frequency and diminished storm intensity. On the other hand, the presence of laminated to burrowed sandstone facies, reflecting partial preservation of tempestites, demonstrates a considerably greater storm energy setting compared to the thoroughly bioturbated shoreface sandstones characteristic of the Viking Formation at the Giroux Lake field (*cf.* Chapter VIII) and the Chigwell field (Raychaudhuri, 1989; Raychaudhuri *et al.*, 1992). The Kaybob shoreface constitutes an intermediate state between these two paleoenvironmental extremes. Such intermediate storm-dominated settings characterise many successions, including the Turonian Cardium Formation in Alberta (Pemberton and Frey, 1984; Vossler and Pemberton, 1988), the Campanian Sussex Sandstone and Shannon Sandstone in Wyoming (Chapter IV), and the Campanian Spring Canyon Member, Panther Tongue, and Aberdeen Member, within the Book Cliffs of Utah (*cf.* Howard and Frey, 1984; Frey, 1990; MacEachern and Pemberton, 1992).

The upper portion of the Kaybob shoreface has been removed by a low relief, high energy (erosional) flooding surface (Figure VII-13). This accounts for the paucity of upper shoreface sandstone deposits in the bulk of the succession. No backshore or foreshore deposits are preserved, and any that may have accumulated were subsequently removed. To the east, the Kaybob shoreface has been partially to completely removed by erosion associated with the development of the Fox Creek deposit, tentatively interpreted as an estuarine incised valley complex.

THE KAYBOB FORCED REGRESSION SHOREFACE: SEQUENCE STRATIGRAPHIC SIGNIFICANCE

The character of sequence boundaries generated during forced regression (*cf.* Plint, 1988; Posamentier and Vail, 1988; Posamentier *et al.*, 1992) differs from many other sequence boundary expressions, particularly in that the surface is cut under marine conditions. During falling sea level, sediments previously lying below fairweather wave base are brought into a zone of persistent wave attack. This produces an erosional sequence boundary which passes basinward into a correlative conformity and landward into a subaerial exposure surface. The rapid basinward shift of the shoreline "forces" a shoreface to prograde rapidly over the sequence boundary, with minimal, if any, record of its passage. The diminished accommodation space associated with the base level fall results in the abrupt establishment of shallow water deposits over deeper water sediments, typically occupying a wave cut terrace at the most basinward position of the shoreline.

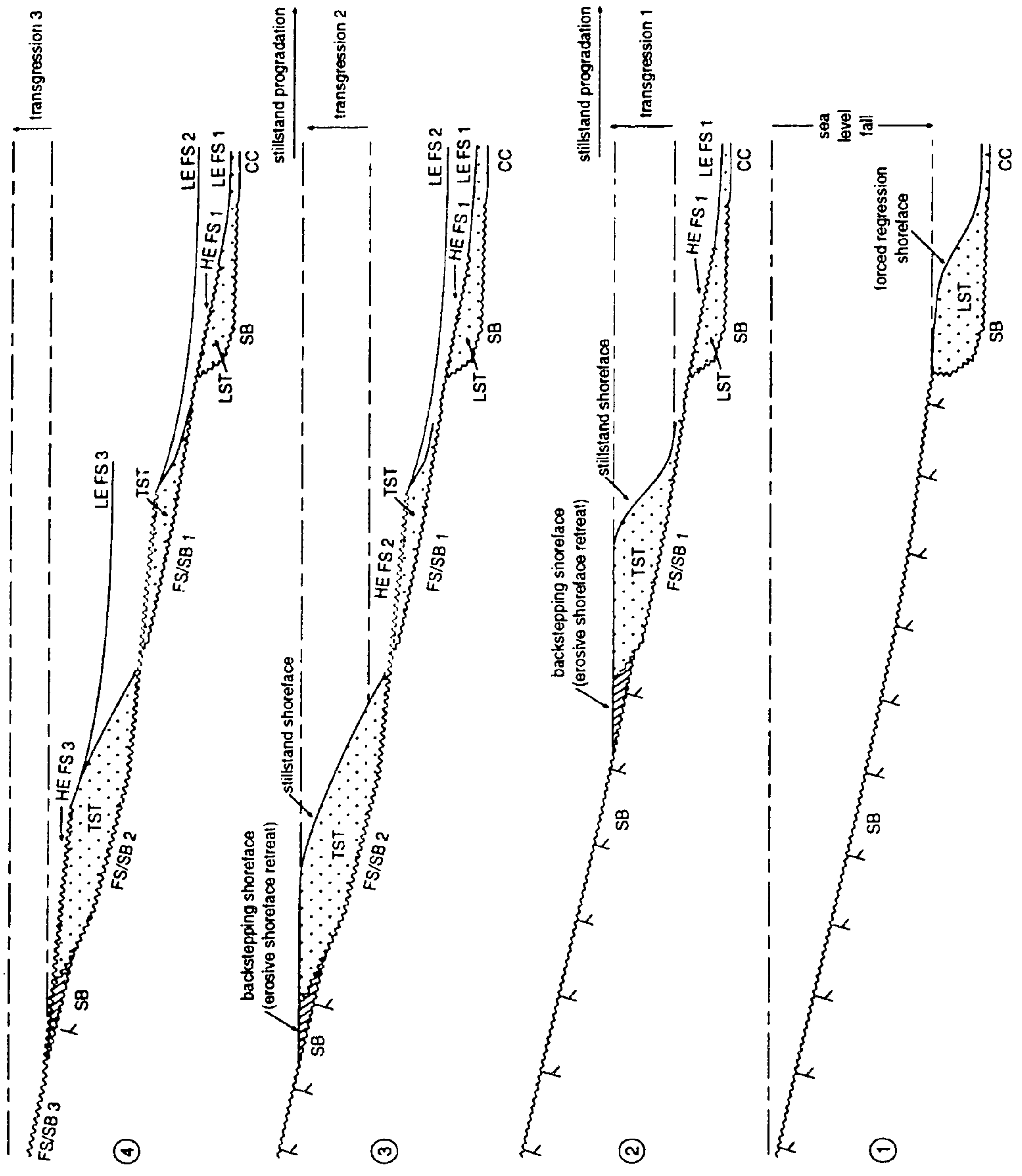
The forced regression shorefaces differ stratigraphically from the more typical regressive shoreface successions, which are associated with simple sediment-induced progradation. The forced regression shorefaces directly overlie a sequence boundary, are generated under conditions of relative sea level lowstand, and are supplied with sediment derived from the cutting of the unconformity. Consequently, these successions are legitimate components of the lowstand systems tract. In contrast, sediment-induced progradational shorefaces directly overlie either marine flooding (FS) or amalgamated sequence boundary and marine flooding surface (FS/SB) and correspond to parasequences, fitting within highstand or transgressive systems tracts, depending on the stacking pattern of the parasequence set. Figure VII-18 schematically illustrates the differences in origin and distribution of such parasequences and forced regression shorefaces.

The Viking Formation at Kaybob displays many of the characteristics of forced regression shorefaces. The presence of a *Glossifungites*-demarcated erosional discontinuity, attenuating the underlying regional parasequences, demonstrates a fundamental break in the succession (MacEachern *et al.*, 1992; Pemberton and MacEachern, in press; Chapters II and III). The facies overlying the discontinuity reflect shallower water depositional conditions, consistent with a relative fall in sea level. The sand body is relatively thin, typically less than 10 m (commonly 4-6 m), and shows rapid upward transition from lower to upper shoreface deposits. These features are consistent with the reduced accommodation space associated with a relative lowering of sea level. The sharp-based nature of the sand body, consistent with observations at Kaybob, has been employed by several workers to support the interpretation of rapid seaward displacement of the shoreface in response to lowered relative sea level (Posamentier and Vail, 1988; Raychaudhuri, 1989; Pattison, 1991a; Posamentier *et al.*, 1992; Posamentier and Chamberlain, 1991; 1993; Walker and Bergman, 1993). Finally, the coarser-grained character of the sand above the discontinuity compared to the sandstones below the break is supportive of lowstand conditions attributed to rejuvenation of fluvial systems draining to the shoreline. The discontinuity separating the regional Viking parasequences from the Kaybob sand body is therefore interpreted to correspond to a sequence boundary, passing eastward into a correlative conformity.

A forced regression setting has also been proposed for the Viking Formation at the Joarcam field (Posamentier and Chamberlain, 1991; 1993; Posamentier *et al.*, 1992). In the few cored intervals from Joarcam studied by the authors, no substrate-controlled suites were observed to demarcate the proposed sequence boundary. Nonetheless, the sharp, erosionally-based character of the shoreface sandstone, coupled with the abrupt increase in sand grain size, attests to an abrupt basinward shift of facies, consistent with a relative fall of sea level. The Viking Formation "A and B" sandstones of the Sunnybrook field have also been interpreted as forced regression shorefaces (Pattison, 1991a). More recently, Davies and Walker (1993) have interpreted several of the coarse-grained onlap markers within Allomember E of the

Figure VII-18. Schematic Model of Forced Regression and Stillstand Shoreface Development in the Viking Formation. **(1)** Relative sea level fall shifts the shoreline basinward, creating a widespread subaerial exposure surface. At the new shoreline position, a wave-cut notch is generated to a depth corresponding to fairweather wave base (FWWB). Below this, a non-erosional correlative conformity (CC) is developed. The subaerial exposure surface, wave-cut notch and CC are manifestations of the same sequence boundary (SB). The new shoreface, termed a forced regression shoreface, progrades over the SB and is an element of the lowstand systems tract (LST). **(2)** Ensuing transgression (transgression 1) generates a low energy flooding surface (LE FS) below FWWB, and a high energy flooding surface (HE FS), generated by erosive shoreface retreat, at and above FWWB. Continued transgression truncates the top of the forced regression shoreface, and cuts an amalgamated flooding surface and SB (FS/SB). The backstepping shoreface sits on the SB. No evidence of subaerial exposure is preserved on the FS/SB. During a relative stillstand of sea level, a shoreface progrades over the FS/SB. Note that since the FS/SB is cut during rising sea level, initial deposits on the surface may correspond to facies lying basinward of FWWB, in contrast to the forced regression shoreface. **(3)** Resumed transgression (transgression 2) generates an LE FS below, and an HE FS at and above the initial FWWB. Here, the HE FS removes the backstepping shoreface. Erosive shoreface retreat creates a new FS/SB landward of the first stillstand shoreface. The remnant of this shoreface constitutes a parasequence. During a pause in transgression, a new stillstand shoreface is produced seaward of the backstepping shoreface, and progrades over the FS/SB. **(4)** Resumed transgression (transgression 3) generates an LE FS below, and HE FS at and above initial FWWB. In this example, a remnant of the backstepping shoreface and, hence the SB, is preserved. Evidence of subaerial exposure is removed landward of this remnant, as a new FS/SB is cut. The progressive landward-stepping stillstand shorefaces produce a retrogradational parasequence set, reflecting the transgressive systems tract (TST).

The only localities where the initial SB is preserved are underlying the forced regression shoreface, small remnants veneered by backstepping shorefaces, and the CC. Erosive shoreface retreat has removed virtually all other evidence of subaerial exposure. The FS/SB is actually a composite surface, made up of segments of FS/SB (*i.e.* FS/SB1 - FS/SB 3) which are genetically related to specific transgressive events. Each FS/SB therefore correlates to its equivalent HE FS and LE FS, not to the previous FS/SB.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CC
③
stillstand progradation
transgression 2
backstepping shoreface
(erosive shoreface retreat)
SB
stillstand shoreface
TST
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SB
backstepping shoreface
(erosive shoreface retreat)
stillstand shoreface
TST
FS/SB 1
HE FS 1
LE FS 1
LST
SB
CC
①
sea
level
fall
SB
forced regression
shoreface
LST
SB
CC

Viking Alloformation (Figure VII-4) to correspond to the basinal expression of forced regressions in the Caroline and Garrington fields. They attributed the forced regressions to have occurred during high frequency sea level lowstand events within an overall transgression. Arnott (1993b) has also interpreted the "D2" cycle of the Falher D Member, Spirit River Formation, as a forced regression shoreface. Some conglomeratic shorefaces of the Turonian Cardium Formation have also been regarded as forced regression shorefaces (Walker and Plint, 1992), and locally contain *Glossifungites* suites of *Thalassinoides* and more rarely, *Skolithos* subtending from the discontinuity (Vossler and Pemberton, 1988).

Additionally, Walker and Bergman (1993) have re-interpreted outcrops of the Shannon Sandstone near Casper, Wyoming to reflect forced regression shoreface deposition rather than offshore bar accumulation. Observation of the Shannon Sandstone where it overlies the sandy shales of the Cody, also displays a *Glossifungites* suite of *Thalassinoides* with associated phosphatic pebbles demarcating the proposed sequence boundary. The Shannon Sandstone typically shows a sharp-based character, with an abrupt shallowing of facies above the discontinuity. Likewise, the Shannon shows considerable accumulations of laminated to burrowed sandstone, similar to the intermediate storm-energy shoreface sandstones of the Viking Formation at Kaybob, providing a well exposed analogue to this subsurface example.

SUMMARY

The Viking Formation at Kaybob serves as an excellent example of both an intermediate storm-energy shoreface (MacEachern and Pemberton, 1992), and a forced regression shoreface (MacEachern *et al.*, 1992b; Pemberton *et al.*, 1992a; Pemberton and MacEachern, in press). From a sedimentological perspective it typifies shoreface successions consisting primarily of preserved remnants of tempestites which have been subsequently biogenically-modified during post-storm conditions. From a sequence stratigraphic perspective, the Kaybob sand body demonstrates many of the characteristics deemed diagnostic of forced regressions, and provides data regarding the identification of discontinuities and their interpretation as sequence boundaries.

The laminated to burrowed sandstones of the lower and middle shoreface display well-developed ichnological and sedimentological elements. The integration of ichnology and sedimentology indicates that storms, though relatively abundant, were not of high frequency, allowing considerable development of both opportunistic and fairweather suites. The minimal removal of fairweather assemblages and minor amounts of significant erosional amalgamation of the tempestites suggest that the storm events were not of exceedingly high intensity, particularly when compared to strongly storm-dominated successions such as the Cadotte Member of the Peace River Formation (*cf.* Chapter VI). The persistence of laminated to burrowed successions affords the opportunity to see the ichnological nature of both the unstable storm assemblage and the stable fairweather assemblage. The storm (or pioneer) assemblage is dominated by traces of opportunistic (r-selected) species, typical of initial colonisation of an unexploited substrate. Such r-selected behaviour favours rapid exploitation of the unused environmental niche. The fairweather (resident) assemblage is dominated by traces demonstrating K-selected behaviours, reflecting a return to an equilibrium benthic community under unstressed, fully marine conditions. Most tempestites show alternations between opportunistic suites of the *Skolithos* ichnofacies and fairweather equilibrium suites of the *Cruziana* ichnofacies, reflecting *in loco* fluctuations in energy, rather than variations in sea level (Figure VII-17). Proximal *versus* distal tempestite accumulations along the shoreface depositional profile are primarily determined by changes in the character of the fairweather (equilibrium) trace fossil suite, and therefore, must be separated from the opportunistic suite. This requires the full integration of ichnology and sedimentology.

From a sequence stratigraphic point of view, the Viking Formation at Kaybob affords the opportunity to assemble data in order to generate an integrated ichnological and sedimentological model of forced regression shoreface deposition. The use of ichnological successions and substrate-controlled trace fossil suites provides unique insights into criteria for the recognition of sequence boundaries and the facies of the shoreface. This can be combined with purely physical criteria such as sand body thickness, sharp-based character and presence of coarse-grained lags. An integrated model such as this may ultimately permit discrimination between high energy transgressive-stillstand parasequences (*cf.* Chapter VIII), highstand parasequences (Chapter VI) and forced regression shorefaces. Only the latter succession is a legitimate component of the lowstand systems tract. Differentiating these successions from one another has important ramifications for the sequence stratigraphic interpretation of an area (Figure VII-18).

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CHAPTER VIII

THE VIKING FORMATION IN THE GIROUX LAKE FIELD: A CASE STUDY OF A WEAKLY STORM-INFLUENCED SHOREFACE AS A HIGH ENERGY PARASEQUENCE

INTRODUCTION

The Viking Formation of the Giroux Lake area is ideally suited to illustrate two relatively new models associated with shoreface deposition. The first is the characterisation of a shoreface consisting of thoroughly bioturbated facies, which constitutes the low energy end member in a continuum of strongly storm-dominated shorefaces to weakly storm-affected shorefaces (MacEachern and Pemberton, 1992). The Giroux Lake deposit is considerably less influenced by storm events than either the Cadotte Member of the Peace River Formation (*cf.* Chapter VI) or the Viking Formation at Kaybob (*cf.* Chapter VII). These thoroughly bioturbated facies, typical of low energy successions, lack many of the physical sedimentary features commonly employed to resolve the various depositional subenvironments. The well preserved trace fossil suites are, however, ideally suited to subdivide the succession into the different shoreface environments by utilising vertical changes in the behaviour of the tracemaking organisms as interpreted from the ichnogenera encountered (Pemberton *et al.*, 1992a). The Giroux Lake area, therefore, facilitates the integration of ichnology and sedimentology, in order to characterise and interpret these shoreface types.

The Viking Formation of the Giroux Lake field is also well-suited to illustrate a high energy parasequence model. A high energy parasequence is herein defined to be a progradational (shallowing upward) succession of genetically related strata overlying a high energy (erosional) marine flooding surface (HE FS), and overlain by either a HE FS or a low energy (non-erosive) flooding surface (LE FS). It must be made clear that the sequence stratigraphic significance of the parasequence is directly related to the underlying discontinuity and is completely independent of the depositional energy of the progradational body. In the Giroux Lake area, the basal flooding surface is interpreted to be amalgamated with a sequence boundary (*i.e.* an FS/SB), and is overlain by shelfal shales which gradually coarsen upward into upper shoreface sandstones. The nature of the succession shows rapid deepening immediately above the basal discontinuity prior to progradation, in marked contrast to forced regression-type shorefaces (*cf.* Plint, 1988; Posamentier and Vail, 1988; Posamentier *et al.*, 1992; Posamentier and Chamberlain, 1991; 1993; Chapter VII). The top of the succession at Giroux Lake is truncated by a second high energy erosion surface. Careful integration of the ichnology with the sedimentology permits the characterisation and differentiation of these transgressive-stillstand shorefaces from highstand progradational shorefaces as well as lowstand (forced regression) shorefaces.

STUDY AREA

The Giroux Lake field is situated in Tp 66, R21W5 (Figure VIII-1). The Viking A pool is quite small and produces oil and gas centred on sections 3, 4, 8 and 9 of the township. The sand body constituting the subject of this paper occurs near the top of the Viking Formation, and is oriented along a NW-SE trend, extending from Tp 66, R22W5 southeast to Tp 63, R18W5. The sandstone also persists eastward to Tp 65, R18W5. The study is based on 15 cored intervals in the Giroux Lake field. In addition, 11 cores from Kaybob North, immediately south of Giroux Lake, were incorporated in the study, in order to characterise the nature of the shoreface.

REGIONAL STRATIGRAPHY

The Viking Formation is upper Albian (Lower Cretaceous) in age, passes upwards out of the marine shales of the Joli Fou Formation, and is overlain by Lower Colorado marine shales. Slipper (1918) informally gave the name "Viking" to gas-producing sandstones of the Viking-Kinsella field near Viking, Alberta. Wickenden (1949) first referred to the black shales at the base of the Colorado Group, overlying the Mannville Group, as the Joli Fou shale. Stelck (1958) later formally raised both the Viking and the Joli Fou to formation status.

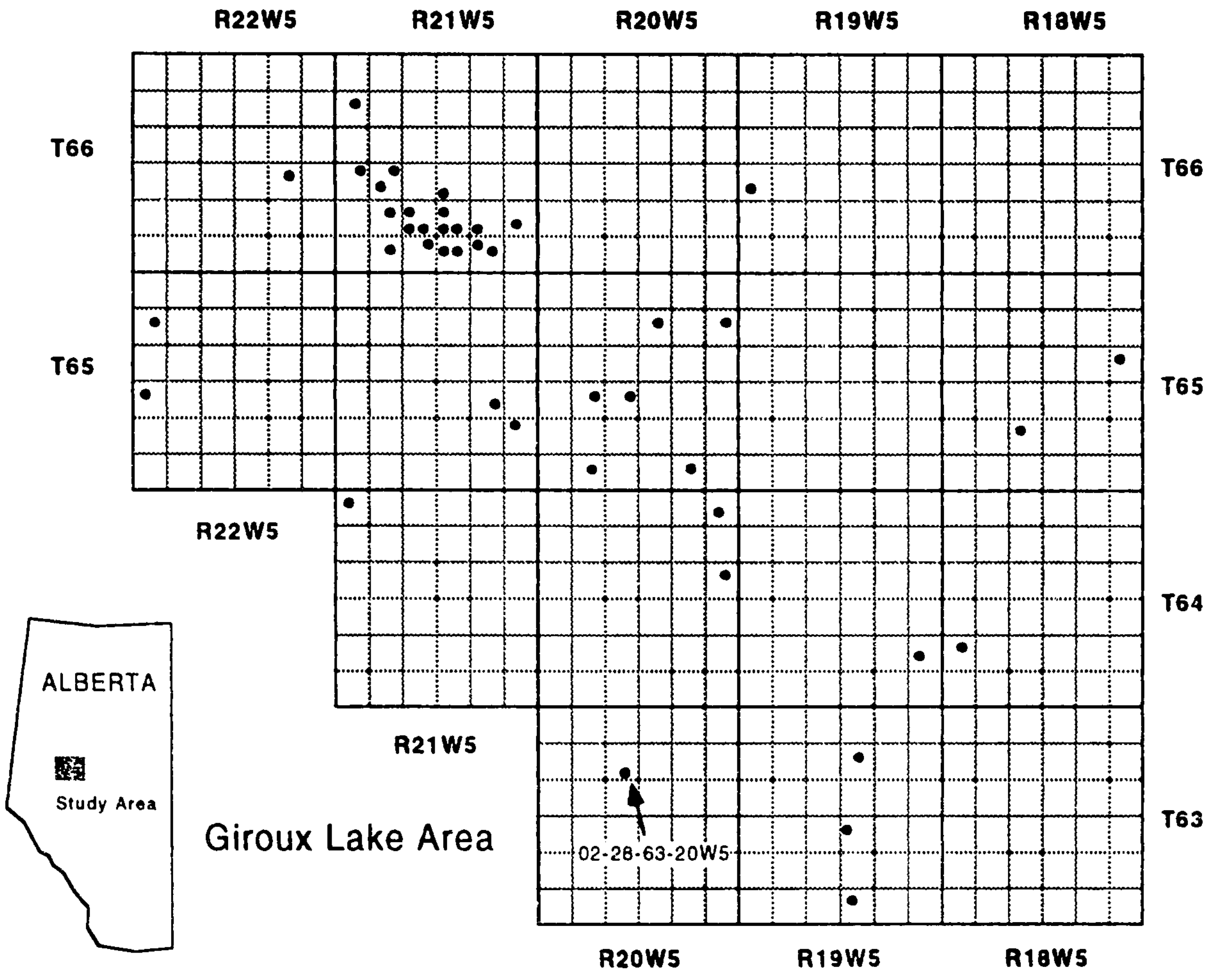


Figure VIII-1. Giroux Lake study area, showing the cored well locations. The 02-28-63-20W5 core has a remnant of Joli Fou Fm shale.

The general stratigraphic equivalents of the Viking and Joli Fou are given in Figure VIII-2. The Joli Fou Formation unconformably overlies the Mannville Group. Intervals roughly equivalent to the Joli Fou Formation include the Skull Creek shale of Colorado Group in Montana and the Thermopolis shale in Wyoming (McGookey *et al.*, 1972; Weimer, 1984). The Viking Formation is roughly equivalent to the Paddy Member of the Peace River Formation (Koke and Stelck, 1985; Stelck and Leckie, 1990; Leckie and Singh, 1991), the upper part of the Bow Island Formation (Glaister, 1959; Cox, 1991; Raychaudhuri and Pemberton, 1992), as well as the Muddy Sandstone, Newcastle Formation and J-Sandstone in Montana, Wyoming and Colorado, respectively (McGookey *et al.*, 1972; Beaumont, 1984; Weimer, 1984).

The overlying marine shales are typically referred to as the lower Colorado shales (Stelck, 1958), the Lloydminster shale (Tizzard and Lerbekmo, 1975) or the unnamed shale member of the Colorado Group (Evans, 1970; Downing and Walker, 1988). More recently, Bloch *et al.*, (1993) have proposed that the Colorado Group, from the top of the Viking Formation to the Second White Speckled Shale, be subdivided and assigned formal units. They are, in ascending order, the Westgate Formation, the Base of Fish Scale Formation, the Belle Fourche Formation and the Second White Speckled Shale Formation. The shales overlying the Viking Formation are equivalent to the proposed Westgate Formation. The shales of the Westgate Formation are stratigraphically equivalent to the lower part of the Shaftesbury Formation, overlying the Peace River Formation (Stelck and Leckie, 1990; Leckie *et al.*, 1990; Bloch *et al.*, 1993), and to part of the Hasler Formation, the Goodrich, and the lower part of the Cruiser Formation in N.E. British Columbia (Stelck and Koke, 1987; Stelck and Leckie, 1990). In the United States, the shales are equivalent to the Mowry shale in Montana and North Dakota (McGookey *et al.*, 1972).

A formal biostratigraphy, using arenaceous foraminiferal assemblages, has been established for the upper Albian Hasler Formation in N.E. British Columbia and its equivalents (Figure VIII-3), largely based on the work of Stelck (1975), Caldwell *et al.* (1978), Stelck and Hedinger (1983), Koke and Stelck (1985), Stelck and Koke (1987), Stelck and Leckie (1990) and Stelck (1991). The Joli Fou and Viking formations occupy the *Haplophragmoides gigas* Zone, overlying the *Ammobaculites wenonahae* subzone of the *Gaudryina nanushukensis* Zone. The zone is, in turn, overlain by the *Verneuilina*

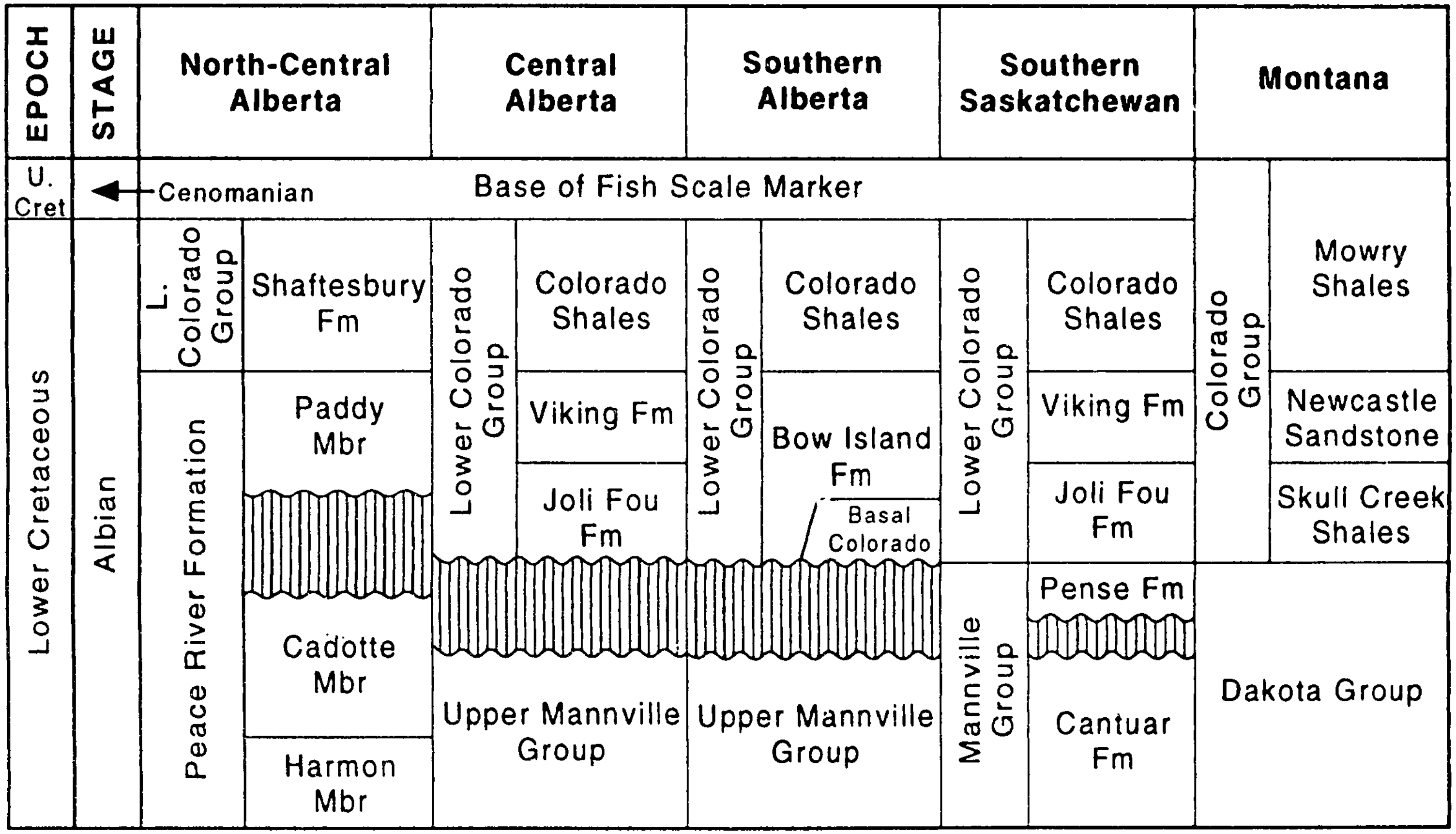


Figure VIII-2. Stratigraphic correlation chart for the Viking Formation and equivalents.

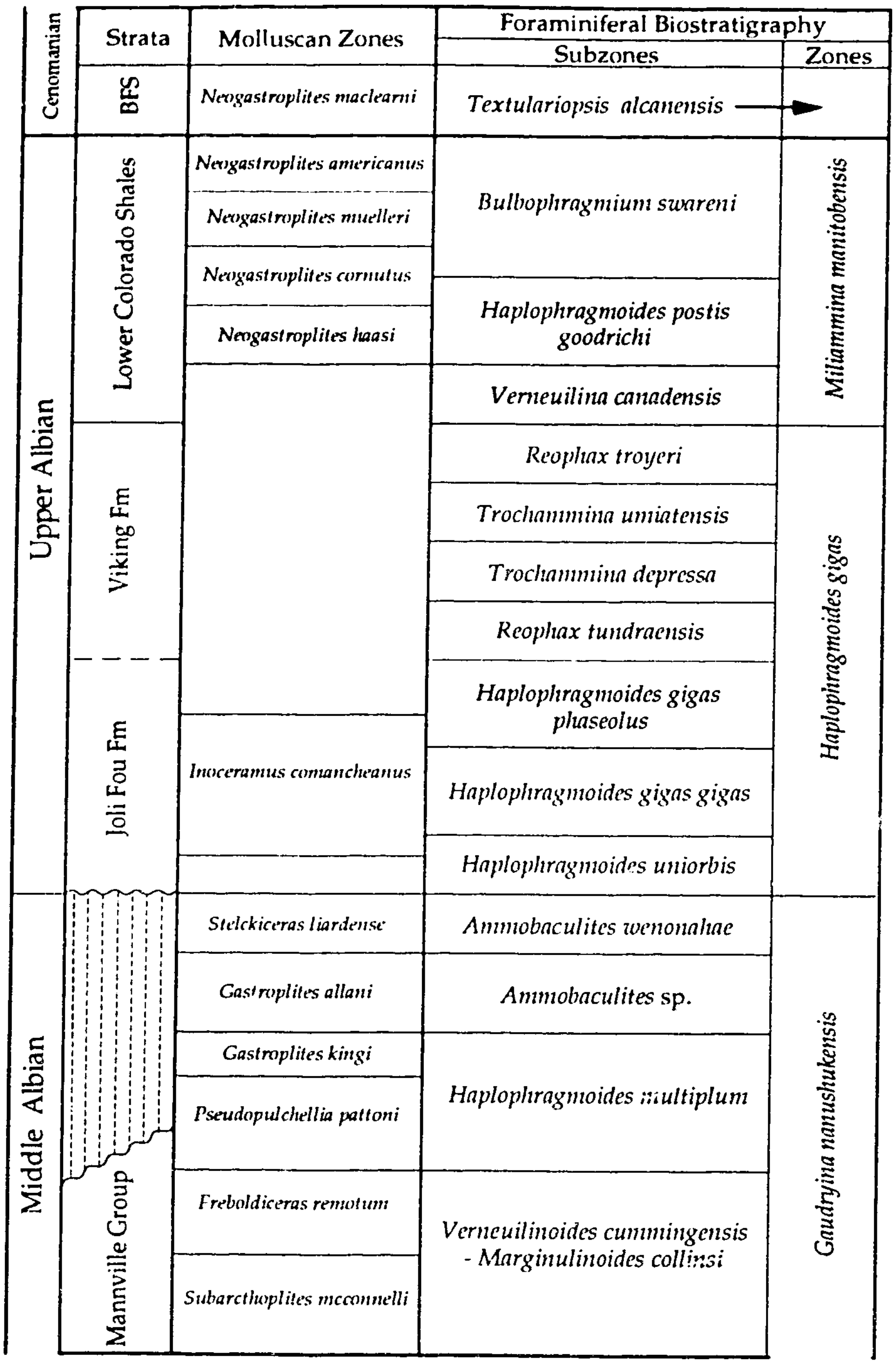


Figure VIII-3. Correlation of Molluscan Zones and Foraminiferal Zones/ Subzones within the Albian, and its relationship to the Joli Fou and Viking formations. BFS refers to the Base of Fish Scales Marker [modified from Stelck (1991) and Stelck (pers. comm., 1993)].

canadensis subzone of the *Miliammina manitobensis* Zone. Detailed studies of the Hasler Formation shales have led to the subdivision of the *H. gigas* Zone into seven discrete subzones. Unfortunately, this subdivision has not yet been successfully carried south into central Alberta.

Several authors have suggested that there exists a disconformity of both local and regional extent between the Joli Fou and Viking formations (*e.g.* Jones, 1961; Evans, 1970; *cf.* Beaumont, 1984), although there does not appear to be an absence of any molluscan or foraminiferal zones. Stelck (1958) recognised a general thinning of the Viking to the north and west. Boreen and Walker (1991) described a veneer of scattered granules separating black shales of the Joli Fou Formation from the siltier shales of the basal Viking Formation in the Willesden Green area, although they could not demonstrate erosion on the surface. For the most part, the disconformity, if present, does not appear to occur as a regional surface between the Joli Fou shales and the regionally extensive parasequences of the basal Viking Formation.

The Viking Formation is highly complex internally, and contains numerous discontinuities which have led to several attempts to subdivide the interval into regionally correlative units (*cf.* Figures VIII-4 and VIII-5). Downing and Walker (1988), Raddysh (1988), Raychaudhuri (1989), Davies (1990), Boreen and Walker (1991) and Pattison (1991a,b, 1992) have sought to establish a formal allostratigraphic framework for the Viking Formation, according to the rules of the North American Code of Stratigraphic Nomenclature (NACSN, 1983). Of these attempts, the most notable and effective have been Boreen and Walker (1991; Figure VIII-4) and Pattison (1991a,b; Figure VIII-5). Others have taken a sequence stratigraphic approach to the subdivision of the interval (*e.g.* Posamentier and Chamberlain, 1991, 1993; Leckie and Reinson, in press). To date, a paucity of good internal markers and lack of a precise biostratigraphic framework for the interval in central Alberta have limited the ability of researchers to carry their correlations reliably across the area.

The Joli Fou is not preserved in the Giroux Lake area, having been erosionally removed by one of a number of intra-Viking discontinuities. In the 02-28-63-19W5 core (Figures VIII-6 and VIII-7), a remnant of the Joli Fou Formation is present, which yielded an arenaceous foraminiferal suite consistent with the *Haplophragmoides gigas phaseolus* subzone of the

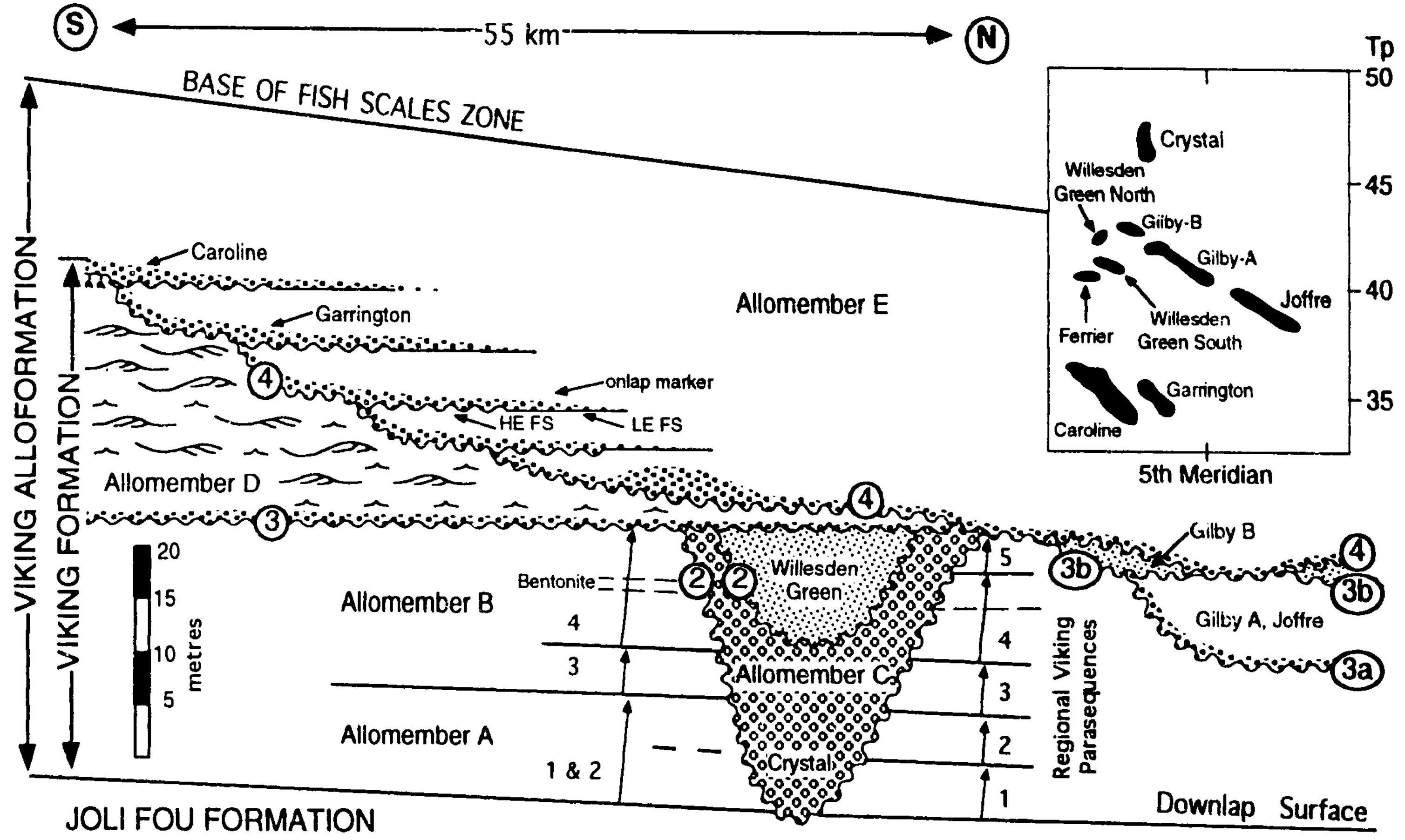


Figure VIII-4. Allostratigraphic framework proposed for the Viking Formation. The Viking Alloformation contains 5 Allomembers (A-E), separated from one another by regional discontinuities. The main discontinuities are VE2 (2), VE3 (3) and VE4 (4), with secondary erosion surfaces present as well. Figure modified after Boreen and Walker (1991).

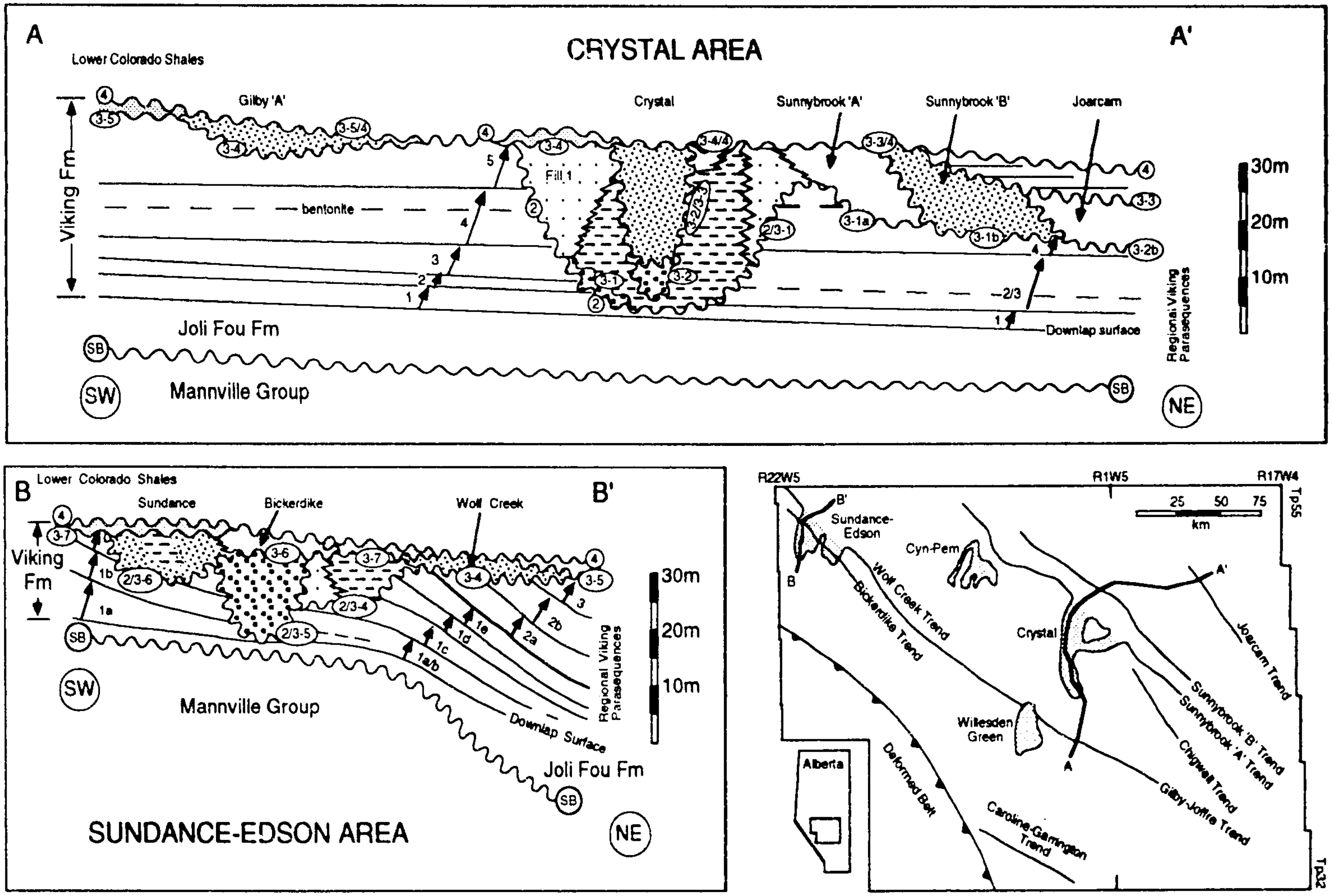


Figure VIII-5. Revised allostratigraphic framework for the Viking Formation by Pattison (1991a). The VE3 surface has been subdivided into 7 discrete surfaces (3-1 to 3-7). In addition, surfaces are locally amalgamated, designated by a backslash (*i.e.* 2/3-5). This second generation allostratigraphy highlights the complexity of the VE3 transgression in central Alberta. Figure modified after Pattison (1991a).

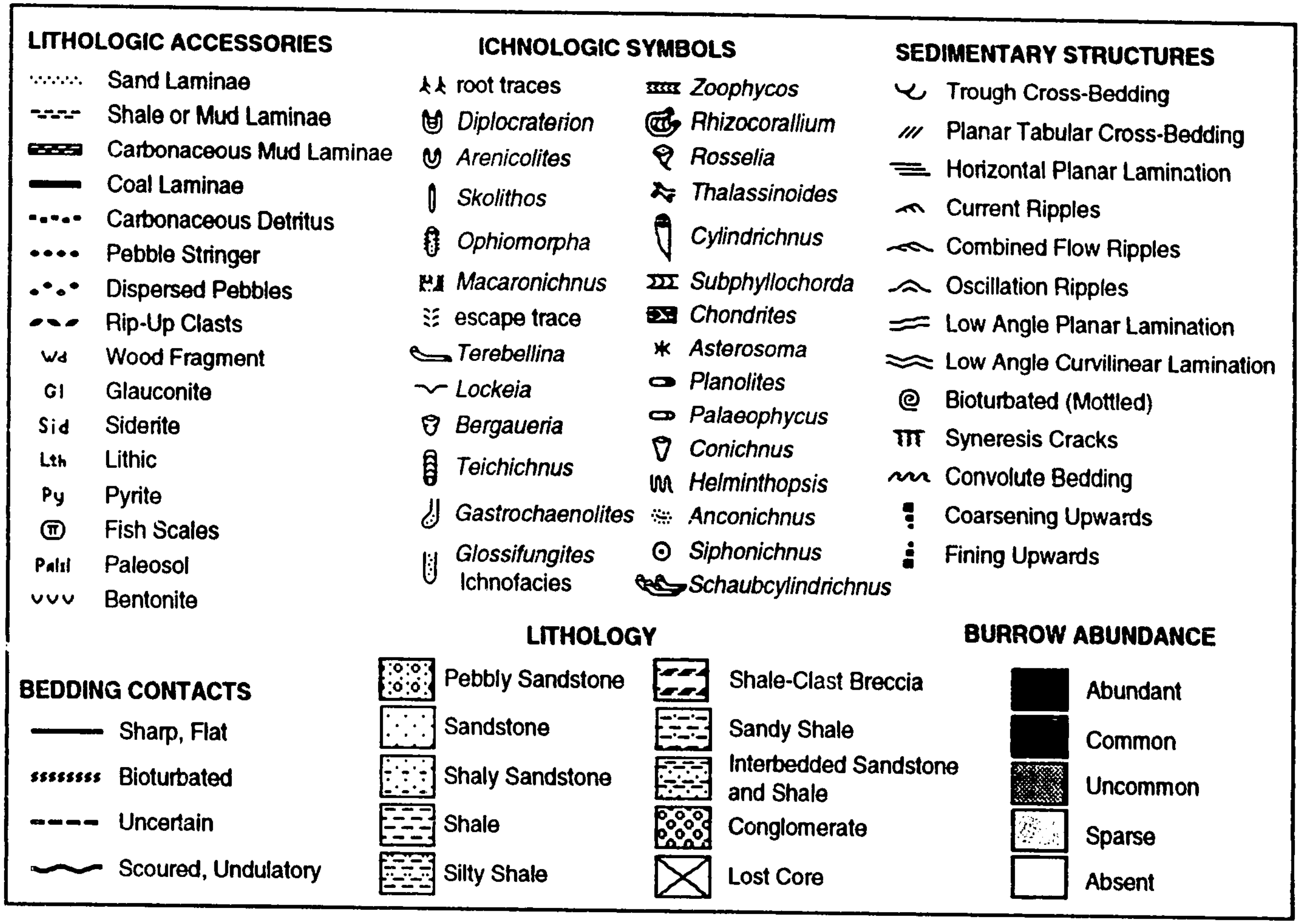
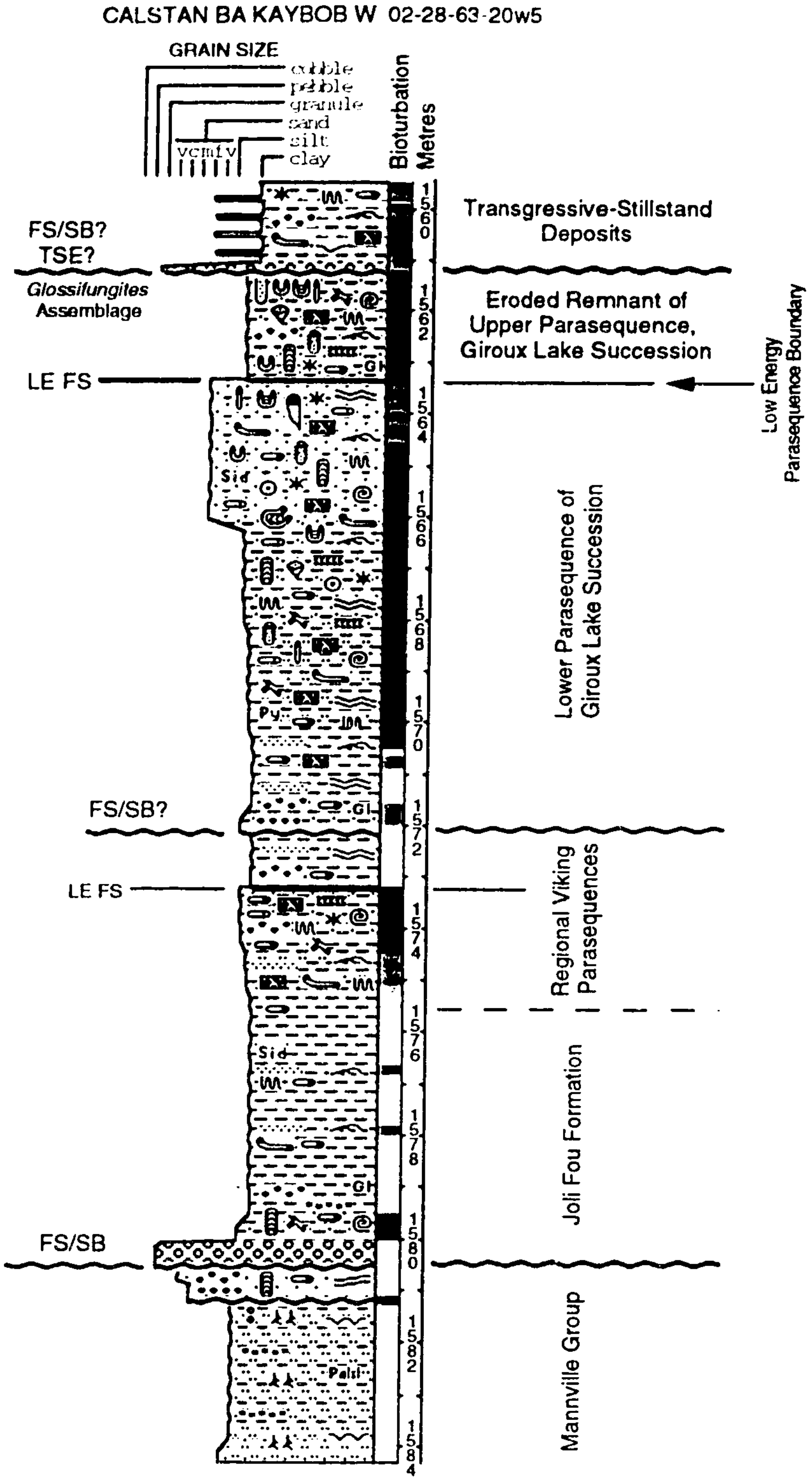


Figure VIII-6. Legend of Symbols used in Lithologs and Cross-section.

Figure VIII-7. Litholog of well 02-28-63-20W5, showing the transgressively-modified sequence boundary on the top of the Mannville Group, passing into Joli Fou Formation marine shales. These shales yield arenaceous foraminifera that reflect late Joli Fou time (*H. phaseolus* subzone; *cf.* Figure VII-3). The shales pass into regionally extensive parasequences of the lower Viking Formation over a short vertical distance. This remnant of Joli Fou and basal Viking is truncated by a probable amalgamated sequence boundary and high energy marine flooding surface (FS/SB), overlain by the lower parasequence of the Giroux Lake area. The location of this well is shown on the study area map (Figure VIII-1). The legend of symbols used in the litholog is given in Figure VIII-6.


CALSTAN BA KAYBOB W 02-28-63-20w5
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
vcmfv
Bioturbation
Metres
FS/SB?
TSE?
Glossifungites
Assemblage
LE FS
FS/SB?
LE FS
FS/SB
Sid
Py
Gl
Paltl
1560
1562
1564
1566
1568
1570
1572
1574
1576
1578
1580
1582
1584
Transgressive-Stillstand Deposits
Eroded Remnant of Upper Parasequence, Giroux Lake Succession
Low Energy Parasequence Boundary
Lower Parasequence of Giroux Lake Succession
Regional Viking Parasequences
Joli Fou Formation
Mannville Group

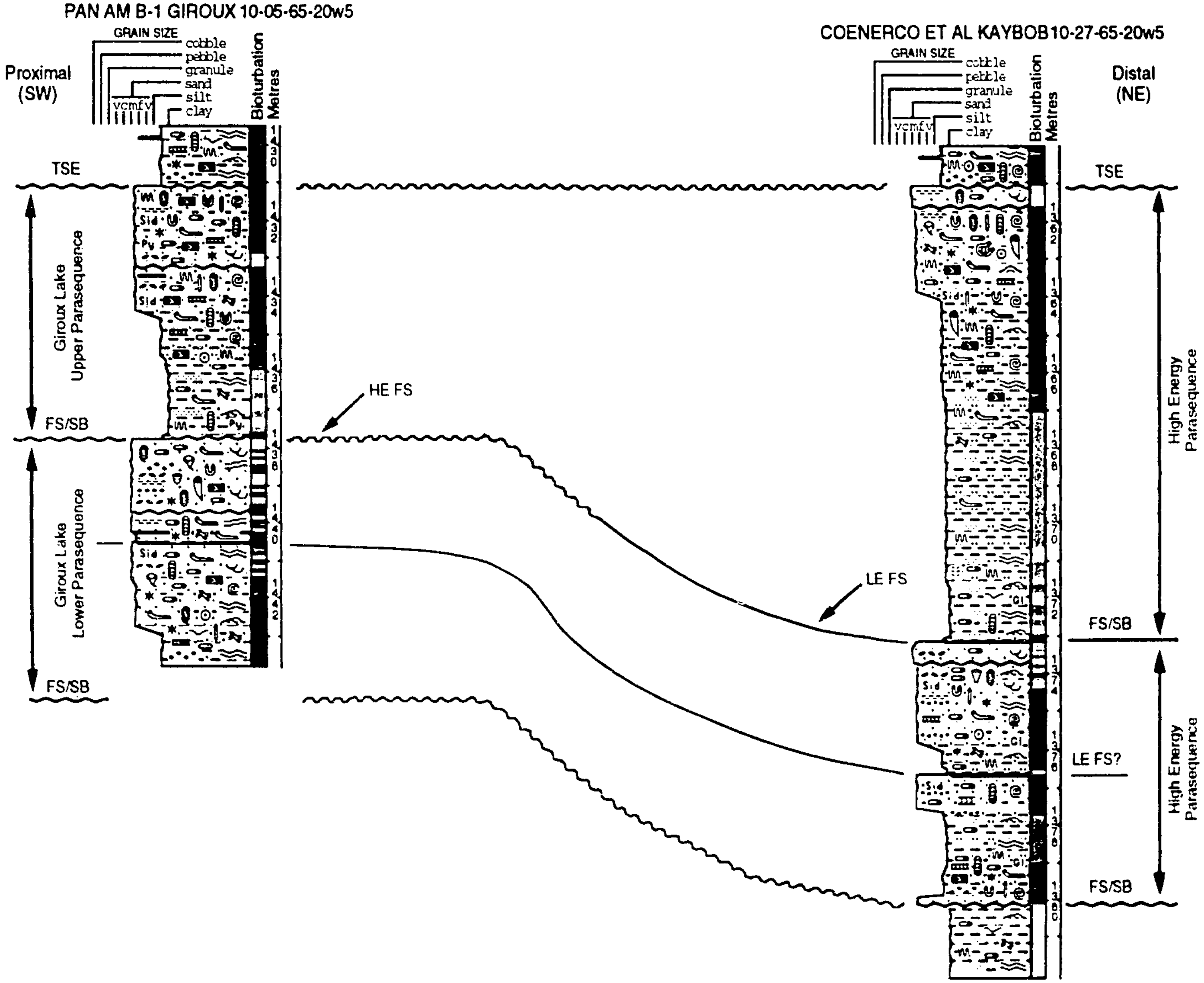
Haplophragmoides gigas Zone (Stelck, pers. comm., 1993). This corresponds to relatively late stage Joli Fou deposition, suggesting that the area may not have been inundated by the Joli Fou sea until much later in the transgression. The remainder of the Joli Fou and all overlying regional Viking parasequences appear to have been erosionally removed by a late-stage intra-Viking discontinuity (Figure VIII-7). In core, this erosion surface is overlain by marine mudstones containing dispersed granules and coarse sand (*cf.* Facies B; MacEachern *et al.*, 1992a), and is interpreted as part of a transgressively modified lowstand surface. Arenaceous foraminifera recovered from marine shales above this break support a late Viking time, possibly corresponding to the *Trochammina umiatensis* or *Reophax tundraensis* subzones of the *H. gigas* Zone (Stelck, pers. comm., 1993). This erosional discontinuity persists northward, forming the base of the lower of two high energy parasequences in the Giroux Lake area. The high energy parasequences represent SW-NE shoreface progradation forming two stacked and gently offlapping sand bodies (Figure VIII-8). The upper parasequence constitutes the subject of this paper.

GIROUX LAKE SHOREFACE OF THE UPPER PARASEQUENCE

The upper succession of the Viking Formation at Giroux Lake consists of a coarsening upward interval overlying a sharp, erosional (high energy) marine flooding surface (HE FS), truncated at the top by a second erosional marine flooding surface. The broad characteristics of the succession conforms with the definition of a parasequence (Van Wagoner *et al.*, 1990), namely a conformable package of genetically-related strata, reflecting progradation, bounded above and below by marine flooding surfaces. The upper parasequence is distinctive in that the basal parasequence boundary is erosional in nature. it is here proposed that parasequences overlying HE FS be referred to as high energy parasequences.

The succession of facies observed in the upper high energy parasequence is consistent with shoreface progradation. Five main facies types are associated with the upper parasequence.

Figure VIII-8. Proximal to distal litholog cross-section showing the upper and lower parasequences in the Giroux Lake area. Note that the lower parasequence may actually be made up of two smaller-scale parasequences separated by a low energy flooding surface (LE FS). Note also that the upper parasequence displays marked thickening of the marine shale deposits in a basinward direction. The FS/SB marking the base of the upper parasequence is manifest by a high energy flooding surface (HE FS) in a proximal position and a LE FS in a seaward direction. Both the upper and lower parasequences at Giroux Lake are underlain by an FS/SB, which locally is erosional. The legend of symbols used in the lithologs occurs in Figure VIII-6.


PAN AM B-1 GIROUX 10-05-65-20w5
COENERCO ET AL KAYBOB10-27-65-20w5
Proximal (SW)
Distal (NE)
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
vcmfv
Bioturbation
Metres
1430
1432
1434
1436
1438
1440
1442
1362
1364
1366
1368
1370
1372
1374
1376
1378
1380
TSE
FS/SB
Giroux Lake Upper Parasequence
Giroux Lake Lower Parasequence
HE FS
LE FS
LE FS?
High Energy Parasequence
Sid
Py
Gl

Basal Discontinuity and Associated Bioturbated Gritty Shale Facies

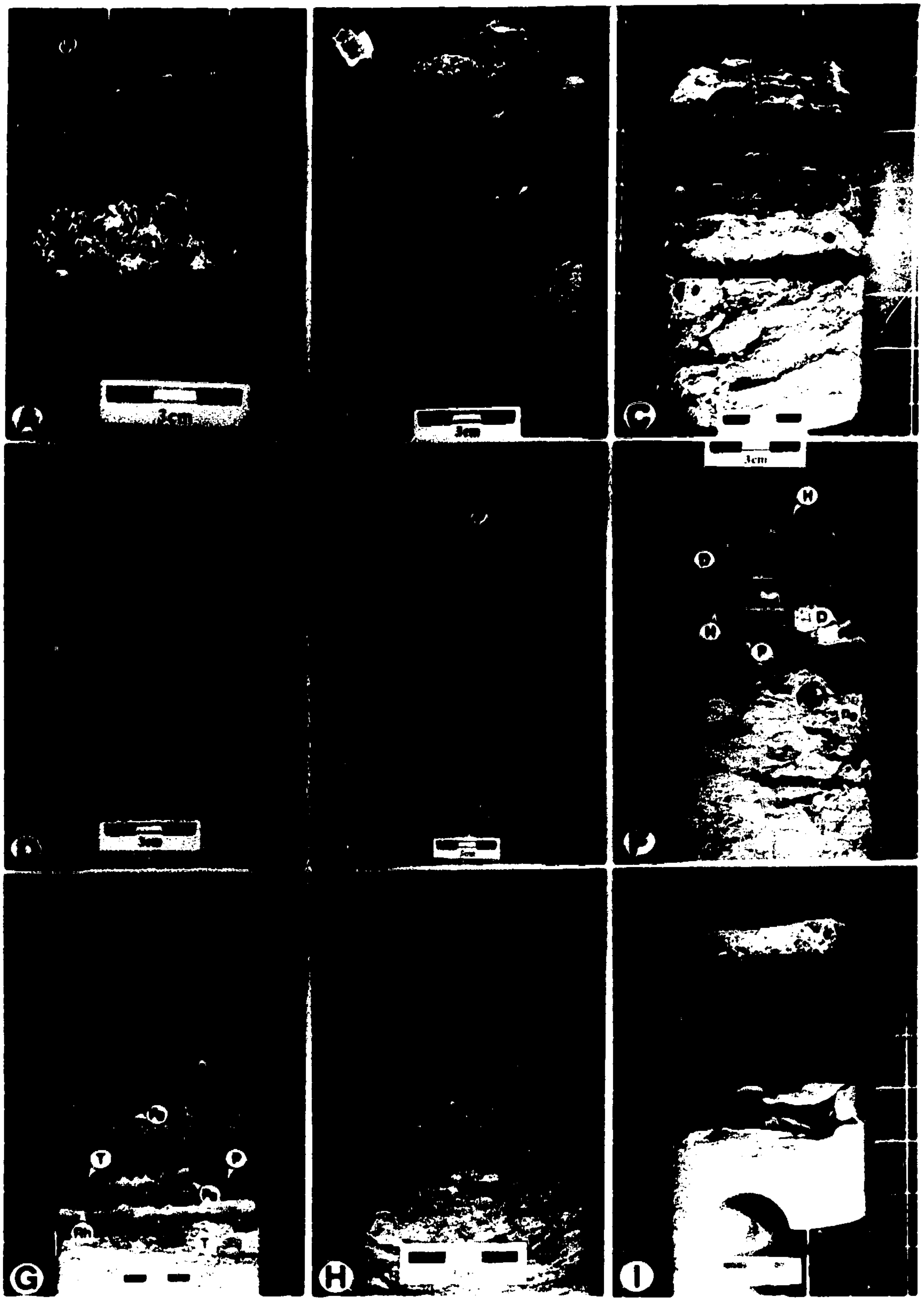
The erosional surface defining the base of the succession is directly overlain by gritty sandy shales and more rarely, muddy sandstones, containing abundant, dispersed coarse-grained sand, granules and pebbles of chert (Figure VIII-9 A-E). The facies is typically 5-50 cm in thickness. Pyrite is locally abundant, with allochthonous wood fragments, carbonaceous detritus and rarer glauconite. Physical structures are rare, but locally, small scale trough cross-bedding is present. Less commonly, a 1-5 clast thick pebble lag overlies the discontinuity, grading upwards into gritty sandy shales (Figure VIII-9 A). In a few localities, the surface displays relatively little evidence of erosion, and appears to be more of a low energy marine flooding surface, reflecting the distal equivalent of the HE FS. This relationship is analogous to a correlative conformity to a sequence boundary.

The degree of burrowing, though variable, is typically common to intense. Individual ichnogenera are locally difficult to identify due to the high degree of biogenic overprinting. Observed ichnogenera are typically *Teichichnus*, *Planolites*, *Diplocraterion* and, in sandier intervals, *Ophiomorpha* and *Palaeophycus*. The facies is very similar to other deposits immediately overlying transgressive surfaces of erosion (*cf.* Facies B; MacEachern *et al.*, 1992a; Chapter X), and is interpreted as the distal deposits of ravinement (*cf.* Stamp, 1921) occurring in shallower water settings. The surface may also correspond to original lowstand conditions, which was subsequently transgressively-modified (*i.e.* an FS/SB). The trace fossil suite corresponds to the proximal *Cruziana* ichnofacies (Figure VIII-10), but the low diversity may reflect a somewhat restricted suite. The low diversity may be a result of higher energy conditions associated with ongoing transgressive erosion. This suite contrasts markedly with the lower energy, equilibrium trace fossil suites typifying the overlying facies.

Silty Shale Facies

The silty shale facies grades upwards out of the gritty shale facies (Figure VIII-11 A-C). The silty shale facies ranges from 1.5 m to 6.5 m in thickness, with a gradual thickening from a SW to NE direction (*cf.* Figure VIII-8). The facies also shows an upward increase in silt content, grading from a silt-poor

Figure VIII-9. Lower and Upper Contacts of the Giroux Lake Parasequence. **(A-E)** Lower Contact. **(A)** High energy (erosional) break developed on silty shales. The pebble lag passes abruptly upwards into silty shale facies of an overlying parasequence. Well 06-18-66-21W5, depth 1335.9 m. **(B)** Bioturbated muddy sandstones of an underlying parasequence, truncated by gritty sandy shales interpreted as the distal deposits of transgressive ravinement. The transgressive deposit is overlain by several metres of marine silty shale. Well 04-15-66-21W5, depth 1350.9 m. **(C)** Trough cross-stratified upper shoreface sandstones of the underlying parasequence, truncated and transgressively reworked into a chert pebble-bearing ravinement deposit. This passes abruptly into sandy shale containing chert pebbles and granules, interpreted as a distal ravinement deposit. Well 09-16-65-20W5, depth 1389.0 m. **(D)** Trough cross-stratified sandstones, interpreted as upper shoreface deposits, erosionally truncated by pebbly sandy shales, reflecting distal deposits of ongoing ravinement. Well 20/10-05-65-20W5, depth 1437.8 m. **(E)** Medium-grained, trough cross-stratified sandstones are erosionally truncated by pebble-bearing, sandy shales grading into silty marine shales of the overlying parasequence. The sandy shales are interpreted as the distal deposits of transgressive ravinement and contain *Planolites* (P) and *Thalassinoides* (Th). Well 14-12-65-20W5, depth 1471.0 m. **(F-I)** Upper Contact. **(F)** Bioturbated sandstone, interpreted as a middle shoreface deposit of the parasequence, has been erosionally truncated. The surface has been biogenically reworked. A chert pebble (pe) is located near the contact. Overlying gritty sandy shales, interpreted as the distal deposits of ravinement, contain *Planolites* (P), *Helminthopsis* (H) and *Diplocraterion* (D). Well 04-10-66-21W5, depth 1401.8 m. **(G)** Sandstones near the top of the parasequence, reflecting initial transgression, biogenically modified by *Rhizocorallium* (Rh), *Palaeophycus* (Pa), *Terebellina* (T) and *Planolites* (P). A chert pebble lag indicates erosional modification during resumed transgression. Well 11-24-65-18W5, depth 1360.3 m. **(H)** Bioturbated muddy sandstone, erosionally truncated and overlain by a transgressive pebble lag passing into marine shales. Well 10-14-66-21W5, depth 1360.9 m. **(I)** Trough cross-stratified upper shoreface sandstone, sharply overlain by a low energy marine flooding surface with a few intraformationally-derived mudstone and siderite-cemented rip-up clasts. The chert pebble-bearing sandstone above may reflect resumed transgression. Well 09-17-65-20W5, depth 1387.5 m.


A
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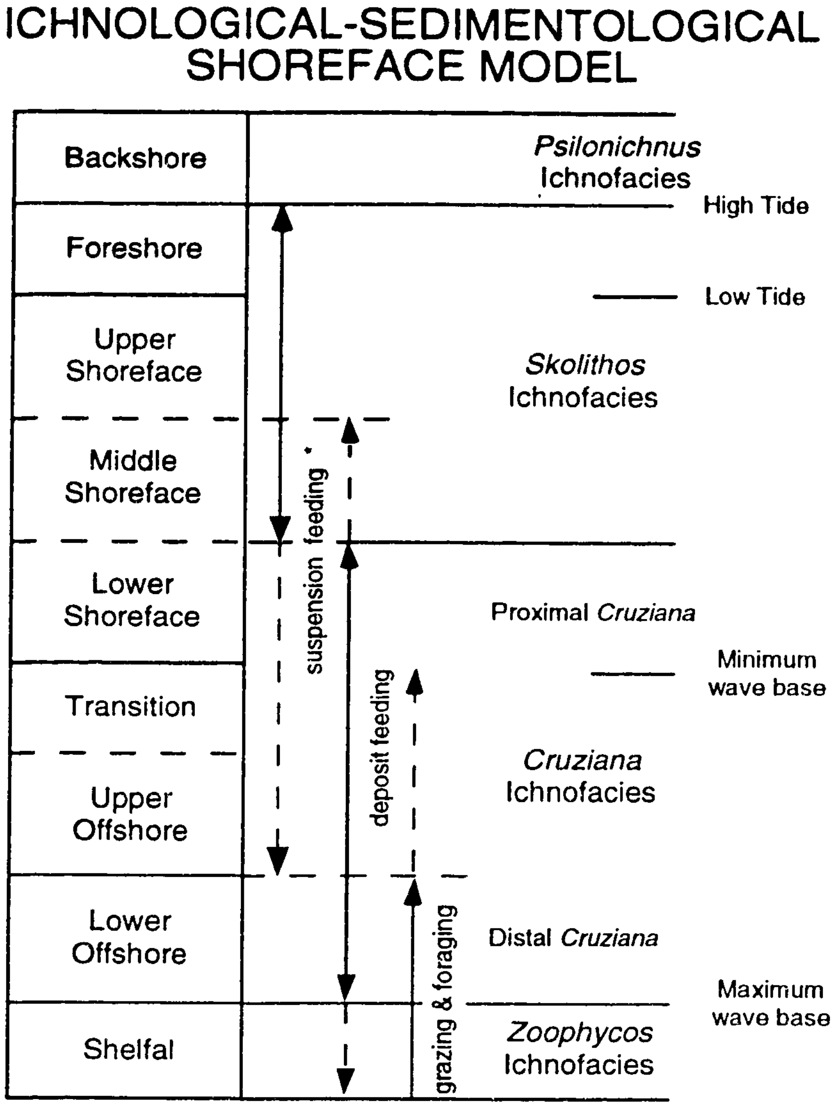
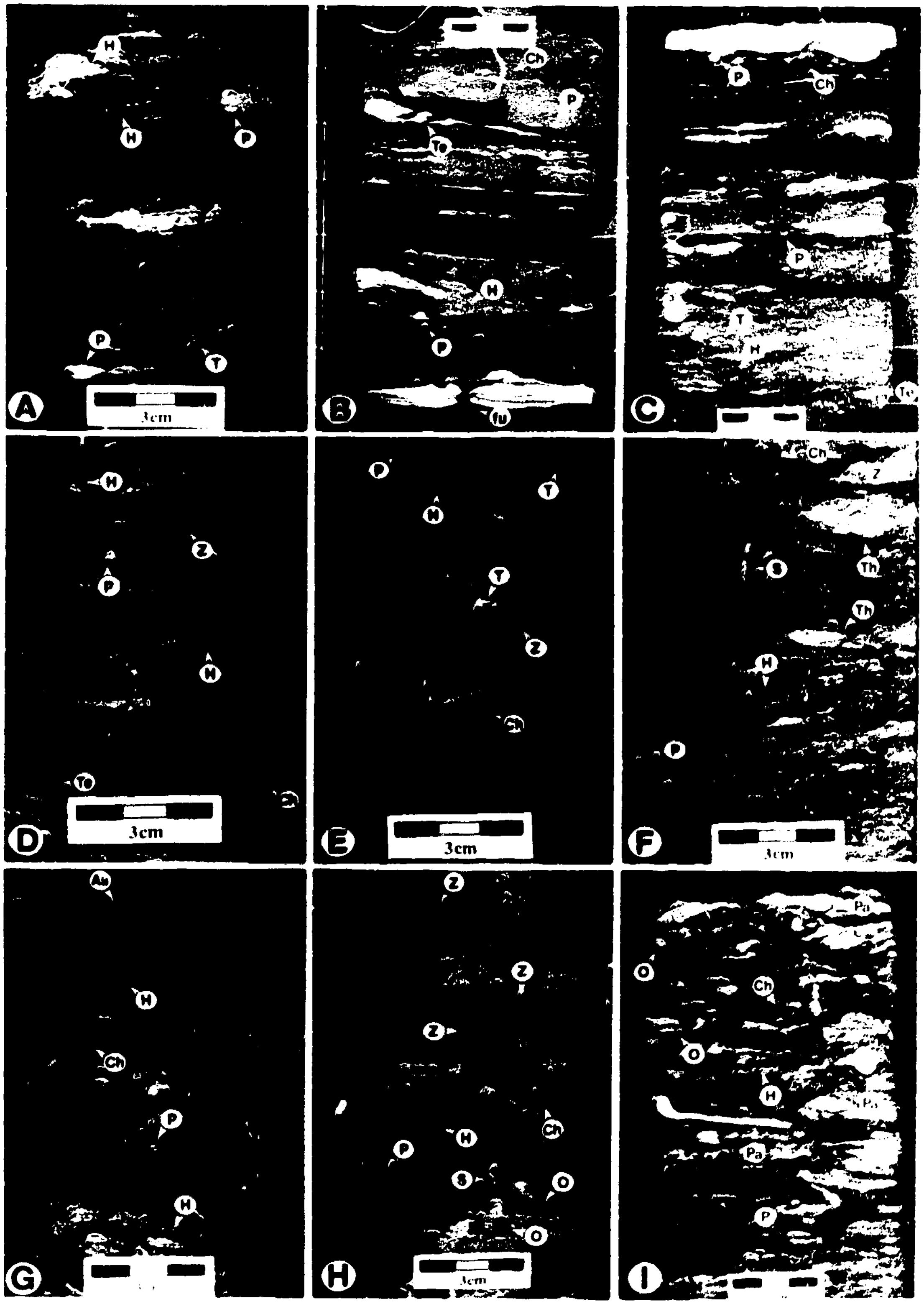


* Many tube dwellers are passive carnivores rather than suspension feeders.

Figure VIII-10. Idealised shoreface model of ichnofacies successions, based on observation of Cretaceous strata of the Western Interior Seaway of North America (modified after Pemberton *et al.*, 1992a).

Figure VIII-11. Distal Facies of the Giroux Lake Parasequence. (A) Silty shale facies containing pyrite lenses and nodules, *Planolites* (P) and *Helminthopsis* (H). The facies is interpreted as shelf to lower offshore deposits. Well 16-04-66-21W5, depth 1420.6 m. **(B)** Silty shale facies with thin, low angle parallel laminated sandstone beds, interpreted as shelf to lower offshore deposits with distal tempestites. Note the fugichnia (fu) extending through the lower tempestite. Other traces include *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch) and *Teichichnus* (Te). Well 11-24-65-18W5, depth 1373.3 m. **(C)** Silty shale facies with considerable interstitial sand and a thin sandstone bed. The facies is interpreted as a lower offshore deposit with distal tempestites. Trace fossils include *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch), *Teichichnus* (Te) and *Terebellina* (T). Well 11-24-65-18W5, depth 1370.4 m. **(D)** Thoroughly burrowed sandy shale facies, interpreted as an upper offshore deposit. Chert granules and organic detritus are dispersed throughout the facies. Note the well-developed *Zoophycos* (Z) near the top of the photo. Other trace fossils include *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch) and *Teichichnus* (Te). Well 16-04-66-21W5, depth 1418.3 m. **(E)** Thoroughly burrowed sandy shale facies, interpreted to reflect upper offshore deposition. Visible trace fossils include *Zoophycos* (Z), *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch) and *Terebellina* (T). Well 10-08-66-21W5, depth 1336.2 m. **(F)** Bioturbated sandy shale facies, reflecting upper offshore deposition, with visible *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch), *Zoophycos* (Z), *Thalassinoides* (Th) and *Skolithos* (S). Well 04-15-66-21W5, depth 1345.7m. **(G)** Bioturbated sandy shale facies reflecting upper offshore deposition, containing *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch) and *Asterosoma* (As). Dispersed granules of chert and organic detritus are also present. Well 04-10-66-21W5, depth 1404.8 m. **(H)** Thoroughly burrowed sandy shale facies of the upper offshore, containing visible *Planolites* (P), *Ophiomorpha* (O), *Zoophycos* (Z), *Helminthopsis* (H), *Chondrites* (Ch) and *Skolithos* (S). Well 10-25-65-20W5, depth 1343.6 m. **(I)** Thoroughly burrowed sandy shale facies of the upper offshore, containing *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch), *Palaeophycus* (Pa) and *Ophiomorpha* (O). Well 11-24-65-18W5, depth 1369.0 m.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3cm
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Ch
O
H
Pa
Pa
P

mudstone towards the base, to a silty shale with appreciable sand content. The facies is very dark in colour, organic rich, and contains abundant pyrite. Siderite-cemented zones are not common, but are locally present in most cored intervals. Thin (<5 cm and generally <2 cm) sandstone interbeds are also present, becoming more common upwards. Sandstone stringers contain low angle parallel lamination and to a lesser degree, oscillation and combined flow ripple laminae (Figure VIII-11 B, C). With increasing numbers of sandstone interbeds, and increasing silt content, biogenic disruption becomes more apparent (Figure VIII-11 B).

In general, burrowing intensities appear low, ranging from rare to moderate. This is interpreted more as a function of taphonomic parameters rather than environmental stresses (*cf.* Facies E, MacEachern *et al.*, 1992a). As silt and sand content becomes greater, lithological contrast is enhanced, highlighting the biogenic structures present. This lack of environmental stress is supported by the abundant and relatively diverse arenaceous foraminiferal suites recovered from samples of the facies (Stelck, pers. comm., 1993). These foraminiferal assemblages are part of the benthic community and display little or no evidence of unfavourable environmental conditions. Trace fossils are dominated by *Planolites*, *Chondrites* and *Helminthopsis*, with moderate to rare numbers of *Zoophycos*, *Thalassinoides*, *Terebellina*, *Teichichnus* and *Lockeia* comprising the remainder of the assemblage. The thin sandstone interbeds locally display small biogenic disturbances in the laminae, interpreted as fugichnia (escape traces).

The facies is interpreted to reflect progressive shallowing following maximum flooding over the initial transgressive deposits. The lower, silt-poor portion of the facies is characterised by grazing and deposit feeding structures, with lesser numbers of dwelling structures, consistent with a *Zoophycos* to distal *Cruziana* ichnofacies (Figure VIII-10). This suggests that the silt poor portion of the facies reflects shelfal to lower offshore deposition. The siltier portion of the facies contains a greater proportion of deposit feeding and dwelling structures, corresponding to a distal *Cruziana* ichnofacies, reflecting lower offshore depositional conditions. The thin sandstone stringers are interpreted as distal tempestites, with fugichnia corresponding to the attempts of organisms entrained by the flow or buried by the storm bed to reach the sediment-water interface. There is relatively little other disruption of the storm beds, due to a combination of such factors as the small size of the infauna, the high degree of contrast between burrowing styles associated with non-storm substrates and tempestite substrates, and the slowness of post-storm recolonisation in distal settings (*cf.* Chapter IV). With progressive shallowing, these distal storm beds show a reduced preservation potential despite their greater thickness, related to: a) an increase in the size of infaunal organisms, b) a corresponding increase in the degree of substrate penetration, c) a greater diversity of organism behaviours, enhancing the likelihood of substrate colonisation, and d) a higher rate of post-storm recolonisation, among others (*cf.* Pemberton *et al.*, 1992b; Chapter IV).

Bioturbated Sandy Shale Facies

The bioturbated sandy shale facies grades upwards out of the silty shale facies, and ranges from 2.0-3.5 m in thickness (Figure VIII-11 D-I). The sand size varies from lower fine to lower coarse, but is typically lower fine to lower medium. Pyrite, dispersed wood fragments, carbonaceous detritus and very rare chert granules are present throughout the facies. In contrast to the silty shales underlying it, preserved sandstone stringers are exceedingly rare. Some intervals show remnant low angle parallel laminae, indicating that deposition of storm beds occurred, but were subsequently obliterated by the activity of infaunal organisms.

The facies is thoroughly burrowed, with little or no evidence of physical sedimentary structures. Intensely burrowed intervals display a churned appearance, while less thoroughly burrowed intervals have a wavy to lenticular appearance. The trace fossil suite is both abundant and diverse, characterised by *Helminthopsis, Chondrites, Zoophycos, Asterosoma, Rosselia, Rhizocorallium, Cylindrichnus, Teichichnus, Thalassinoides, Planolites*, and *Palaeophycus*, with lesser numbers of *Arenicolites, Skolithos* and *Ophiomorpha*. These ichnogenera are relatively uniformly distributed throughout the facies, although *Ophiomorpha, Arenicolites, Skolithos, Palaeophycus, Rosselia* and *Asterosoma* are encountered more commonly towards the top of the facies than at the base.

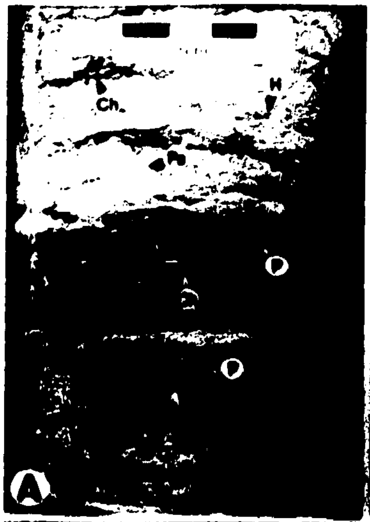
The trace fossil suite reflects a predominance of deposit feeders and mobile carnivores along with fairly abundant grazers. Suspension feeders and passive carnivores are conspicuous elements to the suite as well. The assemblage corresponds to a well-developed *Cruziana* ichnofacies, grading into a proximal *Cruziana* suite towards the top of the facies, where suspension feeders and passive carnivores are more abundant (Figure VIII-10). The facies is interpreted to reflect an upper offshore environment. Storm events do not appear to have been frequent, nor of high intensity, permitting thorough reworking of tempestites by the infaunal community (Howard, 1972; 1975; MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992b).

Bioturbated Muddy Sandstone Facies

The bioturbated muddy sandstone facies grades upwards out of the bioturbated sandy shale facies, and ranges from 1.5 to 3.0 m in thickness in the Giroux Lake area (Figure VIII-12 A-H). Towards the east (*e.g.* 11-24-65-18W5; Figure VIII-13), the sandstone reaches a maximum thickness of 7 m. The sand is moderately-sorted, and ranges from lower fine to upper medium in grain size. Towards the east, the maximum grain size of the sand decreases to upper fine. Interstitial mud content is variable. Lower intervals contain abundant interstitial mud as wisps and lenticles, while upper portions of the sand body are characterised by dispersed mud and muddy burrow linings. A few intervals contain thin (<2 cm) dark mudstone interbeds. As in the lower facies, dispersed organic detritus, wood fragments and chert granules and glauconite are present. A single interval contains a few preserved pelecypod shells. Pyrite is a common accessory to the sandstone, replacing wood fragments, some burrow fills and some burrow linings.

The bulk of the facies is totally bioturbated, with little or no preservation of primary physical stratification. In a few localities, thin (<5 cm) low angle parallel to subparallel laminated sandstone beds are preserved (Figure VIII-12 H). These sandstone beds are moderately well- to well-sorted, and typically range from lower to upper fine in grain size. The beds are sharp-based and truncate underlying burrows. The tops are burrowed, and grade into the overlying bioturbated muddy sandstones. Preservation of these thin sandstone interbeds is greater towards the top of the interval, as well as towards the east. The character of the upper part of the sandstone in the 11-24-65-18W5 well (Figure VIII-13) is more akin to the "laminated-to-burrowed" sandstone facies of the Viking Formation in the Kaybob field (*cf.* Chapter VII),

Figure VIII-12. Proximal Facies of the Giroux Lake Parasequence. (A) Thoroughly burrowed muddy sandstone facies with a mud interbed, interpreted as distal lower shoreface. Trace fossils include *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch) and *Palaeophycus* (Pa). Well 09-17-65-20W5, depth 1389.4 m. **(B)** Bioturbated muddy sandstone facies, interpreted to reflect a distal lower shoreface. Trace fossils include *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch), *Teichichnus* (Te), *Asterosoma* (As) and *Zoophycos* (Z). Well 10-25-65-20W5, depth 1340.0 m. **(C)** Thoroughly burrowed muddy sandstone facies interpreted as a distal lower shoreface deposit. Trace fossils include *Planolites* (P), *Asterosoma* (As) reburrowed by *Chondrites* (Ch), *Skolithos* (S) and *Ophiomorpha* (O). Well 10-27-65-20W5, depth 1362.2 m. **(D)** Bioturbated muddy sandstone facies, interpreted to reflect lower shoreface deposition. Visible trace fossils include *Planolites* (P), *Helminthopsis* (H), *Chondrites* (Ch) and *Skolithos* (S). Well 20/10-05-65-20W5, depth 1432.1 m. **(E)** Bioturbated muddy sandstone facies, interpreted as a lower shoreface deposit. Visible trace fossils include robust *Ophiomorpha* (O), *Chondrites* (Ch) and *Palaeophycus* (Pa). Well 09-17-65-20W5, depth 1391.2 m. **(F)** Bioturbated muddy sandstone facies, interpreted to reflect lower shoreface deposition. Visible trace fossils include robust *Asterosoma* (As) and *Rosselia* (Ro). Well 10-30-66-21W5, depth 1252.4 m. **(G)** Thoroughly burrowed muddy sandstone facies, interpreted as a middle shoreface deposit. Visible trace fossils include robust *Diplocraterion* (D), *Chondrites* (Ch) reburrowing muddy interlaminae, *Palaeophycus* (Pa) and *Ophiomorpha* (O). Well 16-04-66-21W5, depth 1412.1 m. **(H)** Bioturbated muddy sandstone facies with an intercalated low angle parallel to subparallel laminated sandstone bed. The muddy sandstone is interpreted to reflect middle shoreface deposition, with the laminated sandstone corresponding to a thin tempestite. The tempestite has been disrupted by an escape trace (fugichnia; fu). The muddy sandstone contains visible *Planolites* (P), *Chondrites* (Ch), *Helminthopsis* (H), *Siphonichnus* (Si), *Skolithos* (S) and *Terebellina* (T). Well 04-15-66-21W5, depth 1343.4 m. **(I)** Trough cross-stratified, medium-grained sandstone, interpreted to reflect upper shoreface deposition. Sandstone contains *Ophiomorpha* (O). Well 10-27-65-20W5, depth 1361.5 m.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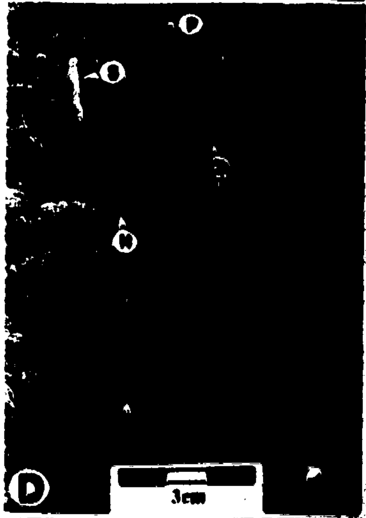
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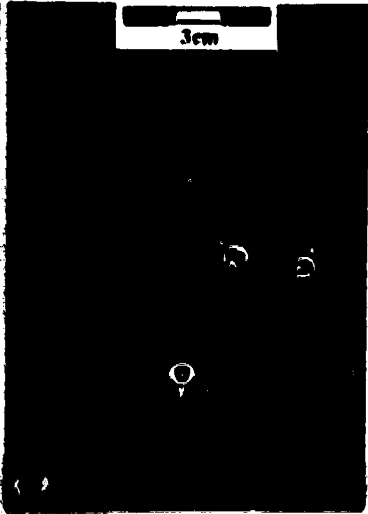
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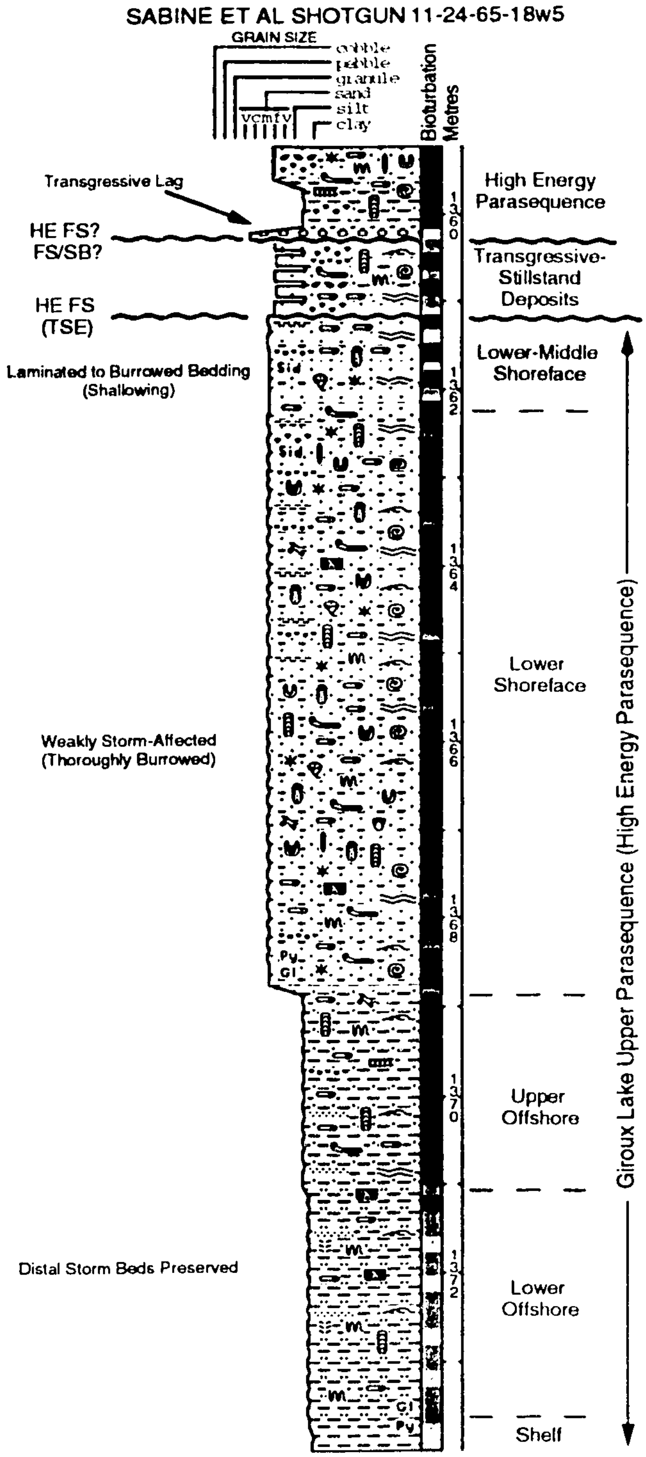


Figure VIII-13. Litholog of the Giroux Lake upper parasequence in the northeast portion of the study area. Note the thoroughly burrowed character of the shoreface succession. The upper portion of the parasequence is truncated by a high energy flooding surface (HE FS). The legend of symbols used in the litholog occurs in Figure VIII-6.

and is interpreted to reflect tempestite beds subsequently modified by infaunal colonisation.

The trace fossil assemblage of the bioturbated muddy sandstone facies is both abundant and diverse. The main elements include *Ophiomorpha, Palaeophycus, Teichichnus, Planolites, Rosselia, Asterosoma, Skolithos,* and *Diplocraterion,* with subordinate numbers of *Chondrites, Helminthopsis, Zoophycos, Terebellina, Cylindrichnus, Siphonichnus, Bergaueria, Arenicolites* and *Conichnus.* The discrete mudstone interbeds typically contain *Helminthopsis, Chondrites* and *Planolites.* The less common parallel laminated sandstone interbeds possess fugichnia, *Arenicolites* and *Skolithos.* Many of the *Chondrites* are closely associated with the reburrowing of muds associated with *Rosselia, Asterosoma* and, to a lesser extent, *Ophiomorpha.* Additionally, many of the *Rosselia* and *Asterosoma* structures are siderite-cemented. The bulk of the *Skolithos, Arenicolites, Diplocraterion, Bergaueria* and *Conichnus* occur towards the top of the facies.

The trace fossil suite shows a predominance of structures constructed by deposit feeders, suspension feeders and mobile carnivores, with highly subordinate grazing and foraging structures. Suspension feeding structures become more common upwards, with a decline in surface deposit feeding structures. Traces made by passive carnivores are also relatively common. The assemblage corresponds to a proximal *Cruziana* ichnofacies, which grades upwards into the *Skolithos* ichnofacies, interpreted to reflect lower shoreface grading into middle shoreface environments (Figure VIII-10). The discrimination between lower and middle shoreface environments is predominantly based on the change-over from a *Cruziana* ichnofacies to a *Skolithos* ichnofacies of the fairweather infaunal community (Howard, 1972; 1975; MacEachern and Pemberton, 1992). Increasing degrees of storm dominance and the corresponding enhancement of tempestite erosional amalgamation tends to truncate or obliterate the record of fairweather burrowing. Consequently, discriminating lower shoreface from middle shoreface deposits becomes progressively more difficult.

The abundance of trace fossils and the ubiquitous cross-cutting relationships, supports slow continuous deposition with little preserved record of storm events (*i.e.* Howard, 1975). The sandy character of the facies suggests persistent wave shoaling, supporting deposition at or above fairweather wave base. The parallel laminated sandstone interbeds, preserved towards the top of the facies and towards the east, are interpreted as preserved tempestites. The fugichnia corresponds to the disturbances made by organisms entrained within the flow, or buried by the event bed, as they attempt to reach the sediment-water interface. The *Skolithos* and *Arenicolites* penetrating the tempestites reflect the initial opportunistic colonisation of the new substrate, common to storm beds (*cf.*, Pemberton and Frey, 1984; Pemberton *et al.*, 1992b; Chapter IV).

Trough Cross-Stratified Sandstone Facies

The trough cross-stratified sandstone facies sharply overlies the bioturbated muddy sandstone facies (Figures VIII-9 I and VIII-12 I). It is developed in only a few intervals, and ranges from 20 to 60 cm in thickness. The sand is moderately-sorted, upper fine to upper medium in grain size, and locally contains small siderite-cemented mudstone rip-up clasts. The facies locally contains chert granules, wood fragments and organic detritus. A few intervals display thin (<2 cm) intercalated dark coloured organic-rich mudstone layers. Primary stratification consists of thin (<10 cm) beds of trough cross-stratification. The upper part of the facies is typically truncated by an erosional discontinuity.

The facies is only sporadically burrowed and of low intensity. The most common ichnogenus is *Ophiomorpha*, with considerably rarer *Palaeophycus* and fugichnia. The fugichnia record the disturbances generated by the escape of infauna buried during the progradation of the small subaqueous dunes. *Ophiomorpha* and *Palaeophycus* constitute elements of the *Skolithos* ichnofacies (Figure VIII-10) and reflect the relatively high energy nature of benthic existence in proximity to migrating bedforms. Both the *Ophiomorpha* and *Palaeophycus* are lined, and the former deeply penetrating, which are attributes of dwelling structures suited to inhabiting these physically dynamic settings. The facies is interpreted to reflect the erosional remnant of the upper shoreface complex.

Overlying Discontinuity and Associated Bioturbated Gritty Sandy Shales

The erosional discontinuity which truncates the top of the facies, is directly overlain by gritty sandy shales (Figure VIII-9 F-I), analogous to those at the base of the succession (*cf.* Facies B; MacEachern *et al.*, 1992a). In some localities, an initial low energy (non-erosional) marine flooding is present, with only a few sideritic mudstone rip-up clasts mantling the contact (Figure VIII-9 I). Sand sizes are variable, ranging from upper fine to upper coarse, and dispersed throughout the interval. Chert pebbles and granules are commonly present, and locally form a lag 1 to 10 clasts thick on the discontinuity. Primary physical structures are rarely present in the facies although locally remnant low angle (<15°) parallel to subparallel lamination is preserved (Figure VIII-9 H). These appear to represent deposition of distal storm beds. For the most part, burrowing is intense and few discrete ichnogenera are preserved due to abundant overprinting. The most commonly encountered trace fossils include *Teichichnus, Terebellina, Planolites, Asterosoma* and *Chondrites,* with rarer *Helminthopsis* and *Palaeophycus.* The suite is characterised by a low diversity of ichnogenera and is dominated by deposit feeding structures, reflecting an impoverished *Cruziana* ichnofacies assemblage (Figure VIII-10).

The succession overlying the discontinuity appears to display pronounced deepening. The erosional discontinuity is interpreted to have removed the bulk of the upper shoreface succession and any foreshore or backshore facies that may have accumulated. The bioturbated gritty sandy shales overlying the surface, on the other hand, suggests upper offshore conditions, interpreted as the distal deposits of transgressive ravinement. The coarse detritus corresponds to erosional removal of material in shallower water settings, reworked basinward during storms (MacEachern *et al.*, 1992a). The nature of the erosional discontinuity itself is uncertain. Certainly, the last phase of modification and deposition corresponds to transgressive deepening, however, the initiation of the surface may correspond to initial lowstand conditions (*cf.* Van Wagoner *et al.*, 1990). Under these conditions, the surface may reflect an amalgamated lowstand and transgressive surface (FS/SB), rather than simply a high energy marine flooding surface (transgressive surface of erosion).

GIROUX LAKE SUCCESSION: A WEAKLY STORM-INFLUENCED SHOREFACE

The upper parasequence of the Viking Formation at Giroux Lake displays a gradual coarsening upward cycle, from silty shale of the shelf or lower offshore, through the upper offshore, lower shoreface, middle shoreface and locally, an erosional remnant of the upper shoreface. The cycle ranges from a minimum of approximately 6 m in the southwest to a maximum of 24 m in the northwest. The parasequence thickens basinward along depositional dip to the northeast (Figure VIII-8) and remains approximately uniform in thickness along depositional strike. Interestingly, the thickening of the sandy component of the parasequence is considerably less pronounced along depositional dip. The thickening of the parasequence basinward is almost wholly accounted for by shelfal and offshore shale, infilling the transgressively-enhanced accommodation space.

The trace fossil suites within most facies of the parasequence display high diversity of ichnogenera, intense burrowing and uniform distribution of burrowing, all features consistent with fully marine, equilibrium (K-selected) communities in unstressed environments (Pianka, 1970; Jumars, 1993). The uniform distribution of ichnogenera and the abundance of biogenic overprinting within the softground suite correspond to a slow and generally continuous sedimentation rate (Howard, 1975). Storm events appear to have been relatively infrequent and of low intensity, permitting thorough biogenic mottling. The record of some storm events is actually best reflected in the lower offshore deposits, which display a generally higher preservation potential for tempestites than the upper offshore and lower shoreface, particularly in weakly storm-influenced settings (Pemberton *et al.*, 1992b; Chapter IV; Figure VIII-11 B, C). The bulk of the trace fossil suite can be regarded to correspond to the fairweather community. The transition from a proximal *Cruziana* suite to a *Skolithos* suite within the bioturbated muddy sandstone facies corresponds to the transition from a lower shoreface to a middle shoreface environment (*cf.* Howard, 1972; 1975; MacEachern and Pemberton, 1992; Figure VIII-10). It is the well-preserved fairweather trace fossil suite that permits this discrimination.

Comparatively, the cross-bedded sandstone facies possesses a reduced diversity, a reduced abundance of burrowing and a greater dominance of vertical structures, reflecting the shallower water, higher energy and greater physical stress associated with the dynamic conditions of deposition in the upper shoreface setting. This facies is preserved only as an erosional remnant, truncated by a high energy (erosional) marine flooding surface. This surface removes the top of the upper shoreface and any foreshore and/or backshore deposits that may have accumulated during northeastward progradation. The presence of some upper shoreface deposits is significant, in that it demonstrates that the entire lower and middle shoreface complex is preserved. The absence of large numbers of storm beds indicates that the shoreface system, as a whole, was characterised by low storm-energy conditions. This shoreface type constitutes an end member in shoreface variability, contrasting markedly with strongly storm-dominated successions (*cf.* Chapter VI) and moderately storm-dominated systems (*cf.* Chapter VII; MacEachern and Pemberton, 1992).

HIGH ENERGY PARASEQUENCES: STILLSTAND SHOREFACES

Although several Viking Formation oil and gas fields in central Alberta produce hydrocarbons from NW-SE trending shoreface successions (*e.g.* Joarcam, Gilby, Joffre, Chigwell, Kaybob, Giroux Lake, Mikwan, Fenn, Judy Creek, Caroline, Garrington, Crossfield, *etc.*), discrimination between forced regression shoreface and high energy parasequence settings has proven difficult. The sequence stratigraphic implications of these interpretations are profoundly different. Figure VIII-14 schematically illustrates the development of areally restricted parasequences and their relationship to forced regression shorefaces (*cf.* Chapter VII). The lower parasequence boundary corresponds to an FS/SB, generated by erosive shoreface retreat across a subaerial exposure surface. The high energy marine flooding surface (HE FS) removes all evidence of subaerial exposure in the Viking examples studied. A decrease in the rate of sea level rise or an increase in sedimentation rate permits the progradation of a shoreface over the FS/SB, seaward of the backstepping shoreface. The progradational shoreface constitutes the parasequence, marking a basinward shift of facies during a period of relative stillstand of sea level (*i.e.* a stillstand shoreface). An increase in the rate of transgression (resumed transgression) produces a low energy flooding surface below fairweather wave base and a high energy flooding surface at and above fairweather wave base. The high energy flooding surface truncates the upper portion of the stillstand shoreface and cuts a new FS/SB landward of the previous one. It is clear that what initially appears to be a single FS/SB is actually a composite surface, generated by multiple, discrete periods of transgressive modification of the sequence boundary.

Differentiating High Energy Parasequences and Forced Regression Successions

It is imperative to differentiate between lowstand-generated forced regression shorefaces and high energy parasequences produced during periods of incremental transgression; the two successions reflect markedly different sequence stratigraphic settings. The forced regression shoreface is an element of the lowstand systems tract and lies directly on the sequence boundary. In contrast, the high energy parasequences are elements of the transgressive systems tract and are separated from the sequence boundary by a marine flooding surface.

In so far as the ichnology of the sediment is concerned, there are few obvious differences between the two stratigraphic settings. The parasequences and the forced regression shorefaces **are** shorefaces, and are therefore subject to much the same environmental conditions. Consequently, animal behaviours, and hence the biogenic structures produced in both settings largely obey existing depositional models (Figure VIII-10). Subtle differences may be expected, related to the inferred higher sedimentation rates and increased fluvial discharge during lowstand conditions, compared with stillstand and highstand conditions. Such differences, however, must be dealt with through a regional synthesis of such settings, in order to eliminate local variations.

Further obscuring differentiation between the two sequence stratigraphic settings is the preserved record of the discontinuity. Both the sequence boundary of the forced regression and the FS/SB or HE FS of the stillstand parasequence boundary are erosionally developed under marine conditions, favouring colonisation by tracemakers of the substrate-controlled *Glossifungites* ichnofacies. In the Viking Formation, both shoreface successions are typically truncated by high energy flooding surfaces during initial or resumed transgression, respectively. In many cases, therefore, it may be difficult to discriminate between the deposits of these fundamentally different stratigraphic scenarios, except on the basis of their regional stratigraphic context.

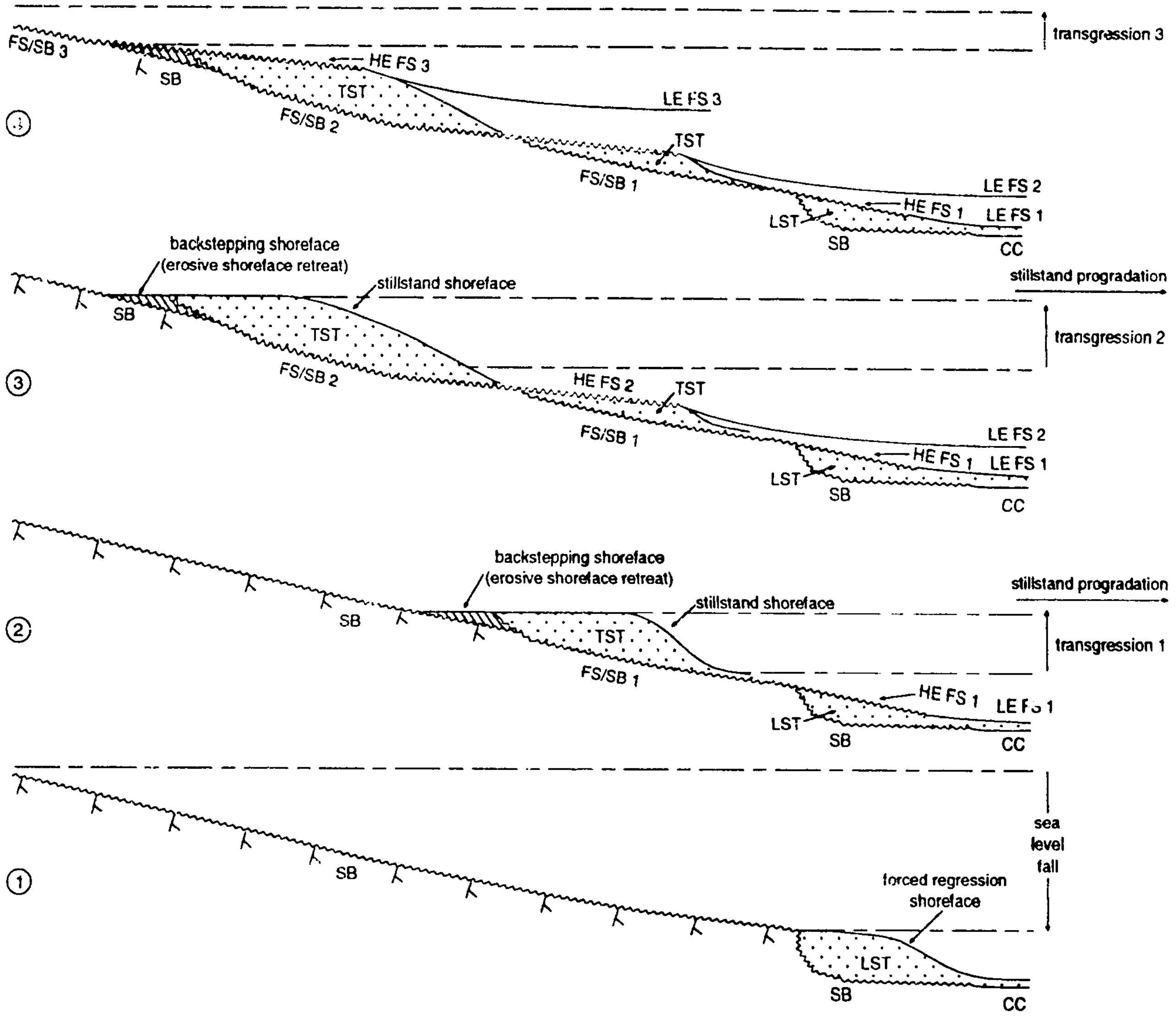
There are, however, a few subtle differences in the character of the two successions that may be employed in order to help differentiate them. In positions lying basinward of the erosional expressions of both the sequence boundary and the FS/SB (*i.e.* the correlative conformity and the low energy flooding surface, respectively), the successions may be virtually identical. In such positions, both intervals are characterised by gradual coarsening upward successions, overlying a generally cryptic surface. Where the surfaces are erosional, however, some differences in the successions are apparent.

Since the erosional sequence boundary extends seaward only to a depth of fairweather wave base, forced regression deposits directly overlying the discontinuity should reflect conditions no deeper than lower shoreface (*cf.* Figure VIII-14). Continued sea level fall produces progressively shallower water facies overlying the sequence boundary. The FS/SB is also erosionally generated at initial fairweather (minimum) wave base, but in contrast, is succeeded by rising relative sea level and enhanced accommodation space. Thus, stillstand deposits directly overlying the FS/SB may commonly reflect deeper water conditions than fairweather wave base (*i.e.* offshore or shelfal shales; Figures VIII-8 and VIII-14).

In proximal positions, forced regression shorefaces tend to pass from lower to upper shoreface deposits over relatively thin intervals, due to the reduced accommodation space. Further, since the shoreface is rapidly displaced basinward during falling sea level, lower, upper and even foreshore deposits may lie directly on the sequence boundary. It is this sharp-based character of the shoreface that is commonly employed to interpret an interval as a lowstand shoreface (*e.g.* Plint, 1988; Posamentier and Chamberlain, 1991, 1993; Posamentier *et al.*, 1992; Walker and Bergman, 1993). In contrast, high energy parasequences are associated with enhanced accommodation and therefore typically show more gradual coarsening upward successions. Even in proximal positions, initial deposition on the FS/SB will probably be no shallower than lower shoreface, because the parasequence must prograde basinward to fill the accommodation space.

Figure VIII-14. Schematic Model of Forced Regression and Stillstand Shoreface Development in the Viking Formation. **(1)** Relative sea level fall shifts the shoreline basinward, creating a widespread subaerial exposure surface. At the new shoreline position, a wave-cut notch is generated to a depth corresponding to fairweather wave base (FWWB). Below this, a non-erosional correlative conformity (CC) is developed. The subaerial exposure surface, wave-cut notch and CC are manifestations of the same sequence boundary (SB). The new shoreface, termed a forced regression shoreface, progrades over the SB and is an element of the lowstand systems tract (LST). **(2)** Ensuing transgression (transgression 1) generates a low energy flooding surface (LE FS) below FWWB, and a high energy flooding surface (HE FS), generated by erosive shoreface retreat, at and above FWWB. Continued transgression truncates the top of the forced regression shoreface, and cuts an amalgamated flooding surface and SB (FS/SB). The backstepping shoreface sits on the SB. No evidence of subaerial exposure is preserved on the FS/SB. During a relative stillstand of sea level, a shoreface progrades over the FS/SB. Note that since the FS/SB is cut during rising sea level, initial deposits on the surface may correspond to facies lying basinward of FWWB, in contrast to the forced regression shoreface. **(3)** Resumed transgression (transgression 2) generates an LE FS below, and an HE FS at and above the initial FWWB. Here, the HE FS removes the backstepping shoreface. Erosive shoreface retreat creates a new FS/SB landward of the first stillstand shoreface. The remnant of this shoreface constitutes a parasequence. During a pause in transgression, a new stillstand shoreface is produced seaward of the backstepping shoreface, and progrades over the FS/SB. **(4)** Resumed transgression (transgression 3) generates an LE FS below, and HE FS at and above initial FWWB. In this example, a remnant of the backstepping shoreface and, hence the SB, is preserved. Evidence of subaerial exposure is removed landward of this remnant, as a new FS/SB is cut. The progressive landward-stepping stillstand shorefaces produce a retrogradational parasequence set, reflecting the transgressive systems tract (TST).

The only localities where the initial SB is preserved are underlying the forced regression shoreface, small remnants veneered by backstepping shorefaces, and the CC. Erosive shoreface retreat has removed virtually all other evidence of subaerial exposure. The FS/SB is actually a composite surface, made up of segments of FS/SB (*i.e.* FS/SB1 - FS/SB 3) which are genetically related to specific transgressive events. Each FS/SB therefore correlates to its equivalent HE FS and LE FS, not to the previous FS/SB.


FS/SB 3
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HE FS 3
TST
LE FS 3
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FS/SB 1
LE FS 2
HE FS 1
LE FS 1
LST
SB
CC
transgression 3
backstepping shoreface
(erosive shoreface retreat)
stillstand shoreface
stillstand progradation
transgression 2
SB
TST
FS/SB 2
HE FS 2
TST
FS/SB 1
LE FS 2
HE FS 1
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backstepping shoreface
(erosive shoreface retreat)
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stillstand progradation
transgression 1
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TST
FS/SB 1
HE FS 1
LE FS 1
LST
SB
CC
②
sea
level
fall
forced regression
shoreface
SB
LST
SB
CC
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Giroux Lake High Energy Parasequence

The Giroux Lake successions conform well with the high energy parasequence model, particularly with respect to the presence of transgressive facies overlying the erosional breaks, followed by significant deepening (Figure VIII-14). It seems unlikely that shelfal and lower offshore shales could directly overlie a sequence boundary, cut no deeper than fairweather wave base, unless initial lowstand conditions were followed by transgression. The relatively thick, gradually coarsening upward succession described from the upper Giroux Lake parasequence (Figure VIII-8) records enhanced accommodation space, and contrasts markedly with the sharp-based, comparatively thin sand-dominated successions described from the Viking Formation of the Kaybob (*cf.* MacEachern *et al.*, 1992b; Pemberton *et al.*, 1992; Chapter VII) and Joarcam fields (Posamentier and Chamberlain, 1991; 1993), as well as from outcrops of the Shannon Sandstone near Casper, Wyoming (Walker and Bergman, 1993). These latter successions conform to the forced regression model (Plint, 1988; Posamentier and Vail, 1988; Posamentier *et al.*, 1992). The Giroux Lake succession displays a basinward (northeastward) increase in the basal shale tongue which separates the underlying parasequence from the overlying parasequence, reflecting this transgressively enhanced accommodation space (Figure VIII-8). Shoreface progradation suggests that the overall transgression was punctuated by stillstand events.

SUMMARY

The Viking Formation at Giroux Lake is an excellent example of both a low storm-energy (weakly storm-affected) shoreface succession (*cf.* MacEachern and Pemberton, 1992; Chapter V), as well as a high energy parasequence (*cf.* Pemberton and MacEachern, in press; Chapter III). From a sedimentological perspective, it characterises shoreface successions consisting of thoroughly bioturbated facies, situations relatively common in Cretaceous strata of the Western Interior Seaway. From a sequence stratigraphic perspective, the Giroux Lake shoreface demonstrates many of the features of a high energy parasequence, permitting its differentiation from forced regressions.

The shoreface succession demonstrates a high diversity and uniform distribution of ichnogenera coupled with intense burrowing, with virtually no preserved primary physical sedimentary structures. In the past, such biogenically homogenized intervals were accorded only the most vague of paleoenvironmental interpretations (*e.g.* "shallow marine"). Previous subdivisions of facies largely relied on purely lithological criteria, such as sand content. Detailed analysis of ichnology permits a refinement in the interpretation of these deposits, particularly when integrated with the physical sedimentology. Using the diversity and abundance of ichnogenera, the facies can be identified as possessing fully marine, unstressed, equilibrium (K-selected) assemblages. The uniformity and abundance of burrowing supports slow and generally continuous deposition. Using the relative proportions of various trace fossil behaviours represented by the ichnogenera encountered within the facies, inferences as to the prevalent environmental controls on the benthic community can be made; inferences not resolvable from purely physical sedimentary features. The subdivision of the suite into distal *Cruziana*, *Cruziana*, proximal *Cruziana*, and *Skolithos* ichnofacies, closely matches the transitions from shelf/lower offshore, upper offshore, lower shoreface and middle shoreface environments, respectively (Figure VIII-10). Ultimately, these subdivisions could be employed to determine which, if any, subenvironments are attenuated or absent in a given succession. The discrimination of lower shoreface from middle shoreface subenvironments is almost exclusively restricted to biological criteria. Thoroughly bioturbated intervals afford such data, particularly where the preserved trace fossil suite corresponds to purely fairweather conditions. Increasing storm dominance tends to obscure this distinction (*cf.* MacEachern and Pemberton, 1992; Chapters V, VI and VII of this thesis).

From a sequence stratigraphic point of view, the Viking Formation at Giroux Lake provides considerable data regarding the characteristics of a high energy parasequence. In general, the succession displays abrupt deepening above a well-developed transgressive surface of erosion, which locally has strongly modified an underlying sequence boundary (FS/SB; Figure VIII-14). Due to progressive deepening and landward translation of the transgressive erosion surface, prior to stillstand progradation, the HE FS constituting the parasequence boundary is typically widespread and discernible as an erosion surface far down depositional dip.

The gradual coarsening upward character of the Giroux Lake succession, particularly where it overlies the erosional discontinuity is distinctive and contrasts markedly with that observed in forced regression successions (*cf.* Plint, 1988; Posamentier and Chamberlain, 1991, 1993; Posamentier *et al.*, 1992; Pemberton and MacEachern, in press; Chapter VII). The stillstand parasequences are generally thick and commonly contain shelfal or lower offshore shales either directly overlying the discontinuity or transgressive deposits mantling the discontinuity. In general, forced regression successions are considerably thinner, and display proximal (shallow water) deposits directly overlying the erosional stratigraphic break. Forced regression shoreface successions do not show a gradual coarsening upward profile, except where basinward of fairweather (minimum) wave base, where it overlies the non-erosional correlative conformity. This may constitute important criteria for the discrimination of these sequence stratigraphically distinct deposits.

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CHAPTER IX

AN INTEGRATED ICHNOLOGICAL-SEDIMENTOLOGICAL MODEL FOR VIKING FORMATION INCISED VALLEY FILL SYSTEMS, WESTERN CANADA SEDIMENTARY BASIN, ALBERTA, CANADA[5]

INTRODUCTION

The Viking Formation has been a fairly intensively explored petroleum target in Alberta since the early 1930's, and is generally regarded as a series of elongate NW-SE trending sand bodies, reflecting shoreface successions. Interest in the Viking Formation waned until the discovery of the Crystal Field in 1978 (Figure IX-1). Not only was the new field a prolific oil producer, but it was anomalous in its roughly N-S orientation, virtually normal to the inferred paleoshoreline trends. Reinson (1985) and Reinson *et al.* (1988) were among the first to recognise these Viking Formation deposits as the products of an incised valley system. Other Viking Formation fields such as Willesden Green, Sundance, Edson and Cyn-Pem, discovered in 1955, 1971, 1973 and 1986, respectively, also demonstrated a roughly N-S orientation, but were not interpreted as incised valley fill deposits until considerably later. Boreen (1989) and Boreen and Walker (1991) were the first to characterise the Willesden Green Field as a incised valley system. Pattison (1991a, b) was the first to interpret the Sundance, Edson and Cyn-Pem deposits as incised valley systems, and confirmed Reinson's original interpretation of the Crystal field.

Study of the facies successions and their distribution within the fields demonstrates both the complex history of sedimentation and the variable nature of the processes operating within the valley systems. Stratigraphic analysis highlights the fact that valleys routinely become the locus of re-

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[5] A version of this chapter has been accepted for publication. MacEachern, J.A. and S.G. Pemberton. in press. *In*: R. Boyd, R. Dalrymple and B. Zaitlin (eds.), Incised valley systems: origin and sedimentary sequences. Society of Economic Paleontologists and Mineralogists Special Publication 51.

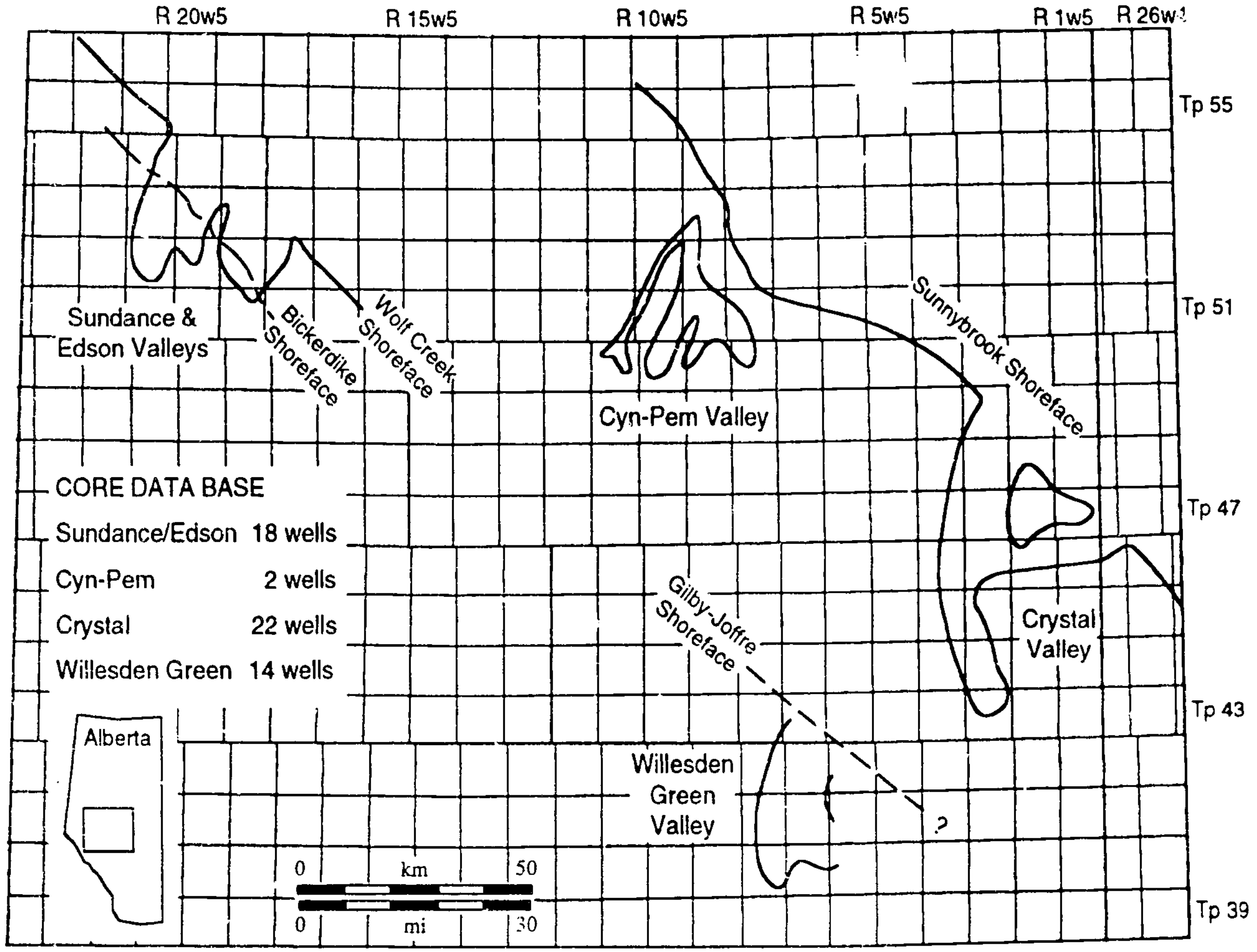


Figure IX-1. Study area map showing the proposed valley outlines for 5 Viking Formation incised valley systems. Modified after Pattison (1991a). The database employed for this paper consists of 56 cored intervals.

incision during successive periods of relative sea level lowstand, producing a lateral and vertical juxtaposition of non-contemporaneous valley-fill deposits and the localised preservation of erosional remnants of earlier estuarine successions. As a result, detailed reconstructions of depositional histories within incised valleys are exceedingly difficult, commonly surpassing the capacity of the existing database to discern (Zaitlin, pers. comm., 1992).

With the exception of Pemberton *et al.* (1992c), detailed ichnological analysis has been an under-utilised tool in the interpretation of the subenvironments operating within valley systems, and in the recognition of the stratigraphic discontinuities associated with their incised fills. Ichnology is ideally suited to impart valuable data about the depositional environment not readily obtainable from lithofacies analysis alone. This paper seeks to demonstrate the effectiveness of integrating ichnological analysis with sedimentology, both in the delineation of the valley margins, and in the enhancement of paleoenvironmental interpretations of facies within estuarine incised valley complexes of the Viking Formation. Enhanced recognition, coupled with more reliable and precise interpretations of the individual facies provides a superior understanding of the conditions responsible for the observed facies associations within the valley systems and the depositional histories of the particular valley deposits.

GENERAL ESTUARINE MODELS

Dalrymple *et al.* (1992) recently provided a good summary of the various definitions and proposed models of estuaries. They suggested a general unified facies model, primarily based on the relative importance of the marine processes (wave and tidal energy) operating on the complex. Fluvial processes, although an important factor in the nature of sediment accumulation, facies distribution within the valley, water salinity, appear to constitute a minor element in the overall character of the estuary. Implicit in their definition of an estuary is that it fills in response to a relative rise in sea level. For the most part, estuaries carry with them the concepts of embayment or channelisation, tides (*cf. aestus* meaning tide) and reduced salinity (brackish waters).

In modern estuaries, a tripartite zonation of facies or facies associations, reflecting the interaction of marine processes and fluvial processes, is readily observed. Van Veen (1936) was one of the earliest to recognise this overall textural zonation of sediment accumulation in his study of the Haringvliet Estuary of the Netherlands. He pointed out that three zones could be distinguished within the tidally-modified portions of the Rhine and Maas rivers and their estuary (the Haringvliet), namely: a fluviatile-sand zone, a central zone where sand was largely absent, and a marine-sand zone. Unfortunately, this doctoral work was largely ignored or overlooked, due to its publication in Dutch. Oomkens and Terwindt (1960) referred to this work in their study of inshore estuarine sediments of the Haringvliet, but the significance of the observed zonation patterns appears to have eluded researchers of the time. Allen (1971), working on the Gironde estuary, France, and Dörjes and Howard (1975), working on the Ogeechee River-Ossabaw Sound estuary of Georgia, observed similar textural variations, which they attributed to the same interactions of marine processes and fluvial energy.

The establishment of a wave-dominated estuary model (Figure IX-2) resulted mainly from the work of Roy *et al.* (1980) on Holocene intervals along the embayed New South Wales coast of Australia. This model appears to explain the facies distributions in many modern estuaries as well as the facies associations for a large number of ancient deposits, including the Viking Formation examples in the Western Canada Sedimentary Basin. Dalrymple *et al.* (1992) regard this facies model as an end member in a continuum of wave-dominated to tide-dominated estuarine settings. The wave-dominated estuary system can be separated into three main depositional complexes: the Bay Head Delta, the Central Basin and the Estuary Mouth, heading from a landward to seaward direction (Figure IX-2).

Pattison (1991a,b) recognised the appropriateness of this wave-dominated estuarine model to explain the observed facies types and their distributions within the Crystal, Sundance-Edson and Cyn-Pem valley systems. Boreen (1989) and Boreen and Walker (1991) recognised the Viking Formation in the Willesden Green field as an estuarine incised valley deposit, but did not place it into this conceptual framework. Observations of the facies and their paleogeographic distributions indicates that the same depositional model effectively explains the accumulation of sediment within the Willesden Green valley system as well. Although detailed sedimentologic and

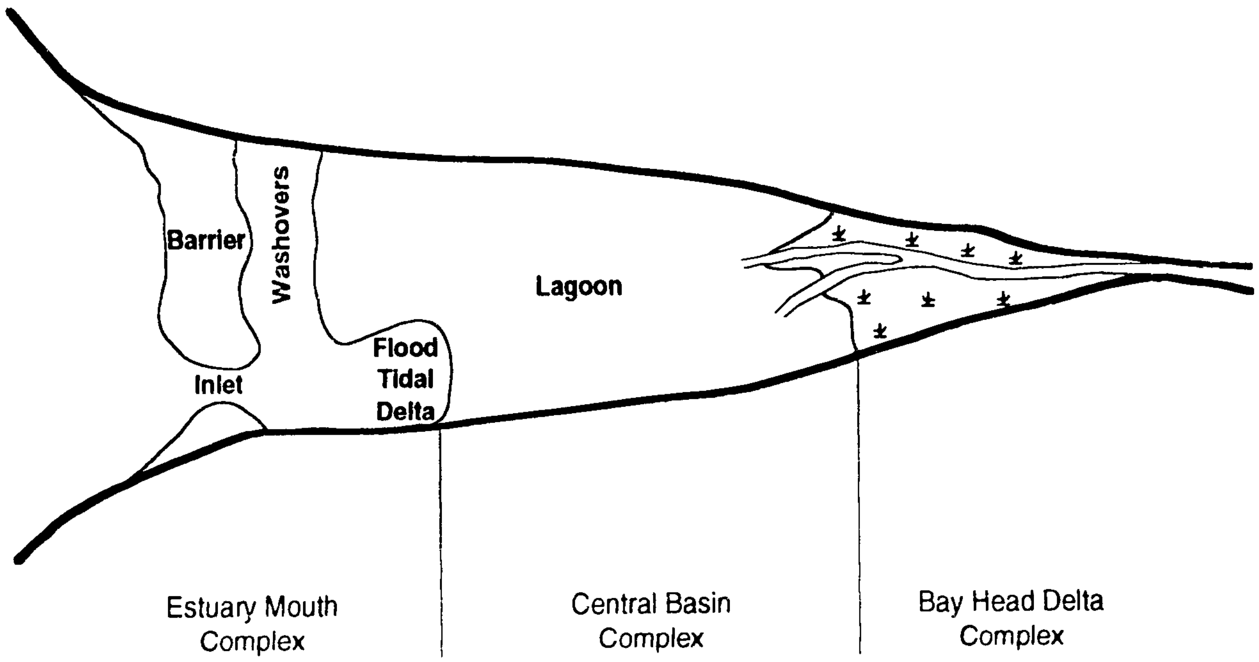


Figure IX-2. Conceptual Model for Wave-Dominated, Embayed Estuarine Depositional Systems. The model best explains the distribution of observed facies and facies associations in the Viking Formation incised valley fills. The system demonstrates a tripartite zonation of facies, corresponding to three main depositional complexes: the bay head delta, the central basin and the estuary mouth. The model is based on observations of embayed estuary systems along the New South Wales coast of Australia, by Roy *et al.* (1980). Figure is modified after Dalrymple *et al.* (1992).

stratigraphic studies have been conducted on these deposits (*e.g.* Reinson *et al.*, 1988; Boreen, 1989; Boreen and Walker, 1991, Pattison, 1991a, 1992), virtually no detailed ichnology has been undertaken, with the exception of Pemberton *et al.* (1992c) who concentrated on the Crystal incised valley alone. This paper builds on the excellent sedimentologic and stratigraphic studies of others, through the integration of detailed ichnological analysis. A total of 56 cored wells were logged for this study, 22 from Crystal, 14 from Willesden Green, 18 from Sundance/Edson, and both cores from Cyn-Pem (Figure IX-1). The integration of ichnology serves to enhance the recognition of incised valley deposits in the ancient record and refine the interpretation of the various depositional subenvironments operating within the estuarine incised valleys.

MODERN BIOLOGICAL BASIS FOR THE ICHNOLOGY OF BRACKISH WATER DEPOSITS

Most marginal marine environments, such as lagoons, bays and estuaries, display steep salinity gradients. These gradients occur in response to variations in the volume and rate of freshwater input from rivers and surface runoff, direct rainfall into the water body, evaporation, tidal range, salinity of the seaway, morphology of the coastal area, and variability in wind direction and approach (Dörjes and Howard, 1975). Marginal marine conditions are physiologically stressful environments for most organisms, not only because of salinity variations, but also due to corresponding changes in temperature, subaerial exposure, water turbulence, oxygen content, water turbidity and sedimentation rates. Estuarine systems are typically characterised by all of these conditions.

Brackish water environments tend to possess organisms which have evolved to control osmotic flooding (osmo-regulation) and the ionic concentration of body fluids (ionic regulation), in order to survive reduced salt concentrations (Croghan, 1983). The extent of this adaptive ability controls the degree of organism tolerance to salinity variations, with freshwater and fully marine faunas constituting the stable end members. Most brackish water assemblages consist of opportunistic euryhaline species, consisting mainly of a marine component, with minor contributions of euryhaline freshwater species, organisms which prefer brackish water, and a migratory component which spends only a portion of their life cycles in brackish waters (Perkins, 1974). Studies of modern brackish water environments indicate that although the biological components are highly variable, there are a number of generalisations possible, which have important ecological and paleoecological ramifications.

Firstly, brackish water settings typically show a reduction in the number and diversity of animal species. This is a direct reflection of the unpredictable and unstable nature of the environment, with the concomitant difficulties in speciation (Slobodkin and Sanders, 1969) and the associated high probability of extinction of the population in these geologically ephemeral systems.

Brackish suites typically consist of greater proportions of marine than freshwater organisms. In general, the reduction of marine forms in response to declining salinity is quite gradual. In contrast, freshwater forms tend to be highly intolerant of even minor increases in salinity. As a result, the brackish water assemblage is more of an impoverished marine community, than a mixture of freshwater and marine biota; there does not appear to be a discrete brackish water fauna (Figure IX-3; Barnes, 1989).

Settings characterised by reduced and/or fluctuating salinity show a pronounced size reduction of fauna compared to fully marine counterparts (Milne 1940). This appears, in part, to be a response to the physiological difficulties in ionic regulation and osmo-regulation. Further, the rigours of inhabiting brackish water imposes an increased oxygen requirement on the fauna, which is minimised by small body sizes (Remane and Schlieper, 1971). The bulk of the community consists of smaller sized animals also due to high mortality rates coupled with rapid reproduction rates. This situation results in a predominance of juvenile organisms compared to adults. Many of these animals also have short life cycles and reach sexual maturity rapidly, favouring an overall smaller body size (Rees *et al.*, 1977).

Brackish water benthic communities are characterised by a predominance of infaunal rather than epifaunal benthic organisms, because the sediment itself tends to dampen the magnitude of salinity variations (Figure IX-4; Sanders *et al.*, 1965; Knox, 1986). Animals living on the bed or within the water column must be able to tolerate considerably greater fluctuations in salinity than those occupying burrows. Hence, the bulk of a brackish water environment's biomass is typically made up of soft-bodied tracemaking

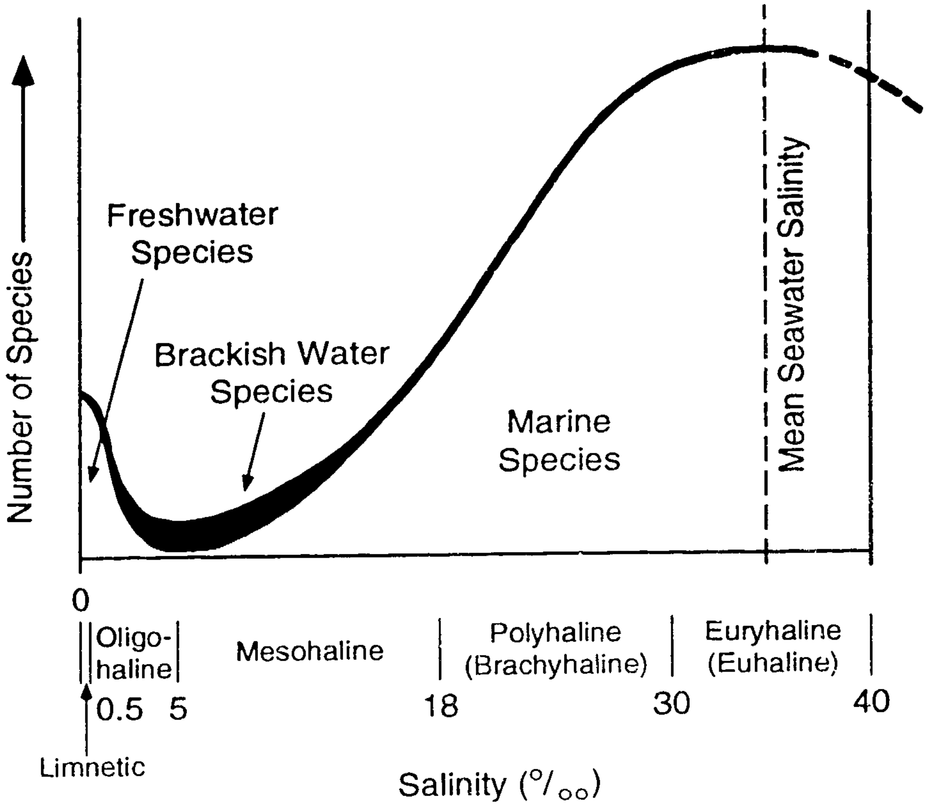


Figure IX-3. Classification of salinity levels and generalised relationship of species diversity with respect to salinity. Note that brackish water faunas are of low taxonomic diversity (modified from Pickerill and Brenchley, 1991).

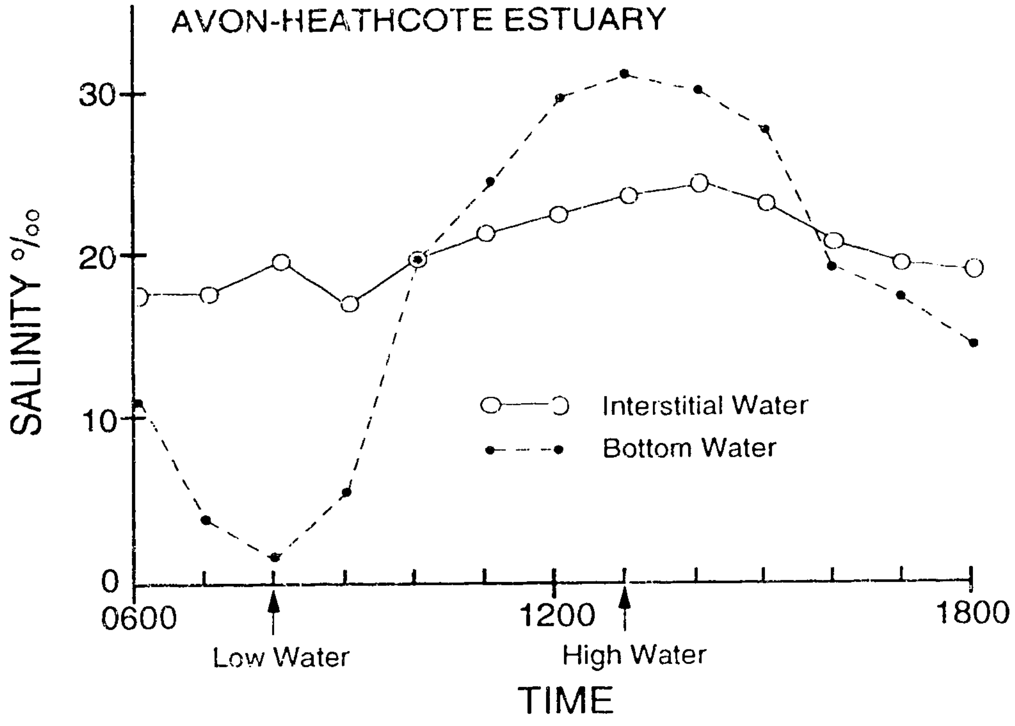


Figure IX-4. Comparison of salinity fluctuations of bottom water and interstitial water at a low tide station in the upper part of the Avon-Heathcote Estuary, New Zealand. Note that there is less variation in salinity fluctuations within the interstitial water, buffering infauna from the more marked variations which occur at the sediment-water interface (modified after Knox, 1986).

organisms. With decreasing salinities, there is also a marked reduction in the numbers of animal groups which form calcareous skeletons (Remane and Schlieper, 1971), favouring greater proportions of soft-bodied fauna.

Most fauna inhabiting brackish water settings correspond to omnivores or trophic generalists (Grassle and Grassle, 1974). The generalised feeding strategies employed by these organisms are closely associated with their opportunistic life cycles. Individual organisms may employ deposit feeding, suspension feeding, predation or scavenging behaviours, depending on the situation. Wolff (1973) found that 35% of the animal species in Dutch estuaries were omnivores, in contrast to the 6-16% which characterise the adjacent freshwater and fully marine settings.

Finally, despite the reduced diversity of species inhabiting brackish water settings, Rosenberg *et al.* (1977) found that such environments support a large biomass. This high abundance of organisms can be attributed partly to the sheltered character of most marginal marine settings, an abundant food supply from rivers, salt marshes, mangroves, coastal zones and *in situ* production, and to generally shallow water conditions, favouring rapid supply of suspended food to the benthic community (*cf.* Pemberton and Wightman, 1992).

The fauna of brackish water environments predominantly employ an r-selected strategy in population dynamics (Levinton, 1970; Pianka, 1970; Jumars, 1993), typical of any organism inhabiting an environment of high physiological stress. Organisms employing an r-strategy are opportunistic and can respond rapidly to an open or unexploited niche. They are typified by a lack of equilibrium population size, a density-independent mortality, an ability to reproduce rapidly, a poor competitive ability, short or reduced life cycles with early onset of sexual maturity, and gregarious colonisation patterns.

The general characteristics of brackish water faunal communities tend to be: 1) an impoverished marine assemblage of benthic organisms, 2) a predominance of infaunal (tracemaking) organisms over epifaunal organisms, 3) an abundance of soft-bodied organisms compared to shelled animals, 4) generally diminished animal body size, 5) a higher proportion of trophic generalists than animals employing specialised feeding strategies, 6) local dominance by single species displaying gregarious colonisation patterns, and 7) generally high abundances of fauna, despite a reduced diversity of species.

Ichnological Implications of Brackish Water Faunal Assemblages

Relatively few studies deal specifically with biogenic structures in modern brackish water settings. Notable exceptions are the work of Howard and Frey (1973, 1975) and Howard *et al.* (1975) dealing with the estuaries of the Georgia Coast. In general, they found that the diversity and abundance of trace fossils tended to increase seaward and that ichnological suites consisted of both vertical and horizontal burrows and burrow systems. Consequently, such assemblages do not conveniently fall into any of the universal ichnofacies of Seilacher (1967). The trace fossil suite tends to constitute a mixture of structures which, if preserved, would result in a low diversity, mixed *Skolithos-Cruziana* ichnofacies. The alternation between the two ichnofacies largely corresponds to fluctuating energy conditions characteristic of estuarine environments.

Trace fossil suites interpreted as brackish water in origin, show similar trends observed in the character of the infauna of modern salinity-stressed settings. The diversity of ichnogenera is generally low, corresponding partly to a decrease in the diversity of tracemakers, but also to a decline in the range of behaviours employed by the infauna. The diversity of ichnogenera increases seaward, as well as with increasingly normal salinity. Most structures also tend to be small, corresponding partly to the diminutive size of tracemakers adapted to the rigours of brackish water habitation (Remane and Schlieper, 1971; Croghan, 1983), and partly to the predominance of juvenile animals over adults. Brackish water trace fossil suites consist overwhelmingly of simple structures of animals which are trophic generalists (Grassle and Grassle, 1974; Wightman *et al.*, 1987; Beynon *et al.*, 1988; Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; Ranger and Pemberton, 1992). Due to the gregarious colonisation character of opportunistic faunal assemblages (Rhoads *et al.*, 1978; Whitlach and Zajac, 1985), intervals may be dominated by a single ichnogenus. The trace fossil suites, as pointed out by Howard and Frey (1973, 1975) and Howard *et al.* (1975), are commonly manifest by a mixed *Skolithos-Cruziana* ichnofacies, corresponding to fluctuating energy conditions and variable sedimentation rates typical of estuaries. In spite of the stresses imposed by such environmental conditions, burrowing intensities may be quite high, reflecting the large biomass of infauna characteristic of many brackish water settings (Rosenberg *et al.*, 1977). With increasingly normal salinities, the trace fossil assemblage tends to become more like fully marine (K-selected or equilibrium) assemblages (*cf.* Pianka, 1970; Jumars, 1993).

REGIONAL SETTING AND STRATIGRAPHY OF THE VIKING FORMATION

The Viking Formation is Lower Cretaceous (Upper Albian) in age and occurs as a regionally extensive interval of sandstones, shales and rare conglomerates throughout the subsurface of Alberta and Saskatchewan (Figure IX-5). The Viking Formation grades out of marine shales of the Joli Fou Formation, which represents a major (2nd order?) transgression over a sequence boundary developed on the Mannville Group. The lower Viking Formation consists of 4th- and 5th-order highstand parasequences which downlap onto the marine shales of the Joli Fou Formation (Figure IX-6; Pattison, 1991a). The upper part of the Viking Formation comprises a complex series of 3rd, 4th and possibly 5th order cycles of progradation, transgression and relative sea level lowstands. The Viking Formation is abruptly overlain by the marine shales of the Colorado Group, reflecting a return to major (2nd order?) marine transgression. The complexity of the Viking Formation is well reflected by the proposed allostratigraphic paradigms for the interval (*cf.* Boreen and Walker, 1991; Pattison, 1991a, 1992; Figures IX-7 and IX-8, respectively), and the continuing controversy regarding its sequence stratigraphic history. The Viking Formation is roughly equivalent in age and stratigraphic position to the Paddy Member of the Peace River Formation in northwest Alberta (Stelck and Koke, 1987), the Bow Island Formation in southwest Alberta (Glaister, 1959), and the Muddy Sandstone of Montana (McGookey *et al.*, 1972).

The lowstand event responsible for the development of some of the Viking incised valley systems has been suggested to correspond to the 98 Ma eustatic fall of sea level of Vail *et al.* (1977), Haq *et al.* (1988), and Reinson *et al.*, (1988) and may also correspond, in part, to the unconformity separating

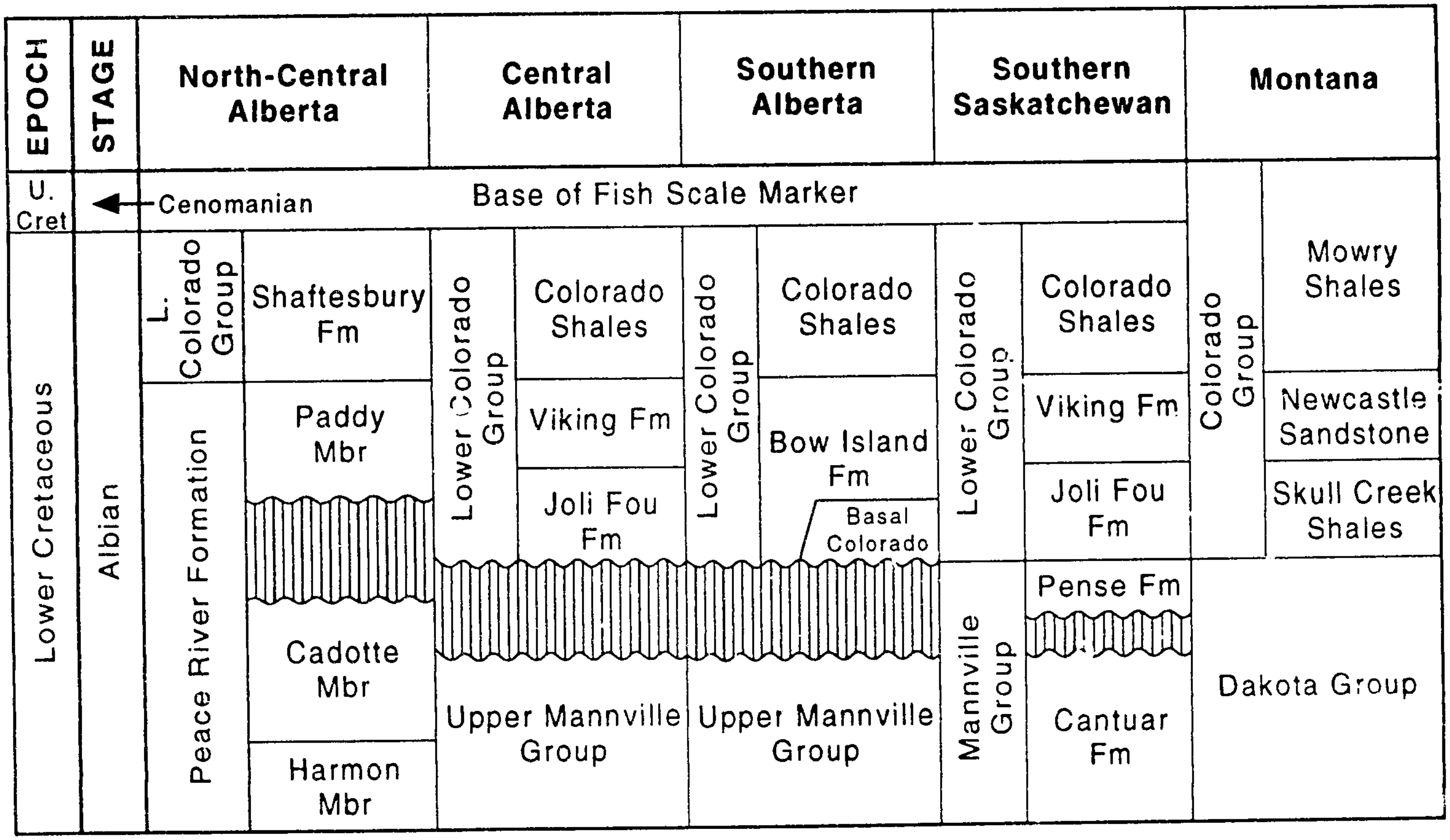


Figure IX-5. Stratigraphic correlation chart for the Viking Formation and equivalents.

FOURTH- AND FIFTH-ORDER PARASEQUENCES IN THE REGIONAL VIKING FORMATION

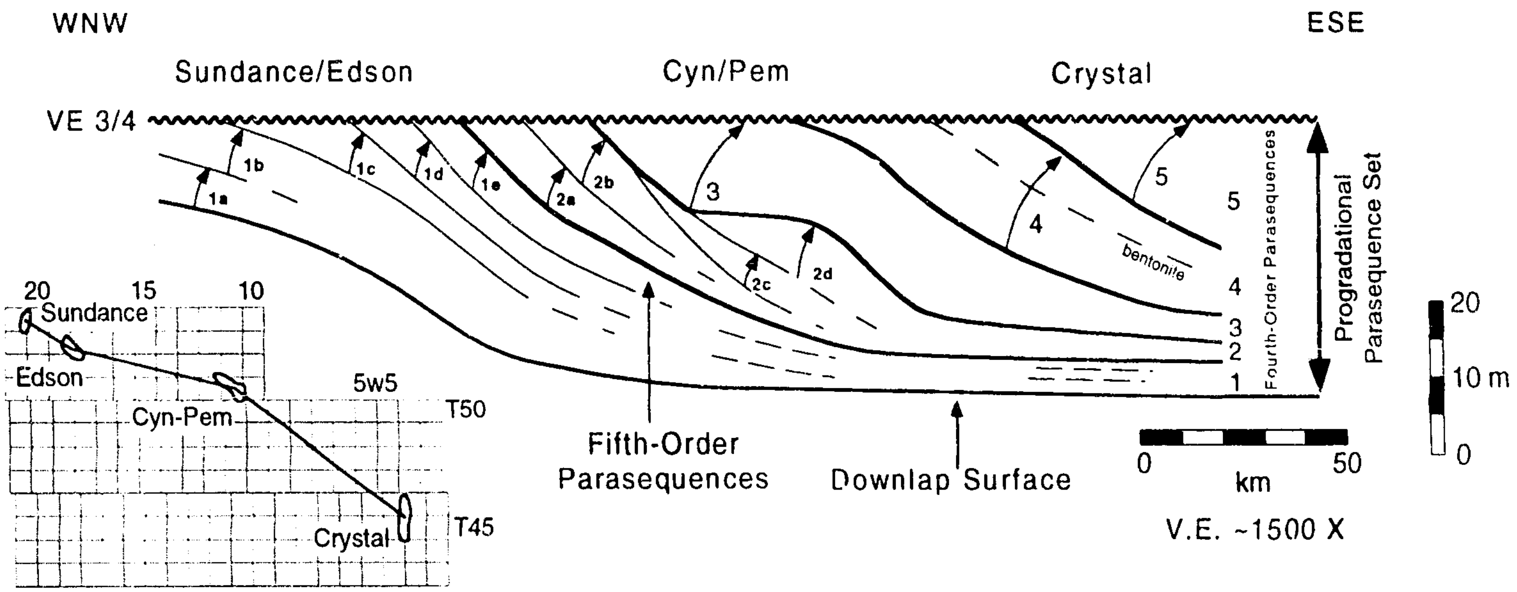


Figure IX-6. Regionally Extensive Parasequences of the Viking Formation. This schematic cross-section shows the character of a number of coarsening upward successions in the basal portion of the Viking Formation. The main successions (1-5) correspond to fourth-order parasequences, consisting of shelfal/lower offshore to lower shoreface deposition. The lower two fourth-order parasequences consist of a number of fifth-order parasequences. All parasequences are generally bounded by low energy flooding surfaces. The overall stacking pattern corresponds to a progradational parasequence set, reflecting a highstand systems tract. The succession is truncated by a high energy flooding surface (VE3/4). The map to the lower left indicates the approximate line of section. Figure modified after Pattison (1991a).

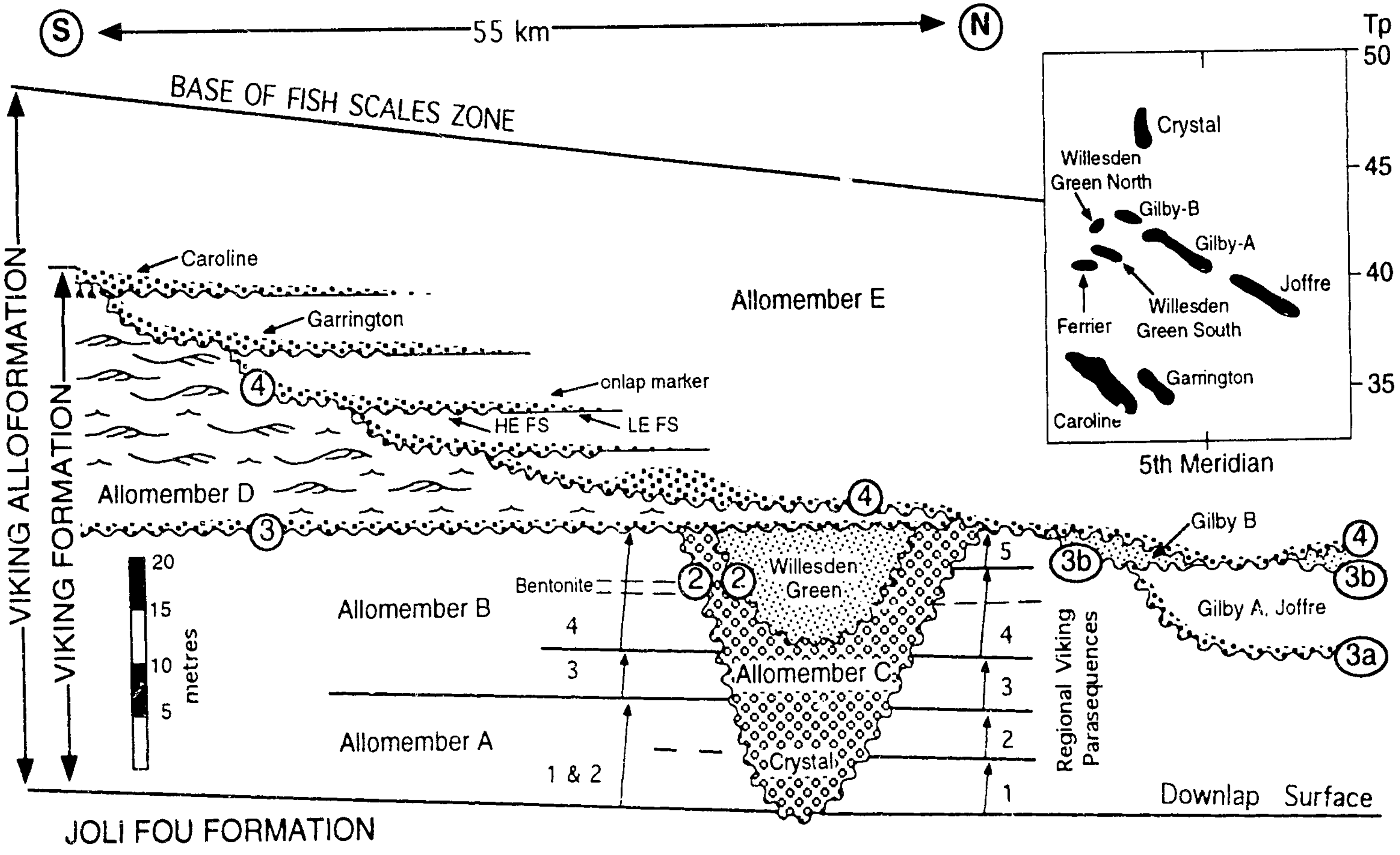


Figure IX-7. Allostratigraphic framework proposed for the Viking Formation. The Viking Alloformation contains 5 Allomembers (A-E), separated from one another by regional discontinuities. The main discontinuities are VE2 (2), VE3 (3) and VE4 (4), with secondary erosion surfaces present as well. Figure modified after Boreen and Walker (1991).

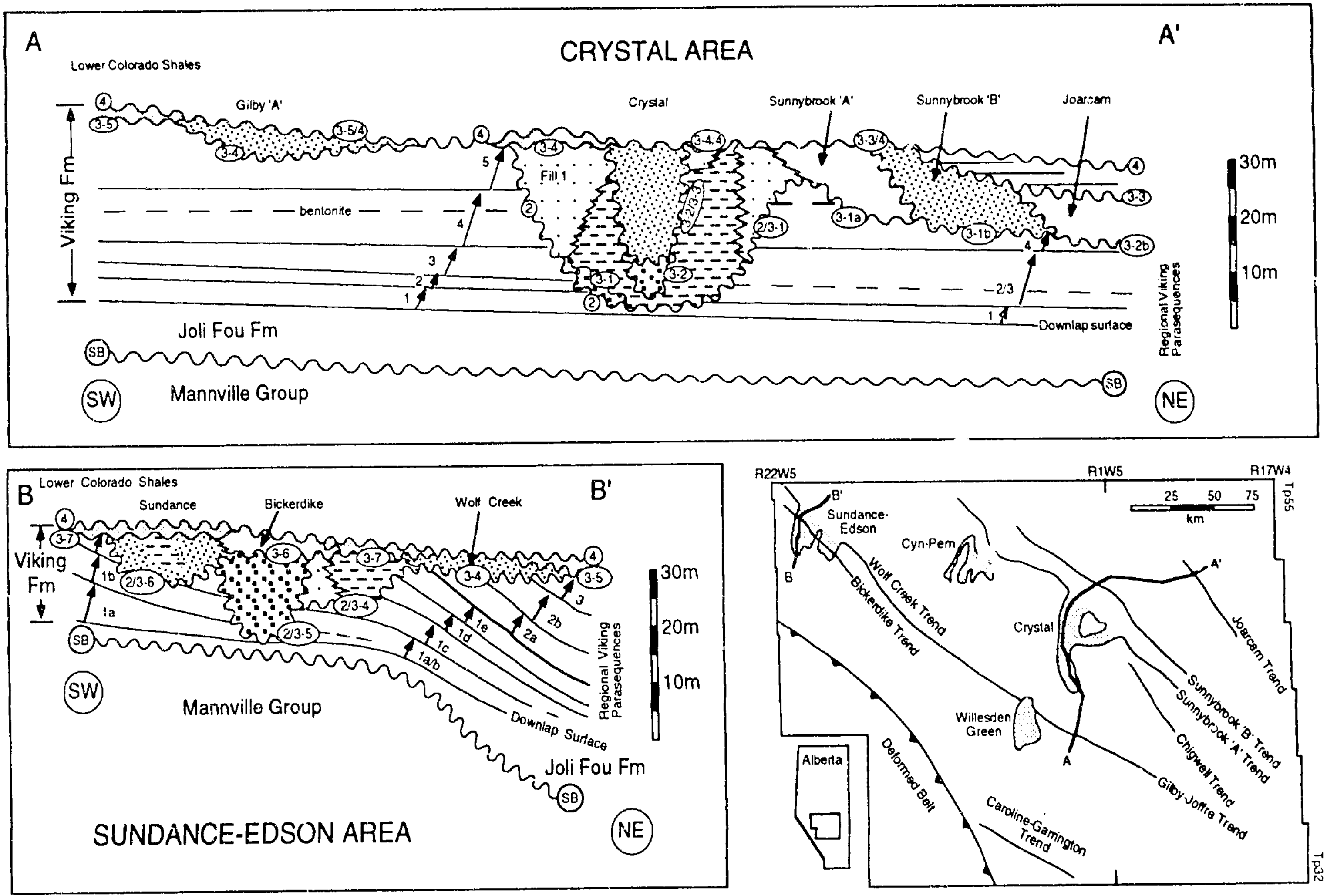


Figure IX-8. Revised allostratigraphic framework for the Viking Formation by Pattison (1991a). The VE3 surface has been subdivided into 7 discrete surfaces (3-1 to 3-7). In addition, surfaces are locally amalgamated, designated by a backslash (*i.e.* 2/3-5). This second generation allostratigraphy highlights the complexity of the VE3 transgression in central Alberta. Figure modified after Pattison (1991a).

the Cadotte Member and Paddy Member of the Peace River Formation in north-central Alberta (Leckie and Reinson, in press).

APPLICATIONS OF ICHNOLOGY TO VIKING FORMATION INCISED VALLEY SYSTEMS

Ichnology can be effectively applied to Viking Formation incised valley complexes in two main ways. The first is through the use of substrate-controlled ichnofacies in recognising and delineating stratigraphic discontinuities, such as the incised valley base and margins and the overlying transgressive surfaces of erosion. The second is through the study of ichnological successions and the recognition of marked differences between the trace fossil assemblages of underlying, fully marine suites and opportunistic suites within the estuarine valley deposits. Variations in the trace fossil suites associated with the different estuarine depositional complexes highlight a number of environmental stresses imposed upon the infaunal tracemakers.

Substrate-Controlled Ichnofacies and Valley Margin Recognition

Traditionally, it was thought that there were only three ways in which trace fossils could be utilised in chronostratigraphy: (1) tracing the evolution of behaviour; (2) as morphologically-defined entities (with no assumptions concerning their genesis); and (3) as substitutes for the tracemaking organisms (Magwood and Pemberton, 1990). More recently, however, trace fossils and in particular, substrate-controlled trace fossils are proving to be one of the most important groups of fossils in delineating stratigraphically important boundaries related to sequence stratigraphy (MacEachern *et al.* 1990, 1991a,b, 1992a,b; Savrda, 1991a, b; Pemberton, *et al.*, 1992a; Pemberton and MacEachern, in press).

Three substrate-controlled ichnofacies have been established (Bromley *et al.*, 1984): *Trypanites* (hardground suites), *Teredolites* (woodground suites) and *Glossifungites* (firmground suites). Although all three suites may indicate the presence of a regional stratigraphic discontinuity, the *Glossifungites* ichnofacies is by far the most common to do so in Viking intervals. The *Glossifungites* ichnofacies (redefined by Frey and Seilacher,

1980) encompasses trace fossils associated with semilithified or firm substrates, predominantly reflected by dewatered, cohesive muds, attributable either to subaerial exposure or burial with subsequent exhumation (Figure IX-9). Less commonly, *Glossifungites* suites may be developed within incipiently-cemented sandstone substrates, although no unequivocal examples have been recognised in the Viking Formation.

Recognition of the *Glossifungites* Ichnofacies

Firmground traces are dominated by vertical to subvertical dwelling structures of suspension feeding organisms (Figures IX-10 and IX-11). The most common structures correspond to the ichnogenera *Diplocraterion, Skolithos, Psilonichnus, Arenicolites,* and firmground *Gastrochaenolites*. Dwelling structures of deposit feeding organisms are also constituents of the ichnofacies, and include firmground *Thalassinoides/Spongeliomorpha,* and *Rhizocorallium*. The presence of such unlined vertical shafts within shaly intervals is anomalous, as such structures are not capable of being maintained in soft muddy substrates. *Glossifungites* ichnofacies traces are typically robust, commonly penetrating 20-100 cm below the bed junction. Many shafts tend to be 0.5-1.0 cm in diameter, particularly *Diplocraterion habichi* and *Arenicolites*. This scale of burrowing is in sharp contrast to the predominantly horizontal, diminutive trace fossils common to shaly intervals. The firmground traces are very sharp-walled and unlined, reflecting the stable, cohesive nature of the substrate at the time of colonisation and burrow excavation (*e.g.* Figure IX-10 E). Many structures, particularly in outcrop, show preserved sculptings or scratch marks on the burrow wall, confirming that construction of the dwelling burrow occurred in a firm substrate. Further evidence of substrate stability, atypical of soft muddy beds, is the passive nature of burrow fill. This demonstrates that the structure remained open after the tracemaker vacated the burrow, thus allowing material from the succeeding depositional event to passively fill the open structure. If such an unlined burrow had been excavated in soft mud, the domicile would have collapsed upon burrow vacation. The post-depositional origin of the *Glossifungites* suite, in relation to the original softground assemblage, is clearly demonstrated by the ubiquitous cross-cutting relationships observed in the rock record. The final characteristic of the *Glossifungites* suite is the tendency to demonstrate colonisation in large

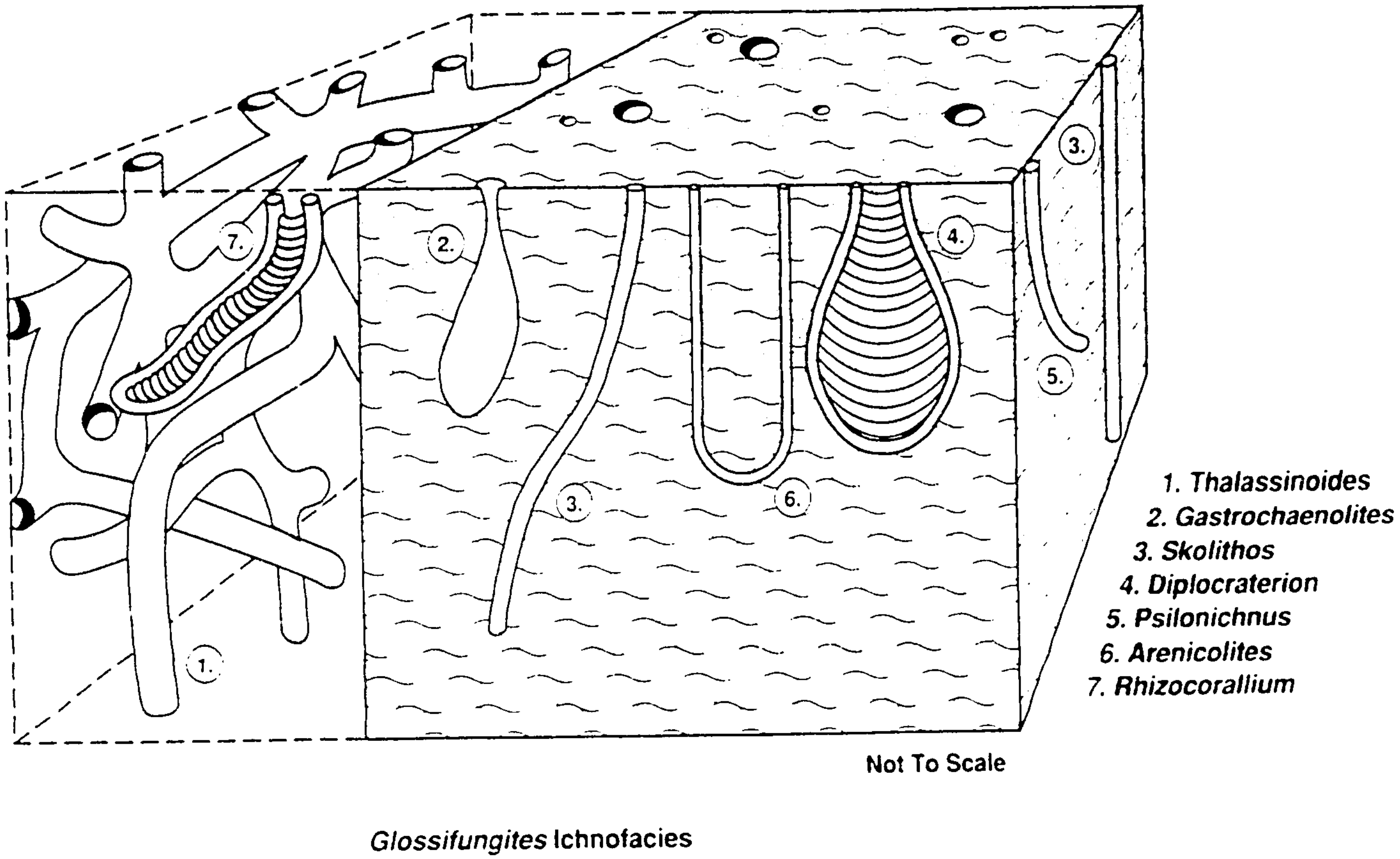
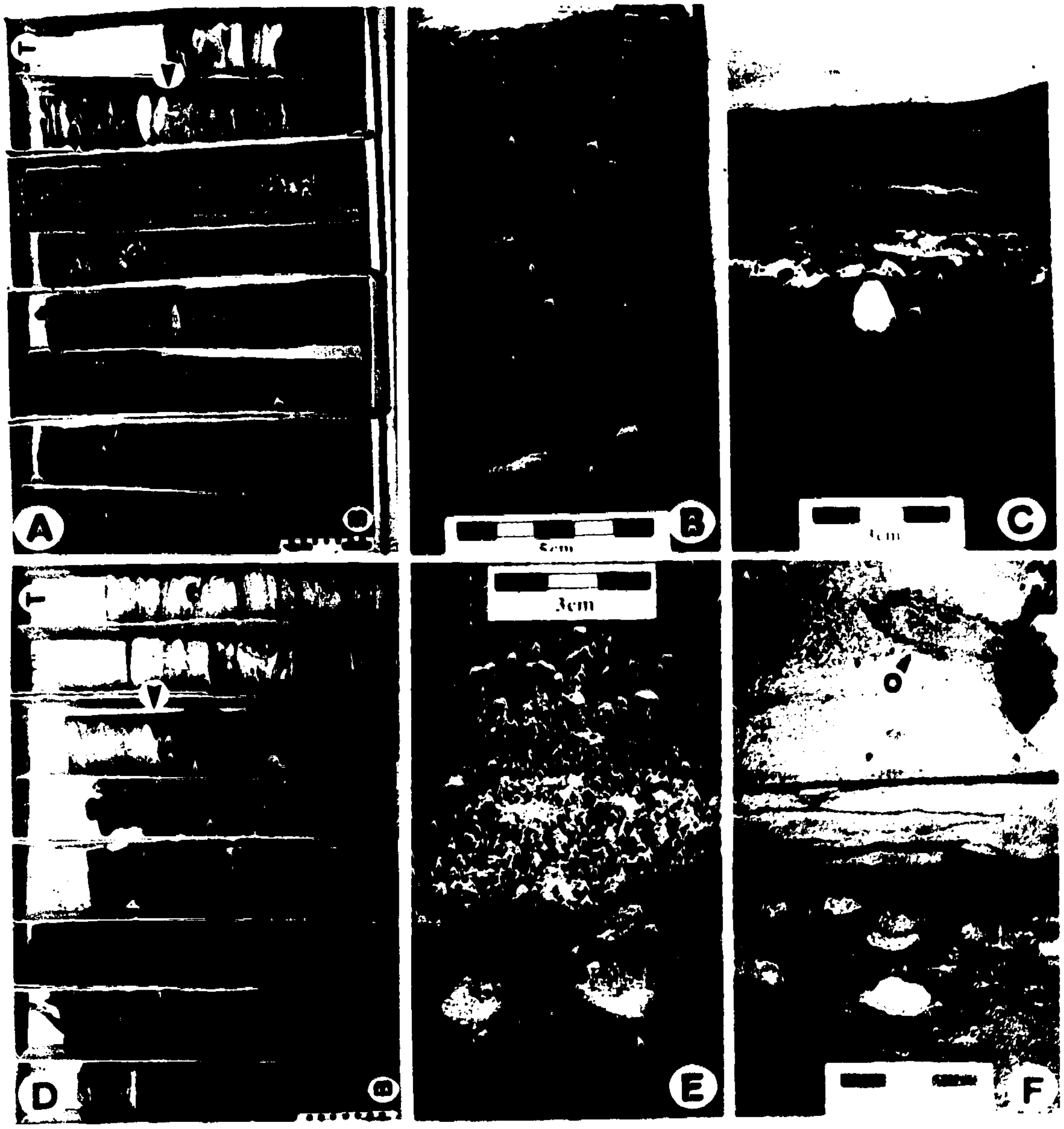


Figure IX-9. Trace fossil association characteristic of the *Glossifungites* ichnofacies (modified from Frey and Pemberton, 1984).

Figure IX-10. Co-planar Surfaces of Lowstand Erosion and Transgressive Erosion (FS/SB) Associated with Incised Valleys. (A & B) Crystal Field, 08-26-45-04W5. **A)** Boxshot (1831.2-1835.8 m) shows thoroughly burrowed, lower offshore silty shales coarsening upward into upper offshore sandy shales of a regionally extensive Viking Formation parasequence. This is erosionally truncated by interbedded sandstones and shales of the Central Basin complex (arrow). 15 cm scale is present in the lower left of photo. Core is read from base at lower left (B) to top at upper right (T). **(B)** The contact (1832 m) shows a *Cruziana* (softground) assemblage, cross-cut by muddy, sand-filled *Diplocraterion* (D) of the *Glossifungites* ichnofacies. **(C)** The Crystal valley surface is also marked by firmground *Gastrochaenolites* in the 04-01-46-04W5 well, at a depth of 1804.7 m. **(D & E)** Willesden Green Field, 10-35-40-07W5. **(D)** Boxshot (2326.2-2329.8 m) shows a coarsening upward parasequence near the base capped by a low energy marine flooding surface (LE FS), passing into shelfal to lower offshore silty shales. These are erosionally-truncated by pebbly sandstones and conglomerates of the Estuary Mouth complex (arrow). 15 cm scale is present in the lower left of photo. Core is read from base at lower left (B) to top at upper right (T). **(E)** The contact (2327 m) is marked by robust *Rhizocorallium saxicava* of the *Glossifungites* assemblage. **(F)** The Willesden Green valley surface is marked by *Diplocraterion* and *Thalassinoides* (Th) of the *Glossifungites* ichnofacies in the 11-31-40-6W5 well, at a depth of 2285.8 m. Note the *Ophiomorpha* in the sandstone of the overlying Channel-fill complex, attesting to a marine influence on valley fill.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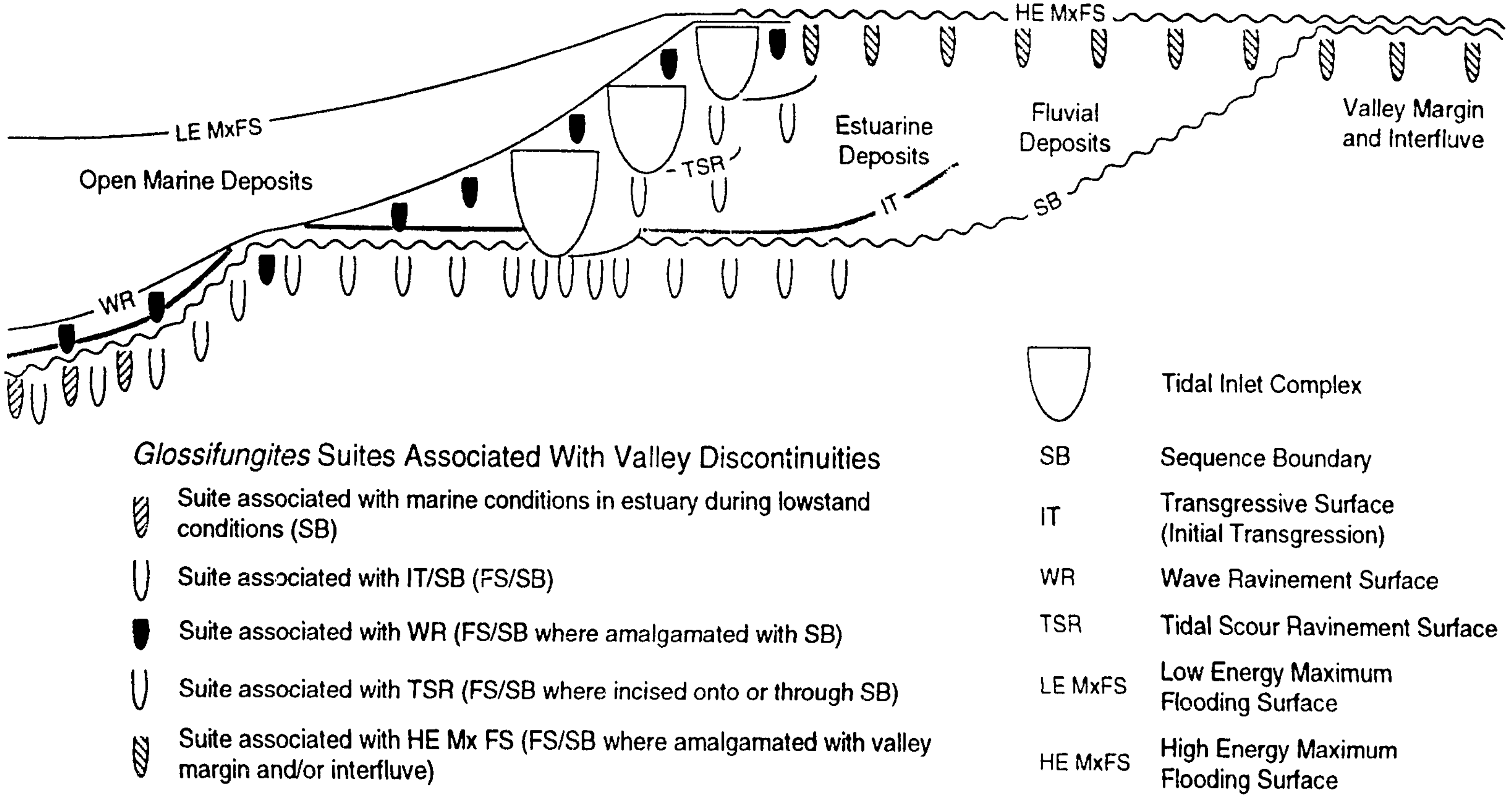


Figure IX-11. Schematic representation of erosional discontinuities within a simple (single stage) incised valley system. The diagram also shows the zones which may contain *Glossifungites* assemblages. The surfaces locally amalgamate with one another, affording the possibility of *Glossifungites* suites of differing stage of valley infill to overprint one another. The diagram is adapted from Zaitlin *et al.* (in press).

numbers. In several examples, seven to fifteen firmground traces, commonly *Diplocraterion habichi*, have been observed on the bedding plane of a 9 cm (3.5 inch) diameter core; this corresponds to a density of between 1100 to 2300 shafts per square meter. Similar populations were observed from *Glossifungites* suites present on the modern coast of Georgia (Pemberton and Frey, 1985). Dense populations are typical of many opportunistic assemblages (Levinton, 1970; Pemberton and Frey, 1984).

Stratigraphic Implications of the *Glossifungites* Ichnofacies

In siliciclastic settings, most firmground assemblages are associated with erosionally exhumed (dewatered and compacted) substrates and, hence, correspond to erosional discontinuities. Although certain insect and animal burrows in the terrestrial realm may be properly regarded as firmground (*e.g.* Fürsich and Mayr, 1981) or, more rarely, hardground suites, they have a low preservation potential and constitute a relatively minor element in the preserved record of these associations. The overwhelming majority of these assemblages originate in marine or marginal marine settings, particularly in pre-Tertiary intervals. As such, a discontinuity may be generated in either subaerial or submarine settings, but colonisation of the surface is associated with marine conditions. This has important implications regarding the genetic interpretation of the discontinuity in question. Finally, the substrate-controlled ichnocoenose, which cross-cuts the pre-existing softground suite, reflects conditions *post-dating* both initial deposition of the underlying unit and its subsequent erosional exhumation following burial. The *Glossifungites* suite therefore corresponds to a depositional hiatus between the erosional event and sedimentation of the overlying unit; significant depositional cover precludes firmground colonisation. These three aspects of the *Glossifungites* suite make it useful both in the recognition of the discontinuity and in its genetic interpretation (*cf.* MacEachern *et al.*, 1992b; Pemberton *et al.*, 1992a; Pemberton and MacEachern, in press).

Ichnology of Viking Formation Incised Valley Surfaces

In many incised valley-fills, determining whether the fill is associated with lowstand conditions, or with the ensuing transgression may, in part, be resolved by trace fossil analysis. In the Viking Formation of the Crystal, Willesden Green, Sundance-Edson and Cyn-Pem fields, the margins of the incised valleys are commonly demarcated by a *Glossifungites* assemblage, indicating that the initial preserved deposits are marine or marginal marine in nature. This suggests that the valleys did not fill until the onset of the ensuing transgression. Either the valleys served as a zone of sediment bypass and possessed little or no fluvial deposits, or these lowstand deposits were subsequently eroded and reworked during the transgression, producing a co-planar (amalgamated) lowstand surface of erosion and transgressive surface of erosion (*i.e.* FS/SB).

More recently, Allen and Posamentier (1993) and Zaitlin *et al.* (in press) have designated a number of transgressive surface types within valley fill successions. They discriminate between the transgressive surface (corresponding to the initial flooding surface), the wave ravinement surface, the tidal scour ravinement surface and the maximum flooding surface (Figure IX-11). All surfaces may be demarcated by a *Glossifungites* assemblage, although the zones of colonisation are clearly restricted to the limits of marine influence within the valley. These zones correspond to Segment 1 and Segment 2 of the valley complex (Zaitlin *et al.*, in press).

Widespread *Glossifungites* suites may be developed within the valley where the initial flooding surface is directly amalgamated with the sequence boundary (FS/SB). Where initial fluvial lowstand deposits separate the two surfaces, a substrate-controlled suite is absent. In situations where the initial flooding surface is highly erosive, lowstand fluvial deposits may be completely reworked, and the sequence boundary colonised. Such *Glossifungites* assemblages may be overlain by relatively thick, transgressively reworked lags. Most of the basal valley surfaces in the Viking Formation probably reflect this type of high energy initial FS/SB.

During continued transgressive fill of the valley, erosive shoreface retreat of the barrier complex generates a relatively widespread wave ravinement surface, which may become amalgamated with the initial flooding surface and/or the sequence boundary. This type of FS/SB is largely restricted to the mouth of the estuary complex and, with continued transgressive fill, rises stratigraphically as the wave ravinement surface incises into previously deposited estuarine valley fill. Consequently, the wave ravinement surface may facilitate firmground colonisation along its entire extent, but correspond to an FS/SB near the valley mouth and pass landward into an inter-valley transgressive surface of erosion (TSE).

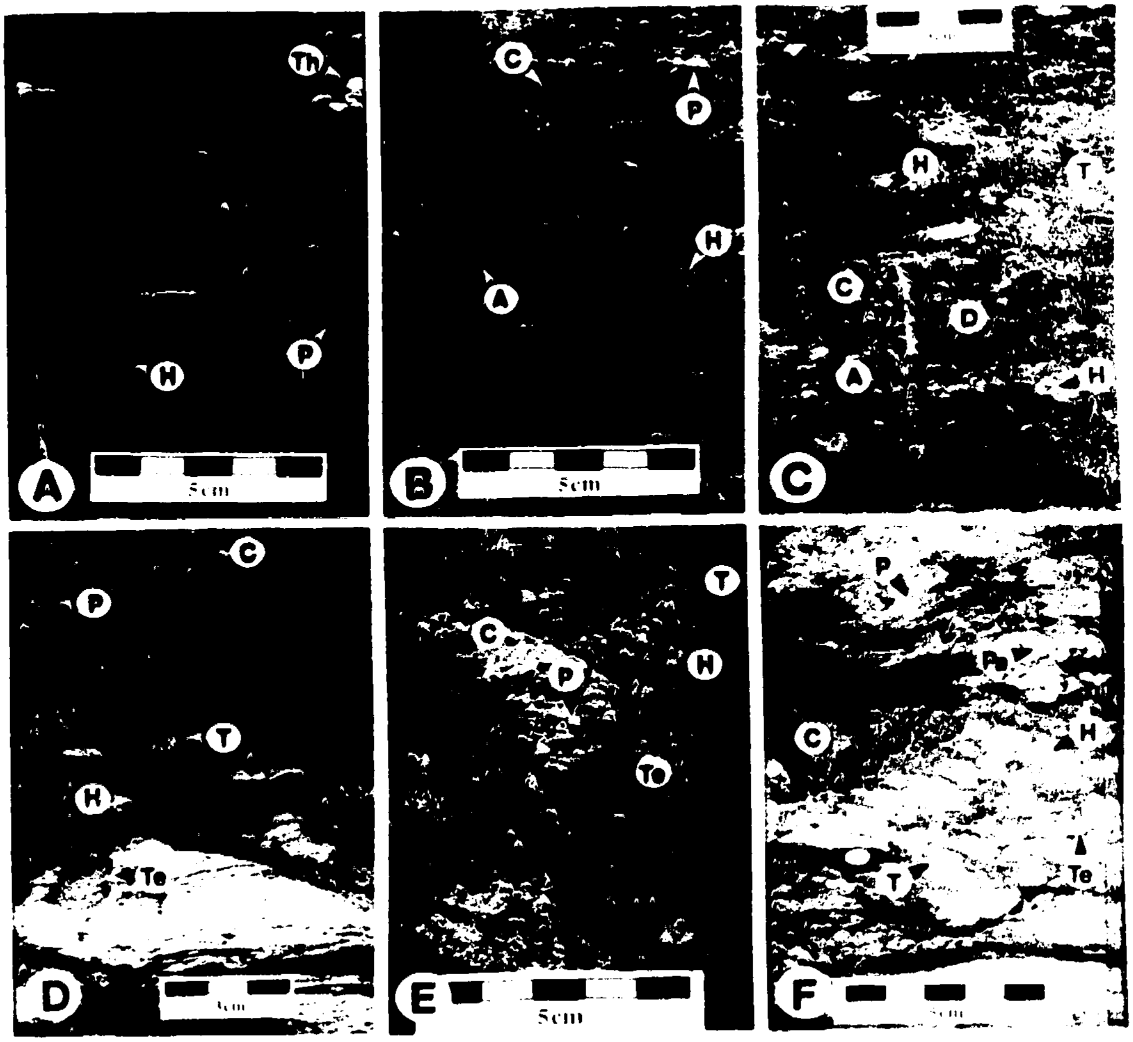
The development and migration of tidal inlets also favours the generation of firmgrounds, which may become colonised by the *Glossifungites* ichnofacies. These tidal scour ravinement surfaces may locally erode through all previous valley fill deposits and incise into the sequence boundary, generating a relatively localised FS/SB. With continued erosive shoreface retreat during transgressive fill of the valley system, these tidal scour ravinement surfaces may rise stratigraphically and incise into previously deposited estuarine deposits, producing areally restricted *Glossifungites*-demarcated TSE. Fluvial channel diastems, which may appear sedimentologically similar, are not colonised, because the surfaces are generated landward of the marine limit in the valley.

If the valley is ultimately filled and transgression overruns the entire system, the potential exists to generate a widespread *Glossifungites*-demarcated TSE corresponding to the maximum flooding surface. A high energy (erosive) maximum flooding surface favours truncation of the upper portion of the valley and generation of widespread firmgrounds across both the valley fill and the adjacent valley margins and interfluves, which may become colonised by a substrate-controlled trace fossil suite. In contrast, low energy (non-erosive) maximum flooding surfaces may not permit firmground colonisation except along the valley margins and interfluves, where subaerial exposure has permitted the substrates to dewater and become firm.

In situations where the valley is subjected to re-incision events during subsequent periods of lowstand conditions, new sets of FS/SB and inter-estuarine TSE may be cut, and colonised. The compound fills of such valley systems typically display numerous dissected and locally amalgamated segments of *Glossifungites*-demarcated surfaces, and require careful stratigraphic analysis in order to discriminate one from another, delineate their extents in the valley, and place them into a sequence stratigraphic framework.

In all Viking Formation examples, the various FS/SB surfaces are excavated into coarsening upward, regionally extensive Viking Formation silty shales, sandy shales and muddy sandstones of the underlying highstand parasequences (discussed below). These intervals contain fully marine, high diversity and abundant distal to proximal *Cruziana* softground suites (Figures IX-12, IX-13, IX-14 and IX-15). In the Crystal Field, the erosional truncation is

Figure IX-12. Depositional Facies Comprising Regionally Extensive Parasequences of the Viking Formation. **(A)** Silty shales with moderate degrees of burrowing, containing thin, biogenically-mottled sandstone stringers. *Planolites* (P), *Helminthopsis* (H) and *Thalassinoides* (Th) are present. The facies is interpreted to reflect lower offshore deposition. Sundance Field, 12-12-54-20W5, depth 2633.7 m. **(B)** Thoroughly burrowed silty shale, with a high proportion of interstitial silt and sand. *Helminthopsis* (H), *Planolites* (P), *Chondrites* (C) and small *Asterosoma* (A) are present. Sundance Field, 12-12-54-20W5, depth 2630.4 m. **(C)** Thoroughly burrowed sandy shale, interpreted to reflect upper offshore deposition. *Helminthopsis* (H), *Chondrites* (C), *Terebellina* (T), *Asterosoma* (A) and *Diplocraterion* (D) are present. Sundance Field, 10-34-54-20W5, depth 2578.6 m **(D)** Thoroughly burrowed sandy shale facies with remnant distal storm bed near the base. Trace fossils include *Chondrites* (C), *Planolites* (P), *Terebellina* (T), *Helminthopsis* (H) and *Teichichnus* (Te). The facies is interpreted to reflect upper offshore deposition. Sundance Field, 07-36-54-20W5, depth 2484.4 m. **(E)** Intensely burrowed muddy sandstone facies interpreted as distal lower shoreface deposits. *Helminthopsis* (H), *Chondrites* (C), *Planolites* (P), *Teichichnus* (Te) and *Terebellina* (T) are visible. Edson Field, 10-04-53-18W5, depth 2410.6 m. **(F)** Thoroughly burrowed muddy sandstone facies with *Terebellina* (T), *Teichichnus* (Te), *Palaeophycus* (Pa), *Planolites*, (P), small *Chondrites* (C) and *Helminthopsis* (H). The facies is interpreted to reflect distal lower shoreface deposition. Crystal Field, 13-05-46-3W5, depth 1754.0 m.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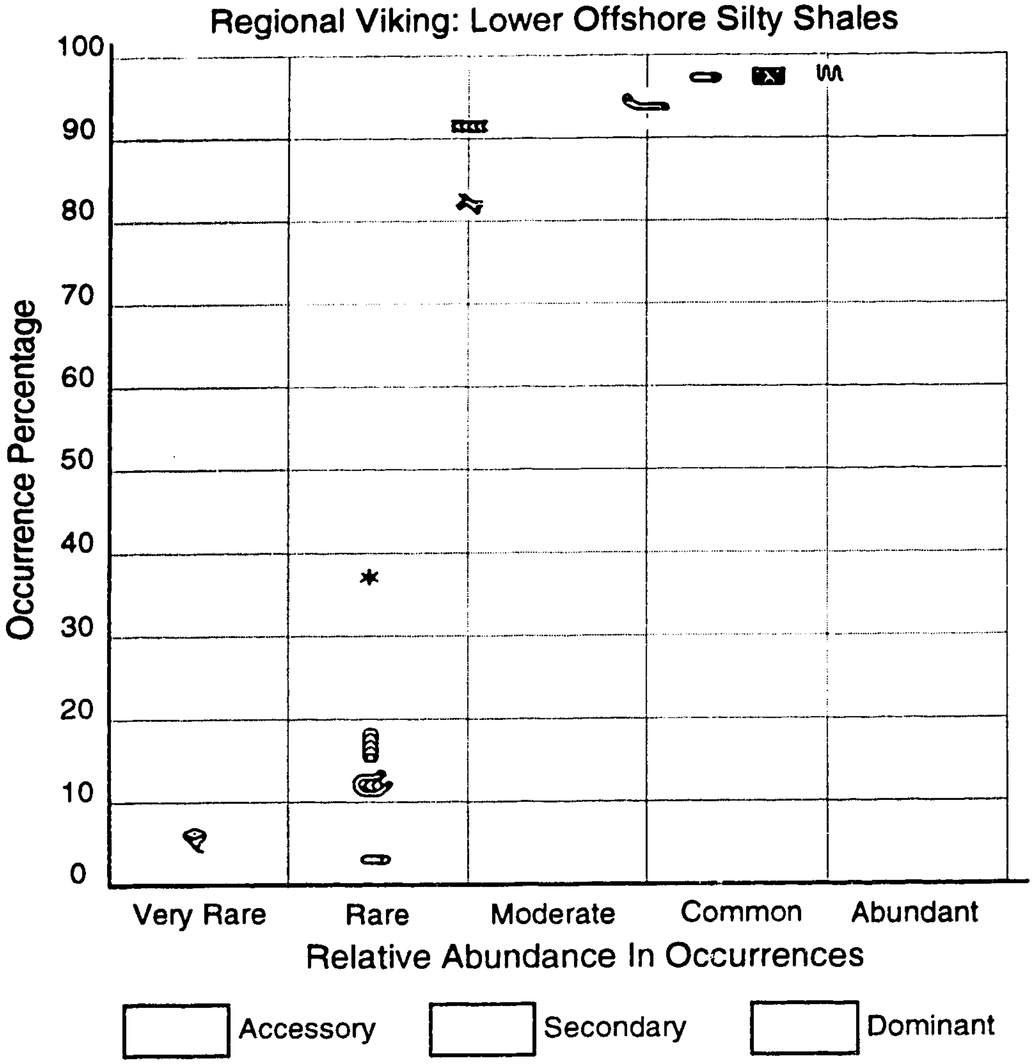


Figure IX-13. Trace Fossil Distributions in Lower Offshore Silty Shales of the Regionally Extensive Viking Formation Parasequences. The legend of symbols for trace fossils is given in Figure IX-18. The vertical axis records the percentage of intervals encountered containing a particular trace fossil. The horizontal axis records the relative abundance of the trace fossil when it does occur in the interval. The graphs are based on observations in core and are not rigorously statistical. Dominant, secondary and accessory fields are subjectively determined. The lower offshore deposits show a predominance of grazing and deposit feeding structures, present in both high abundances and uniform in distribution.

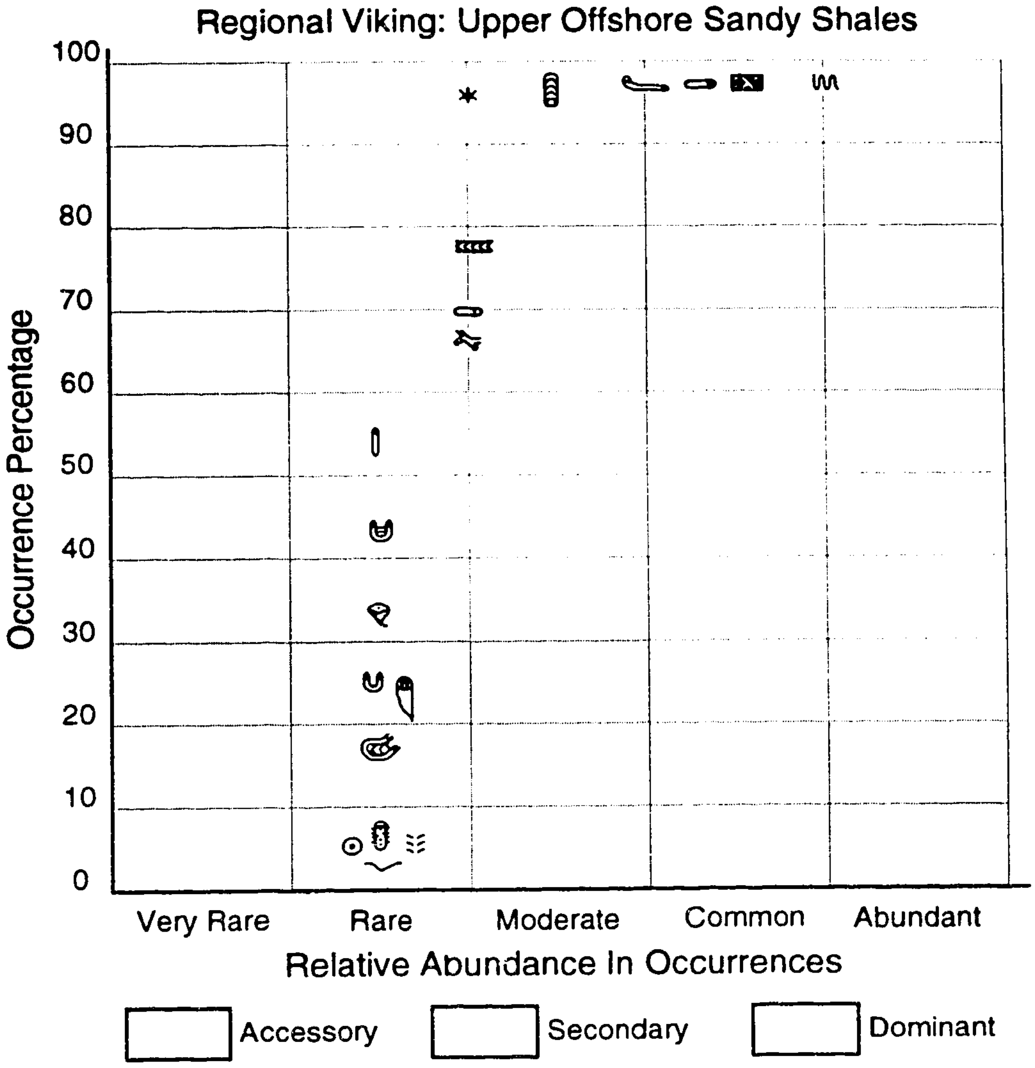


Figure IX-14. Trace Fossil Distributions in Upper Offshore Sandy Shales of the Regionally Extensive Viking Formation Parasequences. The legend of symbols for trace fossils is given in Figure IX-18. An explanation of the chart is given in Figure IX-13. Note that the dominating elements reflect a mixture of deposit feeding and grazing structures, and are both uniform in distribution and of fairly high abundance. Overall, the facies displays a high diversity of ichnogenera.

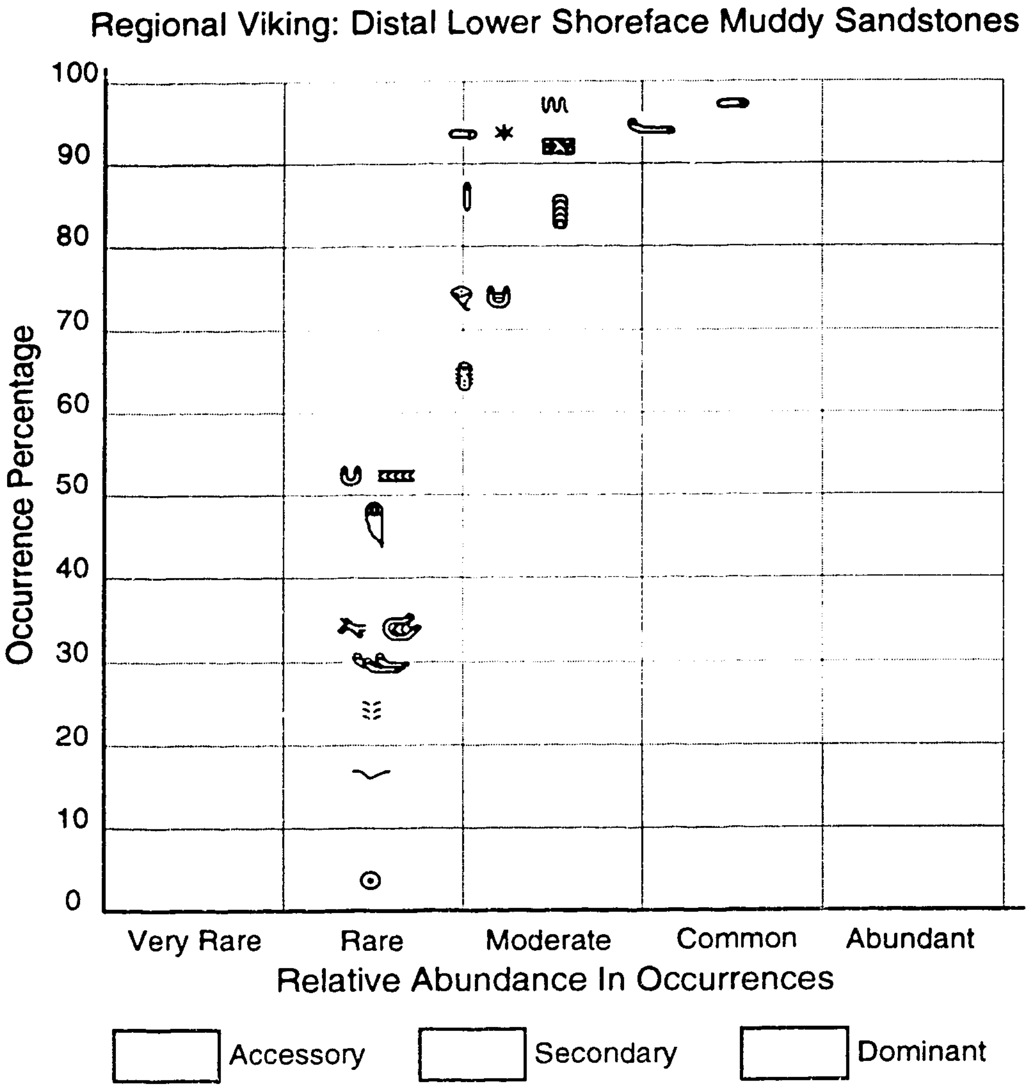


Figure IX-15. Trace Fossil Distributions in Distal Lower Shoreface Muddy Sandstones of the Regionally Extensive Viking Formation Parasequences. The legend of symbols for trace fossils is given in Figure IX-18. An explanation of the chart is given in Figure IX-13. Note the high diversity, and uniform distribution of the dominant elements. Most ichnogenera reflect deposit feeding behaviours, with lesser grazing and suspension feeding structures.

marked by a *Glossifungites* assemblage consisting of numerous sharp-walled, unlined *Diplocraterion* shafts (Figure IX-10 A,B), firmground *Thalassinoides*, *Diplocraterion habichi*, and firmground *Gastrochaenolites* (Figure IX-10 C). At Willesden Green, the valley base is locally marked by a *Glossifungites* assemblage consisting of spectacular *Rhizocorallium saxicava* (Figure IX-10 D,E), *Thalassinoides* (Figure IX-10 F), *Arenicolites*, *Skolithos* and *Diplocraterion habichi*. The Sundance/Edson valley surface is only rarely demarcated by firmground *Thalassinoides/Spongeliomorpha*, while the Cyn-Pem valley is marked by abundant firmground *Arenicolites* and *Skolithos* in one of only two cored intervals in the valley system. The presence of this substrate-controlled trace fossil assemblage greatly enhances the recognition and genetic interpretation of the incised valley discontinuity surface (Pemberton and MacEachern, in press). This, integrated with the distinctive ichnological successions characterising the estuarine deposits, has proven to be a powerful tool in the paleoenvironmental resolution of these complex Viking Formation intervals.

Ichnological Successions of Regionally Extensive Viking Formation Parasequences

Laterally adjacent to, and underlying the incised valley deposits of the Viking Formation, are a number of coarsening upward parasequences of regional extent, informally referred to as the regional Viking cycles. These grade out of the marine shales of the underlying Joli Fou Formation, which transgressively overlie a sequence boundary developed on the Mannville Group (*i.e.* FS/SB; Figure IX-6). Five main coarsening upward successions (fourth-order parasequences), the lower two of which contain numerous minor cycles (fifth-order parasequences) are interpreted to reflect changes in relative sea level (Pattison, 1991a). The parasequences occur as a regionally extensive progradational parasequence set, indicating accumulation within a highstand systems tract, which downlaps onto the Joli Fou Formation marine shales of the underlying transgressive systems tract.

Three facies make up a complete coarsening cycle, although the minor cycles rarely comprise a complete cycle. The basal facies (Facies 1) consists of thoroughly burrowed silty shale (Figure IX-12 A,B). Silt is dispersed biogenically throughout the facies, and may locally be present as discontinuous stringers. Very rare, vfL-vfU sand interbeds (<2 cm thick) containing low angle wavy parallel lamination or combined flow ripple lamination are locally intercalated.

The trace fossils of Facies 1 are uniformly distributed and present in most intervals studied, with the exception of the accessory traces (Figure IX-13). *Helminthopsis, Chondrites, Planolites* and *Terebellina* comprise the dominant elements of the suite while *Zoophycos* and *Thalassinoides* constitute the secondary elements. *Asterosoma, Teichichnus, Rhizocorallium, Palaeophycus* and *Rosselia* are uncommon and comprise the accessory elements.

Grading from the silty shale facies is the sandy shale facies (Facies 2; Figure IX-12 C, D). Sand is typically vfL-fU in grain size, and is present both as biogenically dispersed grains and as remnant wavy parallel laminated, oscillation rippled, or combined flow ripple laminated beds. Burrowing is typically both uniform and intense.

The trace fossil suite of Facies 2 is more diverse than that of the silty shales underlying it (Figure IX-12 C,D), and is dominated by *Helminthopsis, Chondrites, Planolites, Terebellina, Teichichnus* and *Asterosoma* (Figure IX-14). Secondary elements are *Zoophycos, Palaeophycus, Thalassinoides, Skolithos* and *Diplocraterion*. Accessory elements are represented by *Rosselia, Arenicolites, Cylindrichnus, Rhizocorallium, Ophiomorpha, Siphonichnus, Lockeia* and fugichnia (escape traces).

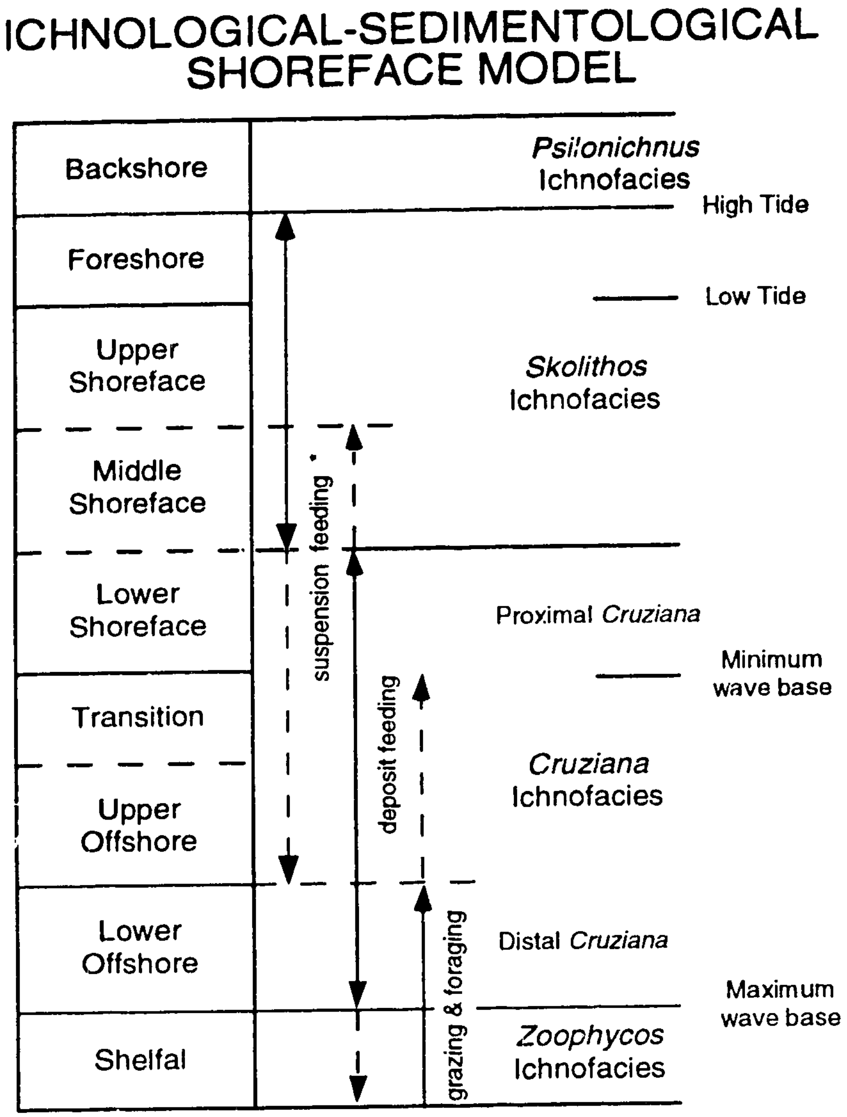
Grading upward from the sandy shale facies is the muddy sandstone facies (Facies 3; Figure IX-12 E, F). The sand size ranges from vfL-fU, though typically fL. Mud is generally dispersed throughout the facies and present as partings and discontinuous stringers. Discrete sandstone beds are rare, but show wavy parallel lamination where present. The general absence of discrete sandstone beds reflects the high degree of bioturbation and the penetrative action of infauna more robust than in the previously described facies (*cf.* Wheatcroft, 1990).

The dominant trace fossil elements of Facies 3 are *Planolites, Terebellina, Chondrites, Helminthopsis, Asterosoma, Palaeophycus, Skolithos, Teichichnus, Rosselia* and *Diplocraterion*, though individual ichnogenera are less abundant and occur with less consistency than in the underlying facies (Figure IX-15). Secondary elements include *Ophiomorpha, Arenicolites, Zoophycos* and *Cylindrichnus*, while *Thalassinoides, Rhizocorallium,* *Schaubcylindrichnus, Lockeia, Siphonichnus* and fugichnia constitute the accessory elements.

The cycles reflect both coarsening upward of facies and an increase in diversity of ichnogenera, under fully marine conditions. Each complete cycle is interpreted as lower offshore to lower shoreface progradation (Figure IX-16). The silty shale facies reflects a dominance of grazing and deposit feeding structures of the distal *Cruziana* ichnofacies and is interpreted as lower offshore deposition. Rare, thin sand beds correspond to the distal deposits of exceptionally strong storms. The sandy shale facies shows a more diverse suite of trace fossils and a dominance of deposit feeding over grazing behaviour. The introduction of suspension feeding and passive carnivore structures is also distinctive. This facies is interpreted as upper offshore deposition at and above storm-weather wave base. Thin sandstones record preservation of storm beds whose thicknesses exceeded the infauna's ability to completely obliterate it. The muddy sandstone facies shows an increase in diversity of behaviour, but less of a dominance by individual ichnogenera. Deposit feeding structures dominate, with diminishing influence of grazing behaviour and enhanced influence of suspension feeding, reflecting a proximal *Cruziana* suite. This facies is interpreted to represent distal lower shoreface deposits. The trace fossil suites show abundant burrowing, characterised by a high diversity of forms, a lack of dominance by a few forms, presence of significant numbers of specialised feeding/grazing structures, and uniform distribution of individual elements, supportive of an equilibrium (K-selected), unstressed community (*cf.* Pianka, 1970) within fully marine environments. Although the r-K paradigm for population dynamics has recently been questioned, it still remains the cornerstone for explaining the population kinematics of benthic organisms (Jumars, 1993). Sedimentation is interpreted to have been relatively slow and generally continuous. These suites stand in marked contrast to suites recognised from facies of the incised estuarine valleys.

Ichnological Successions In Valley Fill Systems

Within the five Viking Formation valley fill systems (Figure IX-1), four main depositional complexes were recognised from the facies, defined on the basis of sedimentology and associated softground trace fossil suites. Three of



* Many tube dwellers are passive carnivores rather than suspension feeders.

Figure IX-16. Idealised shoreface model of ichnofacies successions, based on observation of Cretaceous strata of the Western Interior Seaway of North America (modified after Pemberton *et al.*, 1992a).

these complexes correspond to the major depositional zones within the wave-dominated estuary system, namely: the Bay Head Delta, the Central Basin, and the Estuary Mouth (Figure IX-2). The fourth depositional complex reflects Channel-fill deposition, commonly demonstrating a marine influence.

Bay Head Delta (BHD) Complex.

BHD-1 Facies Association:

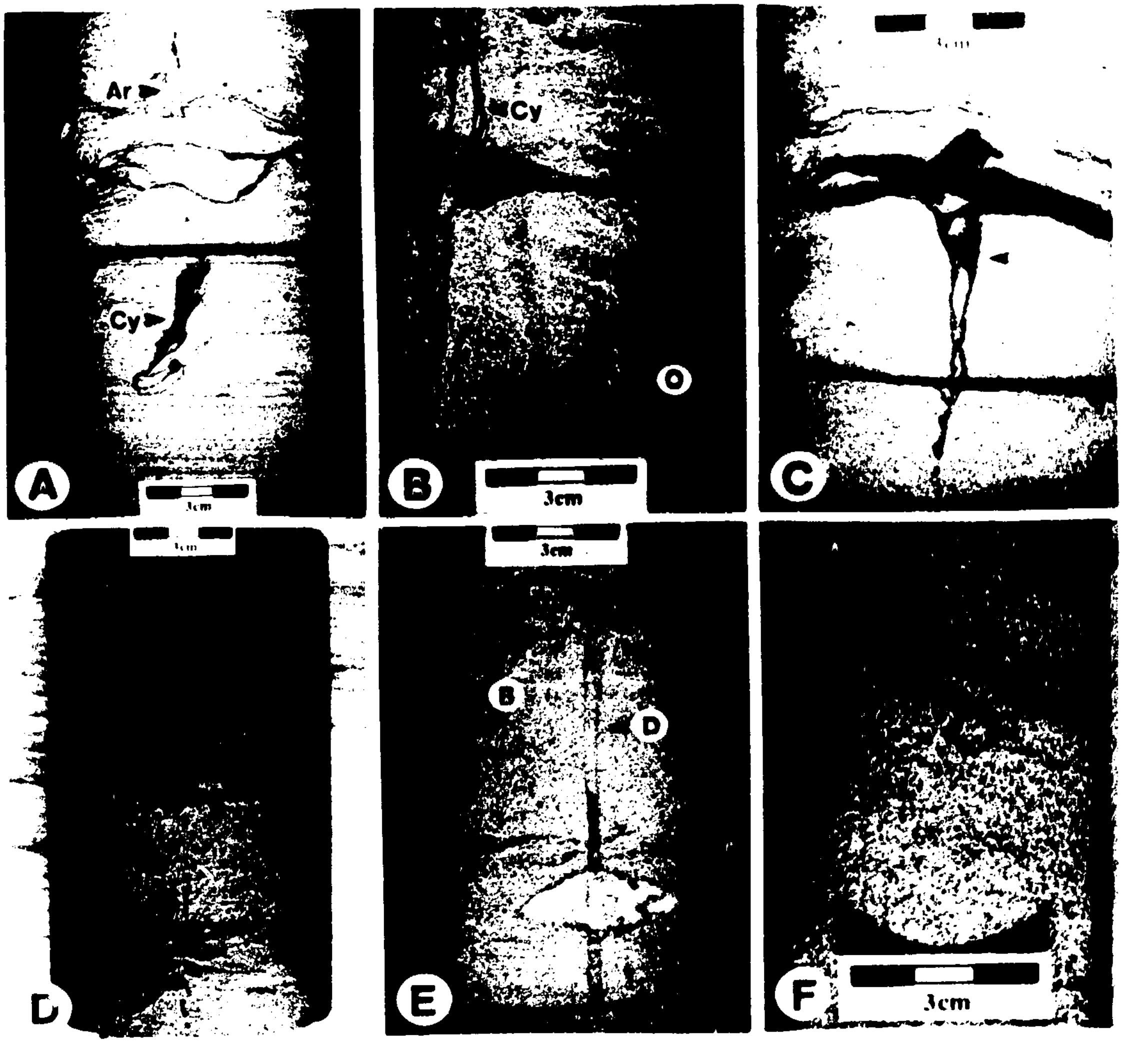
The Bay Head Delta (BHD) complex appears to be characterised by a single facies association (BHD-1 facies association), which consists of an interbedding of four facies. The complex is well represented in the Sundance/Edson and Crystal valley deposits. Neither core from Cyn-Pem system nor any from the Willesden Green valley penetrated this complex. Deposits in this zone are overwhelmingly sandy, with mud beds rare and less than 1 cm thick. Mud also occurs as thin, biogenically disturbed or mottled interlaminae within the sandstone beds. The BHD-1 facies association roughly corresponds to FA4 of Pattison (1991a).

The most common facies in the BHD-1 facies association comprises 10-25 cm thick, well-sorted, wavy parallel laminated, fL-fU grained sandstone beds (Figure IX-17 A-D). These are generally erosionally amalgamated into bedsets greater than 1 m thick, although they may locally grade upwards into combined flow ripple and oscillation ripple laminated sandstones. Muddy interlaminae are moderately abundant and typically occur towards the tops of some beds. Locally, thin (<1 cm) mud layers mantle the rippled tops of beds.

Trace fossils are rare overall, although they may reach moderate abundances near the tops of beds. Fugichnia occur in low numbers in virtually every interval encountered. Near the upper contacts of individual beds, *Ophiomorpha* (Figure IX-17 D), *Skolithos, Teichichnus, Palaeophycus, Arenicolites, Conichnus, Cylindrichnus, Diplocraterion* or exceedingly rare *Macaronichnus simplicatus* may be present. Individual beds rarely possess more than a few ichnogenera.

This first facies is interpreted to reflect episodic storm bed deposition, presumably near the bay head delta front. The thinness of the beds and preservation of waning stage storm deposits near the tops of many beds illustrate the comparatively low energy nature of tempestite emplacement in this zone, particularly when compared with those generated along open coast

Figure IX-17. Depositional Facies of the Bay Head Delta Complex. (A) Wavy parallel laminated, fine-grained sandstone passing into burrowed sandstone, reflecting storm bed deposition on the delta front. *Cylindrichnus* (Cy) and *Arenicolites* (Ar) correspond to opportunistic colonisation of the storm bed. The mottled top of the bed reflects the replacement of this suite by the resident fairweather community. Crystal Field, 16-24-45-04W5, depth 1807.1 m. **(B)** Wavy parallel laminated, fine-grained sandstone corresponding to storm bed deposition on the delta front. Siderite-cemented mudstone interbed is present, penetrated by *Cylindrichnus* (Cy). *Ophiomorpha* (O) is also present. Crystal Field, 11-12-46-04W5, depth 1704.9 m. **(C)** Tempestite with wavy parallel laminae near base, passing into combined flow ripple lamination. *Rosselia* (arrow) occurs near top. Crystal Field, 16-24-45-04W5, depth 1791.4 m. **(D)** Burrowed top of delta front storm bed, with robust *Ophiomorpha* (arrows). Edson Field, 03-22-52-19W5, depth 2613.4 m. **(E)** Stacked, low angle to horizontal parallel laminated sandstone, passing into current ripple lamination. Facies is interpreted as delta slope sediment gravity flow deposits. Note the mud-lined *Diplocraterion* shaft (D) and the *Bergaueria* (B) near the top. Crystal Field, 16-24-45-04W5, depth 1801.3 m. **(F)** Moderately-sorted, medium-grained, trough cross-stratified sandstone facies, interpreted as distal portions of distributary channels. *Palaeophycus* (arrows) demonstrates a marine influence on sandstone accumulation. Sundance Field, 06-27-52-21W5, depth 2871.9 m.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shorefaces (*cf.* MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992b). The tempestites observed in this facies reflect deposition by storm waves which were generated on, and propagated across, the central basin of the estuary itself. The trace fossil suite present in this facies reflects the episodic nature of deposition. Fugichnia record the escape of buried or sediment-entrained organisms, while initial opportunistic colonisation of the top of the storm beds is manifest by a low diversity suite (at any one locality) of vertical dwelling and suspension feeding structures (*e.g. Skolithos, Arenicolites, Diplocraterion, Ophiomorpha,* or *Conichnus*). This assemblage is ultimately replaced by the resident fairweather community of the setting, consisting mainly of deposit feeding structures (*e.g. Teichichnus, Palaeophycus, Macaronichnus, Cylindrichnus,* and *Planolites*). The degree of preservation of the trace fossil suite may reflect the duration of fairweather conditions, the intensity of the succeeding storm event (*i.e.* the degree of erosional amalgamation), or a combination of the two. More thoroughly burrowed muddy sandstone beds probably correspond to longer periods of fairweather conditions or to deposition of thin (<15 cm) storm beds. Thin beds favour more thorough biogenic homogenization because many organism's structures exceed this thickness (Wheatcroft, 1990). This first facies comprises the most intensely burrowed zone of the BHD-1 facies association.

The second facies is commonly interstratified with these tempestites and characterised by 5-20 cm thick, vfU-fU grained, horizontal planar laminated sandstones, passing upward into current rippled, climbing (aggradational) rippled and rarer combined flow rippled sandstones (Figure IX-17 E). Sorting is good, although organic detritus is locally abundant. Clay interlaminae are rare. These beds have been termed "PR" beds by Pattison (1991a). Trace fossils are quite rare; fugichnia are the most common, although a few isolated intervals possess rare *Ophiomorpha, Diplocraterion, Cylindrichnus, Skolithos,* or *Bergaueria*. *Planolites* may also be present, associated with mud interlaminae.

This facies is also interpreted to reflect episodic deposition, but in this case, related to rapid emplacement of sand under high current flow velocities and/or very shallow water (upper flow regime) conditions. The rippled tops record waning stage of flow, locally with associated rapid deposition (*i.e.* aggradational ripples). Possible depositional scenarios include seasonal flood stage deposition from the river/distributary channel, overbank sheet flow, or delta front-style sediment-gravity flow deposition. The latter mechanism is favoured for these deposits, given the close association with the delta front tempestites. The largely unburrowed nature of this facies, coupled with the local presence of syneresis cracks in thin mud layers capping some beds, supports a possible fluvial influence on the event deposition. Failure of organisms to colonise the tops of such beds may reflect generally higher sedimentation rates associated with the bay head delta and/or periodic "freshening" of the central basin during periods of enhanced fluvial discharge through the BHD during seasonal flood conditions.

The third facies of the BHD-1 facies association is less common, and comprises sharp-based, 10-25 cm thick bedsets of fU-mL grained, trough cross-stratified sandstone, amalgamated into intervals 0.5-2.5 m thick (Figure IX-17 F). Mudstone rip-up clasts, locally siderite-cemented, organic detritus and rare coalified wood fragments are generally common, although lithic pebbles, including chert, may also be present. These beds are generally unburrowed, although locally, *Ophiomorpha*, *Palaeophycus* and *Planolites* occur in low numbers, typically associated with muddy interlaminae or thin interbeds.

The thinness of bed sets and the presence of high angle foreset cross-stratification with thin toesets indicate that the bedforms responsible for this facies were small subaqueous dunes. These beds of trough cross-stratification may correspond to distal portions of distributary channels near the delta front. Some beds, particularly the unburrowed ones, may have been deposited under mainly fluvial conditions, although the local presence of burrowing, demonstrates that some intervals were clearly marine-influenced. No obvious tidal structures (*e.g.* tidal bundles) were recognised.

The final facies in the BHD-1 facies association is the least common and consists of massive (apparently structureless) to convolute bedded, fL-fU grained sandstones with rip-up clasts and locally abundant carbonaceous detritus. Sorting is generally good. Upper and lower contacts are poorly preserved. The facies occurs in beds up to 2 m in thickness. No trace fossils were noted.

This facies is interpreted to reflect rapid sediment deposition during river floods, with associated dewatering and corresponding failure commonly achieving liquefaction. Alternatively, these sands may also reflect storm wave-induced liquefaction of sand at the delta front.

The preserved record of the BHD complex (Figures IX-18 and IX-19) is mainly the delta front sandstones, delta slope sandstones, distal portions of distributary channels and possibly, the interdistributary bay deposits. Interdistributary bay deposits are indistinguishable from the sandy facies association of the Central Basin complex, discussed below. Distributary mouth bar deposits probably have a high preservation potential, but have not yet been documented. The lack of delta plain, levee or other shallow subtidal, intertidal and supratidal deposits within the Viking examples at Sundance/Edson and Crystal is the result of transgressive erosion (ravinement) across the system or locally, due to multiple-stage channel re-incision in the valley.

The ichnological record of the BHD shows overall low degrees of burrowing, which is typically localised and sporadic. The trace fossil suite appears to lack any clearly dominant elements (Figure IX-20). Only *Planolites* occurs in all studied intervals and is present in rare to moderate numbers. *Palaeophycus, Skolithos, Ophiomorpha* and fugichnia constitute the secondary elements, along with *Teichichnus, Arenicolites, Cylindrichnus* and *Rosselia. Diplocraterion, Terebellina, Lockeia, Conichnus, Bergaueria, Macaronichnus, Asterosoma, Thalassinoides* and *Siphonichnus* comprise the accessory elements of the suite.

Of interest is that overall, the trace fossil diversity is high; 16 ichnogenera were noted, although any one interval may possess as little as 3 or 4 ichnogenera. The stresses imposed on the organisms and their resulting behaviour appear to be due largely to the episodic nature of deposition and associated variable sedimentation rates rather than to strongly reduced salinity, although brackish water conditions may have been important as well.

The most common biogenic structures in the facies association record escape by buried or entrained organisms within an event bed, followed by opportunistic colonisation of the sandy substrate after the disturbance, reflected by *Skolithos, Ophiomorpha* and *Arenicolites*. Replacement of this initial community by the resident fairweather community is evident by the overprinting of the opportunistic suite by deposit feeding structures such as *Planolites, Palaeophycus, Teichichnus, Cylindrichnus* and *Rosselia*. The remaining ichnogenera record relatively uncommon organism behaviours or overall poor preservation of complete fairweather suites due to the erosional

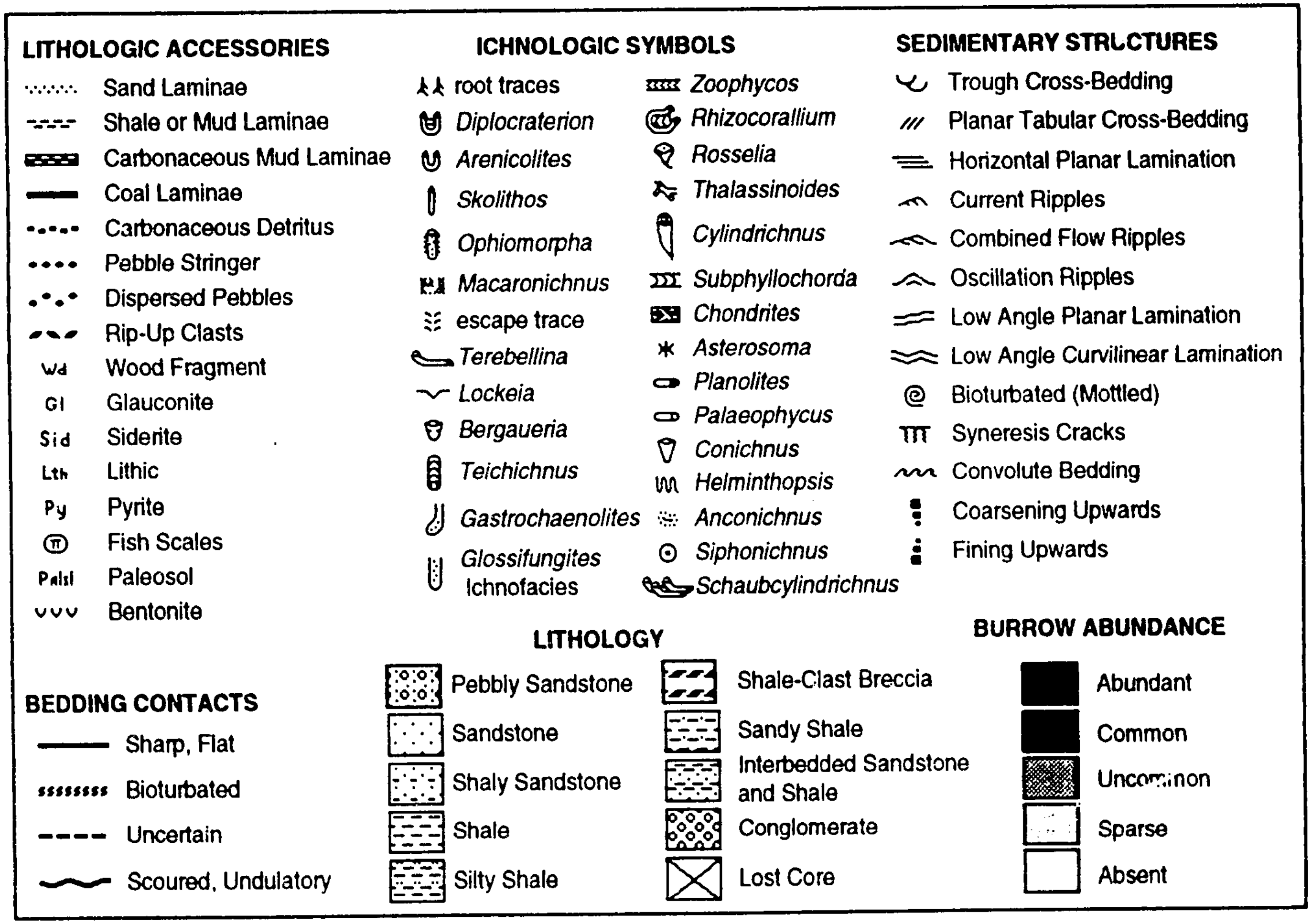

Figure IX-18. Legend of Symbols used in Lithologs.

Figure IX-19. Litholog of a sandy valley fill interval, erosionally truncating regionally extensive Viking Formation parasequences (FS/SB). The lower portion of the valley fill consists of storm beds, "PR" beds, and rare, thin, trough cross-stratified beds of the Bay Head Delta complex. This complex is erosionally truncated by a possible second stage of valley incision and transgressive fill (FS/SB?), manifest by marine-influenced sandstones of the Ch-1 facies association of the Channel-fill complex. The entire valley system is truncated by ravinement (TSE) during renewed transgression. The interval occurs in the 16-24-45-04W5 well in the Crystal valley system. The legend of the symbols used in the litholog is given in Figure IX-18.

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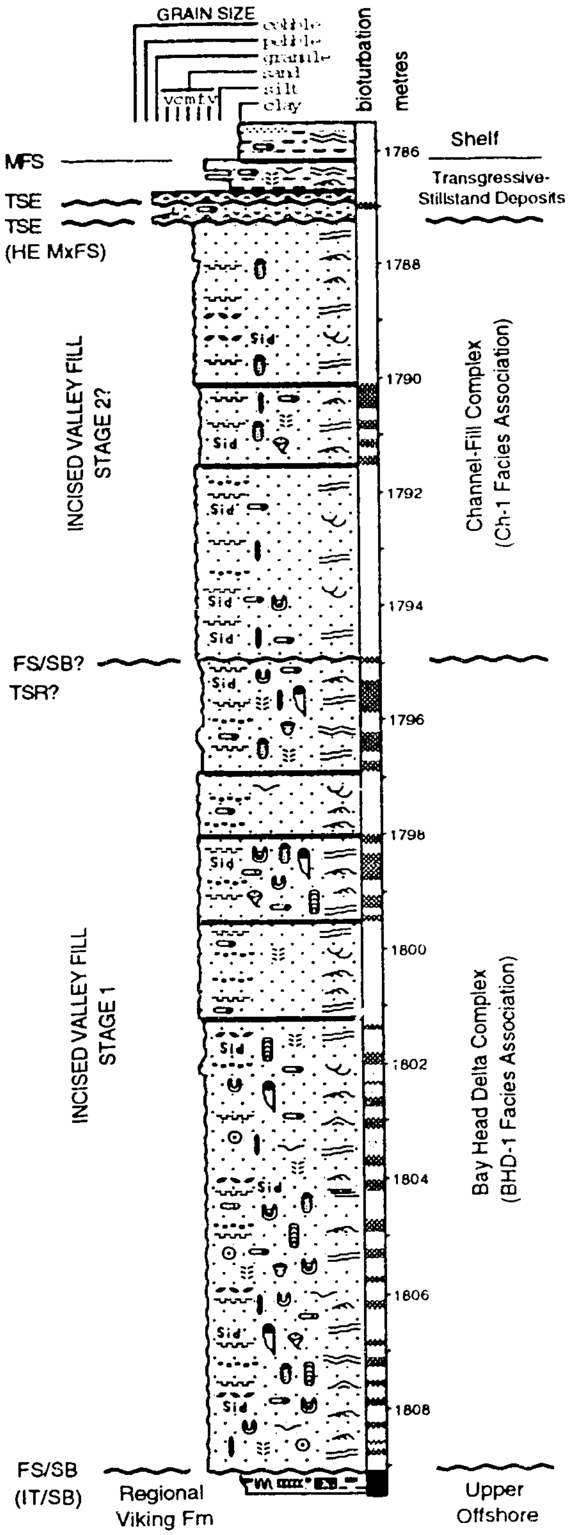


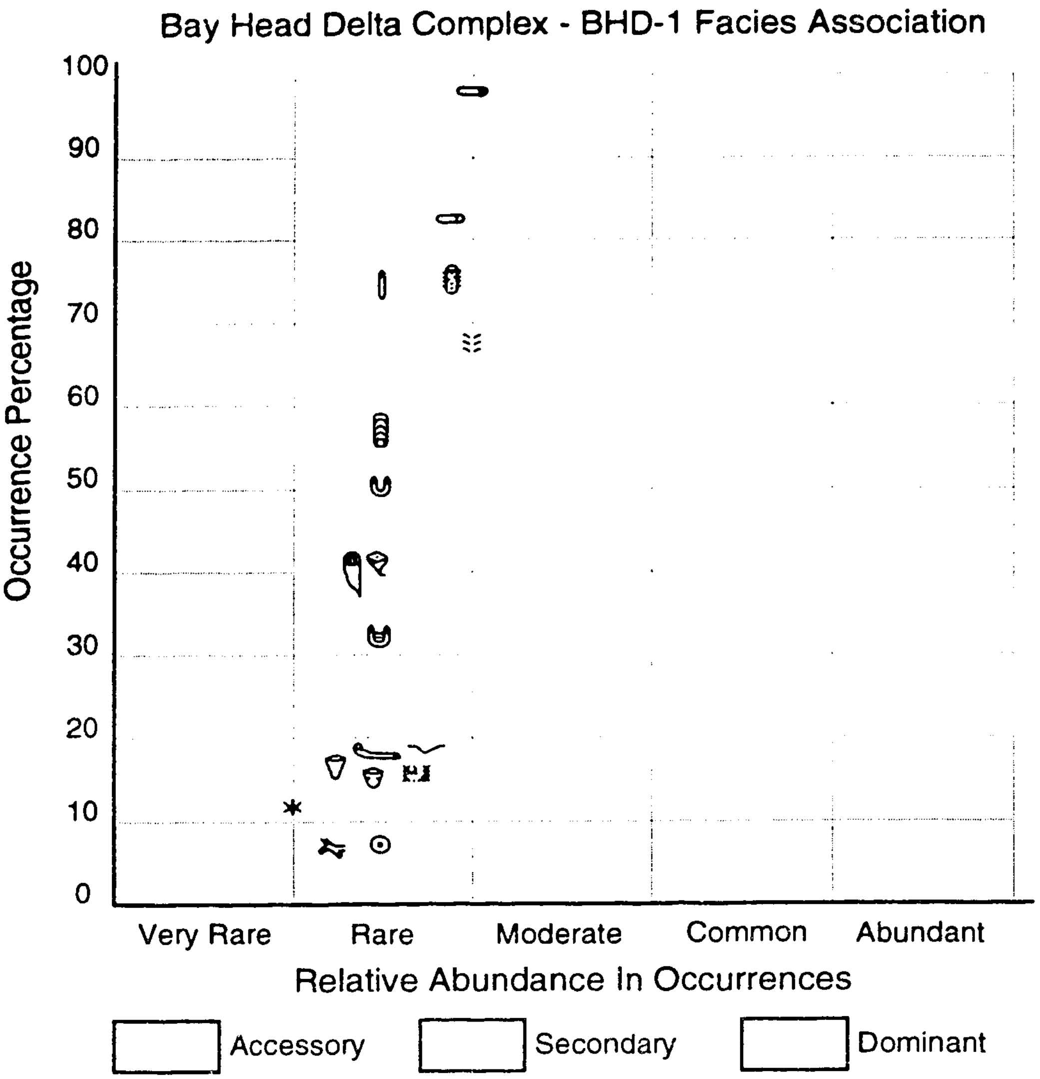


Figure IX-20. Trace Fossil Distribution in Facies of the Bay Head Delta Complex. The legend of symbols for the trace fossils is given in Figure IX-18. An explanation of the chart is given in Figure IX-13. Note the sporadic distribution of ichnogenera and the low intensity of burrowing indicated.

amalgamation of the event beds. Given preservation of shallower water and delta plain deposits of the BHD complex, biogenic structures may reflect a greater indication of brackish water conditions, as observed in estuarine deposits of the McMurray Formation and the Grand Rapids Formation (*e.g.* Wightman *et al.*, 1987; Beynon *et al.*, 1988; Beynon and Pemberton, 1992; Ranger and Pemberton, 1992).

Central Basin (CB) Complex.

The deposits of the Central Basin (CB) complex (Figure IX-21) are well-represented in the Sundance/Edson and Crystal valley fills and, to a lesser extent, in the Willesden Green valley. Neither cored interval in the Cyn-Pem valley system contains facies of this setting. The facies of the CB form facies associations which correspond to FA2 of Pattison (1991a) and FA3 of Boreen (1989).

The CB complex grades laterally out of the BHD complex in the landward portion of the basin and from the Estuary Mouth (EM) complex in a seaward direction (Figure IX-2). Hence, the CB ranges from sand-dominated at either extremity to mud-dominated in the center. Muddy CB deposits (>40% shale) form the CB-1 facies association and are discussed separately from sandy CB intervals (<40% shale; CB-2 facies association).

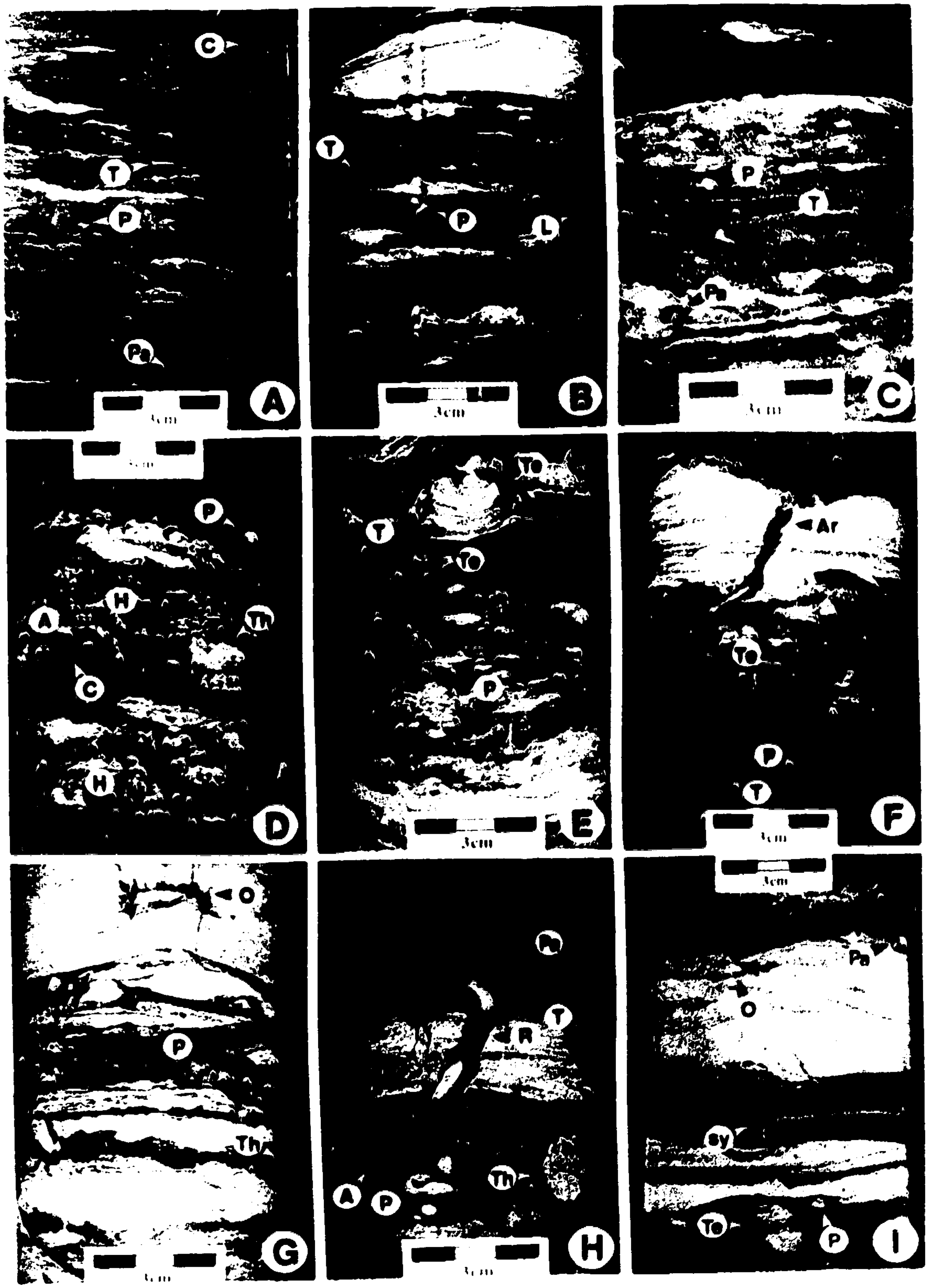
CB-1 Facies Association:

The CB-1 facies association consists of the regular interbedding of two basic facies. The most distinctive facies consists of moderately to intensely burrowed, finely interstratified to thickly interbedded sandy mudstones, weakly burrowed, sand- and silt-poor dark mudstones, and thin (millimeter to centimeter scale) sandstone stringers. The overall sand content of the facies varies from 5-50%, although it is typically 20-30%. This facies constitutes greater than 60% of the CB-1 facies association.

The sandy mudstone beds range from 2 cm to 50 cm, though generally less than 25 cm, and locally contain dispersed pebbles, organic detritus, coalified wood fragments and syneresis cracks. Sand is dispersed into the muds principally through biogenic activity.

Dark, sand- and silt-poor mudstones are commonly intercalated as interlaminae or thin interbeds, but are typically of subordinate significance in the Sundance/Edson successions. In contrast, this component of the facies is

Figure IX-21. Depositional Facies of the Central Basin Complex. **A-F:** Sediments of the CB-1 Facies Association. **(A)** Weakly burrowed, sand-poor shale, reflecting highly stressed conditions in the lagoon. Traces are limited to small *Terebellina* (T), *Planolites* (P), *Palaeophycus* (Pa) and *Chondrites* (C). Sundance Field, 15-07-55-20W5, depth 2667.5 m. **(B)** Weakly burrowed and interbedded combined flow rippled sandstones and shales. The facies reflects minor storm activity and dominant fairweather lagoonal deposition under restricted conditions. Trace fossils are *Planolites* (P), *Lockeia* (L) and *Terebellina* (T). Willesden Green Field, 11-15-42-07W5, depth 2263.1 m. **(C)** Shale-dominated, interlaminated sandstone and shale, moderately-burrowed with thin-walled *Terebellina* (T), *Planolites* (P) and *Palaeophycus* (Pa). Crystal Field, 11-12-46-04W5, depth 1707.7 m. **(D)** Thoroughly burrowed sandstone and shale, largely reflecting fully marine, unstressed conditions in the lagoon. Note the abundant *Helminthopsis* (H), with *Chondrites* (C), *Thalassinoides* (Th), *Asterosoma* (A) and *Planolites* (P). Sundance Field, 01-30-54-19W5, depth 2429.7 m. **(E)** Highly burrowed sandy shales, with remnant storm beds, largely destroyed by infaunal burrowing. *Teichichnus* (Te), *Terebellina* (T) and *Planolites* (P) dominate. Crystal Field, 08-31-46-03W5, depth 1673.1 m. **(F)** Thin, storm-generated, wavy parallel laminated sandstone interbedded with burrowed fairweather sandy shales. Mud-lined *Arenicolites* (Ar) shafts penetrate the tempestite. The sandy shales contain abundant *Planolites* (P), *Teichichnus* (Te) and flattened *Terebellina* (T). Crystal Field, 08-31-46-03W5, depth 1666.9 m. **G-I:** Sediments of the CB-2 Facies Association. **(G)** Sand-dominated, interbedded tempestite sandstones and fairweather sandy shales, lying marginal to the Bay Head Delta complex. *Ophiomorpha irregulaire* (O), *Planolites* (P) and *Thalassinoides* (Th) are visible. Crystal Field, 08-31-46-03W5, depth 1674.4 m. **(H)** Sand-dominated interbedded sandstones and sandy shales deposited near the Estuary Mouth complex. Combined flow rippled sandstone is penetrated by *Rosselia* (R). *Planolites* (P), *Thalassinoides* (Th), *Asterosoma* (A), *Terebellina* (T) and *Palaeophycus* (Pa) are also present. Willesden Green Field, 06-36-40-07W5, depth 2322.7 m. **(I)** Sand-dominated, interbedded sandstones and shales deposited near the Estuary Mouth complex. Sandstones are combined flow ripple laminated and wavy parallel laminated. *Teichichnus* (Te), *Planolites* (P), *Palaeophycus* (Pa) and small *Ophiomorpha* (O) are present. Note the syneresis crack (sy). Willesden Green Field, 04-04-42-07W5, depth 2287.6 m.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a far more significant element in Willesden Green intervals (Figure IX-21 B). These units are typically millimeters in thickness, but may locally reach 10 cm in some intervals. Syneresis cracks are rare.

Discrete sandstone stringers within the facies range from 0.2-5.0 cm in thickness, are vfU-fU grained, and are regularly interstratified with the sandy mudstone beds. The stringers are typically sharp-based, and possess combined flow ripple, oscillation ripple, rare current ripple and wavy parallel laminae. Where burrowing is moderate to abundant, the stringers are preserved as remnants. Load casts are present locally. Glauconite is present but not abundant.

The facies, as a whole, has the appearance of wavy (rare) to lenticular and pinstriped interbedded sandstone and shale. Burrowing is variable on a small scale, but is relatively uniform throughout the facies interval. Examples from Sundance/Edson and Crystal show a significantly greater degree of burrowing than in Willesden Green. Intervals in the Willesden Green valley system are also somewhat more sporadically burrowed.

The recorded ichnogenera are reasonably diverse but variably distributed (Figures IX-19, IX-21 and IX-22). The facies contains large numbers of *Planolites, Teichichnus* and *Terebellina*, with less common *Palaeophycus, Siphonichnus, Lockeia, Chondrites, Helminthopsis, Thalassinoides* and *Rosselia*, rare *Ophiomorpha, Diplocraterion* and *Cylindrichnus*, with very rare *Rhizocorallium* and *Asterosoma*. Of some interest is the general absence of *Helminthopsis* and *Siphonichnus*, and the greatly diminished abundance of *Terebellina, Chondrites, Rosselia* and *Palaeophycus* in the Willesden Green succession, compared to Sundance/Edson and Crystal intervals.

The facies is interpreted to reflect fairweather deposition of sands and muds within the lagoon or bay environment of the CB complex. Small-scale fluctuations in energy are reflected by the small-scale interbedding of fine-grained beds and sand stringers. Some combined flow ripple and oscillation ripple laminae may correspond to weak storms tracking across the basin, or shallow littoral conditions within the basin. The lenticular to pinstripe bedded appearance and rare current ripples may also suggest a tidal influence, possibly restricted to monthly or seasonal extremes in tidal energy. Unequivocal tidal structures are lacking. The dark sand- and silt-poor mudstone interlaminae and thin interbeds may result from river flood discharge through the BHD and rapid suspension fallout of fines into the

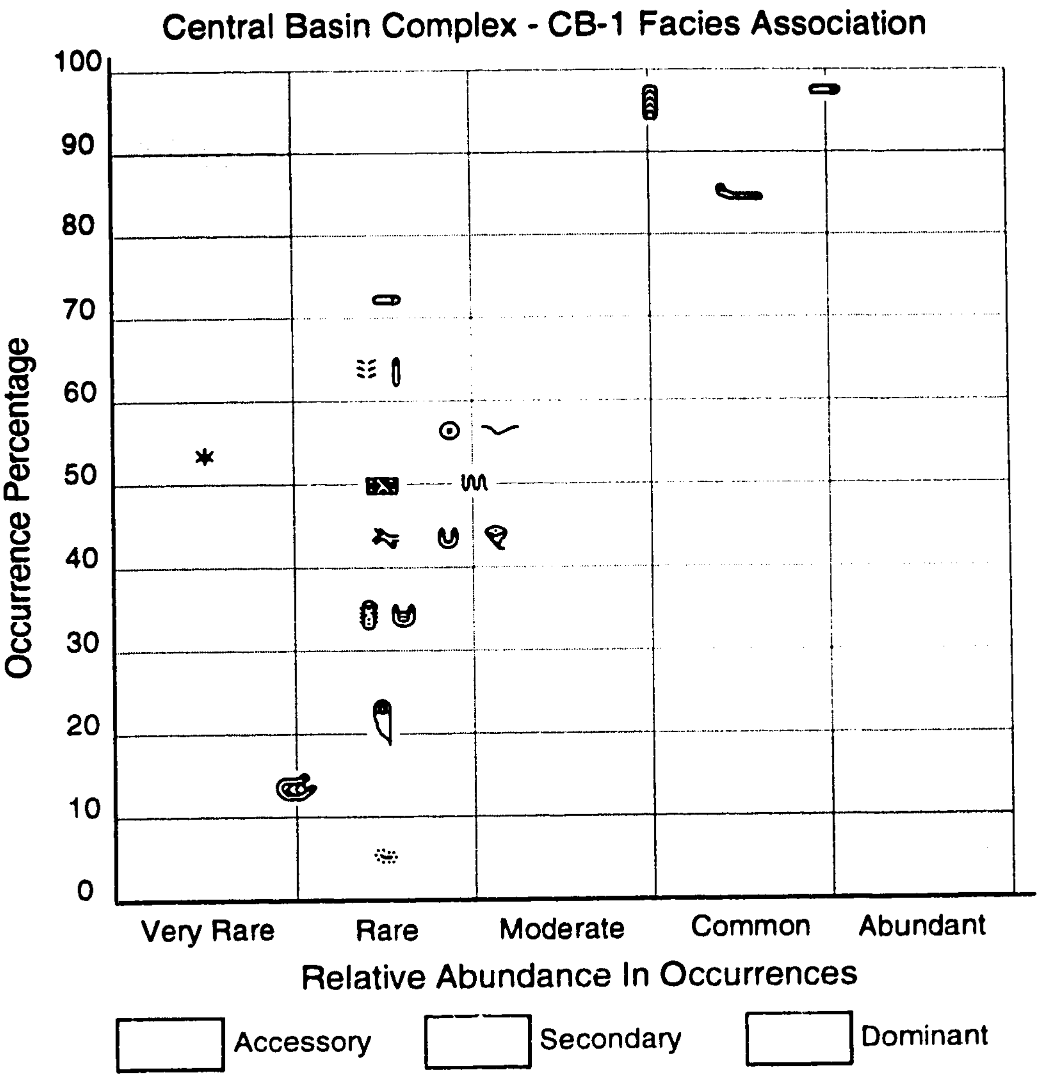


Figure IX-22. Trace Fossil Distribution in Facies of the Shaly CB-1 Facies Association of the Central Basin Complex. The legend of symbols for trace fossils is given in Figure IX-18. An explanation of the chart is given in Figure IX-13. Note that the dominant elements of the suite are restricted to a low diversity and reflect those constructed by trophic generalists. Note also that specialised structures are present, though uncommon. The suite shows a mixture of deposit feeding, suspension feeding, and lesser grazing structures. Most ichnogenera are characterised by low abundances and sporadic distributions.

basin. The largely unburrowed character of such interlaminae and interbeds, and the presence of syneresis cracks may support an association of reduced salinity, enhanced environmental stress and rapid mud deposition, all resulting from increased river discharge into the central basin. As such, there may be a depositional affinity between these units and the "PR" beds of the BHD complex.

Burrowing is uniform on a large scale, but in detail, the distribution of particular ichnogenera is not. Only *Teichichnus, Planolites* and *Terebellina* occur throughout the facies. *Helminthopsis,* though present in many intervals, occurs in bands or zones, and ranges in abundance from rare to relatively common (Figure IX-21 D). Locally, *Helminthopsis* is absent through fairly thick intervals. *Chondrites* is never abundant, but is sporadically present in rare to moderate amounts. *Rosselia* is locally more common, but is not uniformly distributed through the facies and present in only about half the studied intervals. This appears to indicate that conditions in the CB routinely varied from nearly fully marine to brackish. Variability in salinity of the basin is most likely related to variations in river discharge through the BHD, periods of high rainfall, tidal exchange through the tidal inlets, and storm-induced washovers at the estuary mouth barrier bar, any or all of which may reflect seasonal variations.

The other main facies within the CB-1 facies association constitutes less than 40% of the succession and consists of 5-25 cm thick sandstone beds, only rarely erosionally amalgamated into bedsets thicker than 50 cm. The bulk of the sandstones are vfU-fU grained, though very rare mL grained beds are present. Sorting is good to very good with rare interlaminae of mud towards the tops of some beds. Organic detritus is variable in abundance but low overall. Stratification dominantly consists of wavy parallel laminae, locally grading into combined flow or oscillation ripple laminae. Less commonly, the beds consist exclusively of combined flow, oscillation and very rare current ripple lamination. Sandier intervals are dominated by wavy parallel laminated sandstones and also include thin (<5 cm) "PR" beds. Thin conglomerate beds are very rarely present, ranging from 2-25 cm in thickness in some Crystal CB complexes. These beds have not been observed in Sundance/Edson examples. In contrast, thin conglomerate beds and sandstones containing abundant interstratified and dispersed chert pebbles or granules are typical of this facies in the south arm of the Willesden Green valley system.

The sandstone facies is less ubiquitously burrowed than the sandy mudstone facies interstratified with it. Overall burrow intensities are weak to moderate, with thicker beds generally lacking burrowing except towards their tops. Many of the thin sandstone beds possess only remnant primary structures. Fugichnia are relatively rare elements, though they are present in rare numbers in virtually all studied intervals. The sandstone beds are burrowed with *Palaeophycus, Skolithos, Arenicolites* (Figure IX-21 F), rare *Ophiomorpha* (Figure IX-21 G) and *Diplocraterion*, and very rare *Anconichnus*. *Ophiomorpha, Arenicolites* and fugichnia are more common in Willesden Green intervals than elsewhere, probably owing to the generally sandier nature of these deposits. *Anconichnus* is absent from Willesden Green intervals. Cross-cutting these traces are variable numbers of *Teichichnus, Planolites, Terebellina, Lockeia, Thalassinoides, Cylindrichnus* and very rare *Asterosoma*.

This facies is interpreted to reflect storm bed deposition, similar to that described from the BHD complex. The observed suite supports opportunistic colonisation of the tempestite, with subsequent replacement by the resident fairweather suite (Pemberton *et al.*, 1992b). The thin-bedded character of the sandstones and abundance of ripple laminae reflects diminished storm influence as a result of deeper water conditions than those experienced on the delta front of the BHD.

The muddy CB-1 facies association is dominated by *Planolites, Teichichnus* and *Terebellina* (Figure IX-22). *Palaeophycus, Skolithos, Siphonichnus, Lockeia, Helminthopsis, Chondrites, Rosselia, Arenicolites, Thalassinoides* and fugichnia comprise the secondary elements, while *Asterosoma, Ophiomorpha, Diplocraterion, Cylindrichnus, Rhizocorallium* and *Anconichnus* constitute the accessory elements. Dominant ichnogenera in the fairweather sandy shales largely correspond to structures produced by trophic generalists (*i.e.* opportunistic organisms; *cf.* Pianka, 1970; Remane and Schlieper, 1971; Jumars, 1993). These assemblages are characteristic of highly stressed settings, such as those subject to salinity fluctuations. Those dominating the tempestite sandstones reflect rapid colonisation of the event bed by opportunistic organisms as well. These assemblages are characteristic of stresses imposed by episodic deposition and variable substrate consistency.

The regular alternation between these facies produces a mixed *Skolithos-Cruziana* ichnofacies which reflects all three stresses, typical of brackish bays and lagoons (*cf.* Wightman *et al.*, 1987; Beynon *et al.*, 1988; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992; Ranger and Pemberton, 1992).

Many of the secondary and accessory elements of the trace fossil assemblages are not opportunistic, but rather, record more specialised and elaborate feeding behaviours, which are less common in stressful environmental settings. Their sporadic distribution and variable abundances in the facies association are interpreted to reflect salinity fluctuations within the CB, which probably ranged repeatedly from brackish to nearly fully marine. Tracemakers of *Helminthopsis, Chondrites, Asterosoma, Conichnus, Rhizocorallium* and *Macaronichnus* probably only occurred in facies of the CB complex when conditions had approached fully marine and the available substrate was appropriate for that behaviour. *Lockeia, Rosselia, Diplocraterion, Cylindrichnus* and *Siphonichnus* appear to possess greater tolerance for the observed stresses in the environment and, consequently, are more commonly present.

Some structures, notably *Asterosoma, Rosselia,* and *Cylindrichnus,* are much smaller than their fully marine counterparts. The reduction in size is an evolutionary response by some marine organisms to allow them to inhabit brackish water environments. Reduced salinity affects the size of benthic organisms in a number of ways, such as decreased metabolism, retarded growth and development, and early onset of sexual maturity (Remane and Schlieper, 1971). As well, the rigors of inhabiting brackish settings imposes an increased oxygen requirement on the benthic organisms, and a decreased surface area reduces the total oxygen requirements of the fauna (Remane and Schlieper, 1971). Additionally, organisms inhabiting stressful environments are characterised by a high mortality rate; consequently, more of the biogenic structures observed in core may correspond to juvenile rather than adult tracemakers.

CB-2 Facies Association:

The CB-2 facies association consists of the same facies as the muddier CB-1 facies association, but in different proportions. The fairweather sandy mudstone deposits constitute less than 40% of the succession with the tempestite sandstones comprising the remainder. The CB-2 facies association is laterally and vertically intergradational with the CB-1 facies association. As the CB complex grades longitudinally into both the BHD and EM complex (Figure IX-1), as well as laterally towards the valley margins, sand bed content increases, partly as a function of increased proximity to sediment sources as well as decreasing water depths. Amalgamated storm beds may reach thicknesses of 1 m. Thicker storm beds and a progressive decrease in both preserved waning flow deposits and fairweather intervals (*i.e.* increased erosional amalgamation) argues for increasing proximity to either the BHD or the EM complex. Attempts to differentiate sandy CB successions adjacent to the BHD from those adjacent to the EM complex were unsuccessful. The sedimentology and ichnology appear identical, based on the database available. This may reflect thorough mixing of fresh and marine waters across the basin, widespread influence of river floods and/or enhanced rainfall (either of which can "freshen" the basin), and minimal preservation of fairweather deposits in which evidence of salinity variations are typically recorded.

The trace fossil suite of the CB-2 facies association varies significantly from the CB-1 facies association, as the proportions of "fairweather" sandy mudstones and tempestite sandstones changes. The trace fossil suite of the CB-2 facies association is more or less what one might expect from higher energy and increased numbers of episodic depositional events (Figures IX-23 and IX-24). The dominant elements consist of fugichnia, *Arenicolites, Palaeophycus, Skolithos* and *Ophiomorpha*, in addition to *Planolites, Teichichnus* and thin-walled *Terebellina*. The secondary elements in the CB-2 facies association comprise moderate numbers of *Lockeia, Rosselia, Diplocraterion, Cylindrichnus, Thalassinoides* and *Siphonichnus*. Accessory elements include *Helminthopsis, Chondrites, Asterosoma, Conichnus, Anconichnus, Rhizocorallium,* and *Bergaueria*.

The increased number of vertical shafts and dwelling structures reflects the increased occurrences of sandy substrates available for opportunistic colonisation. All dominant elements remain trophic generalists, employing an r-selected strategy of population dynamics (Pianka, 1970; Remane and Schlieper, 1971). Remnant fairweather deposits contain suites similar to those of the CB-1 facies association, and indicate that salinity fluctuations also imparted significant environmental stresses on the tracemaking organisms.

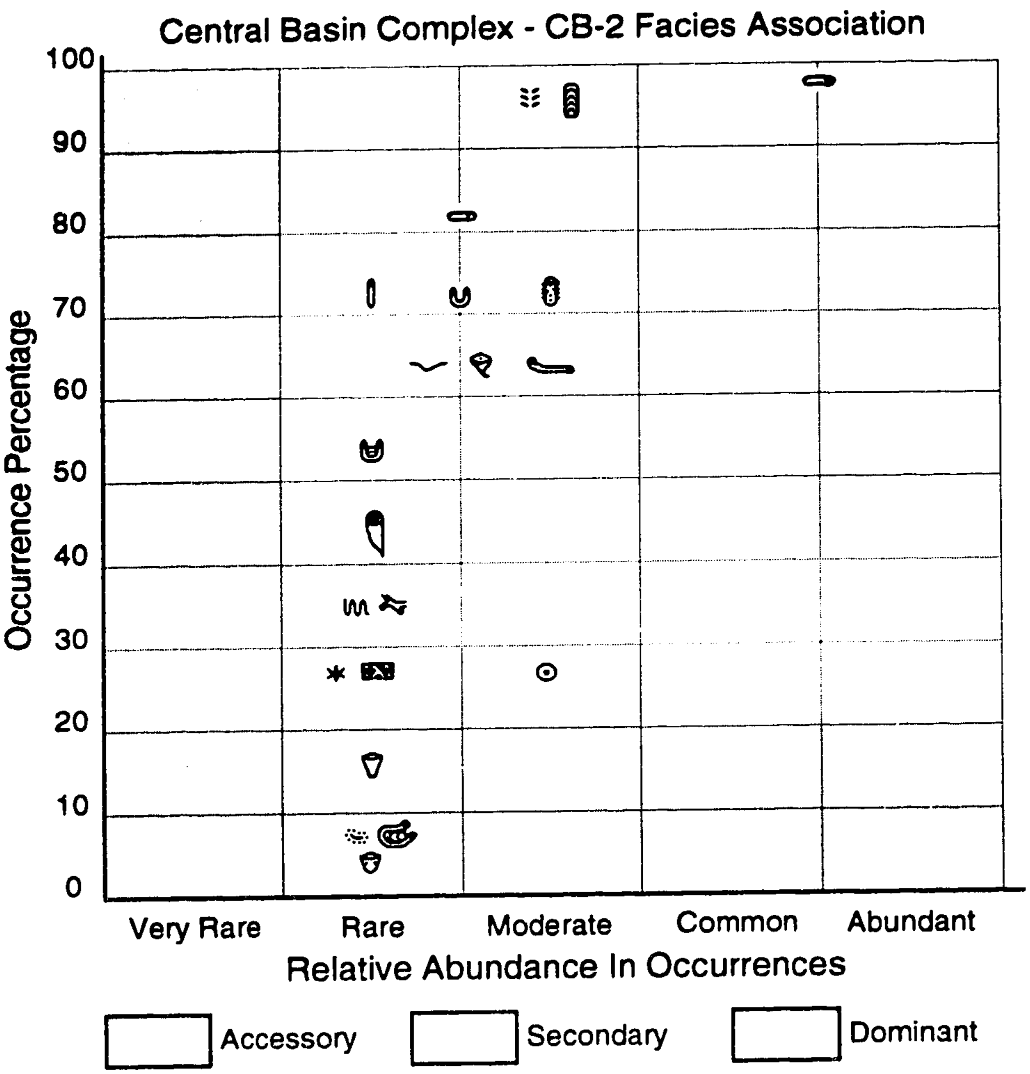
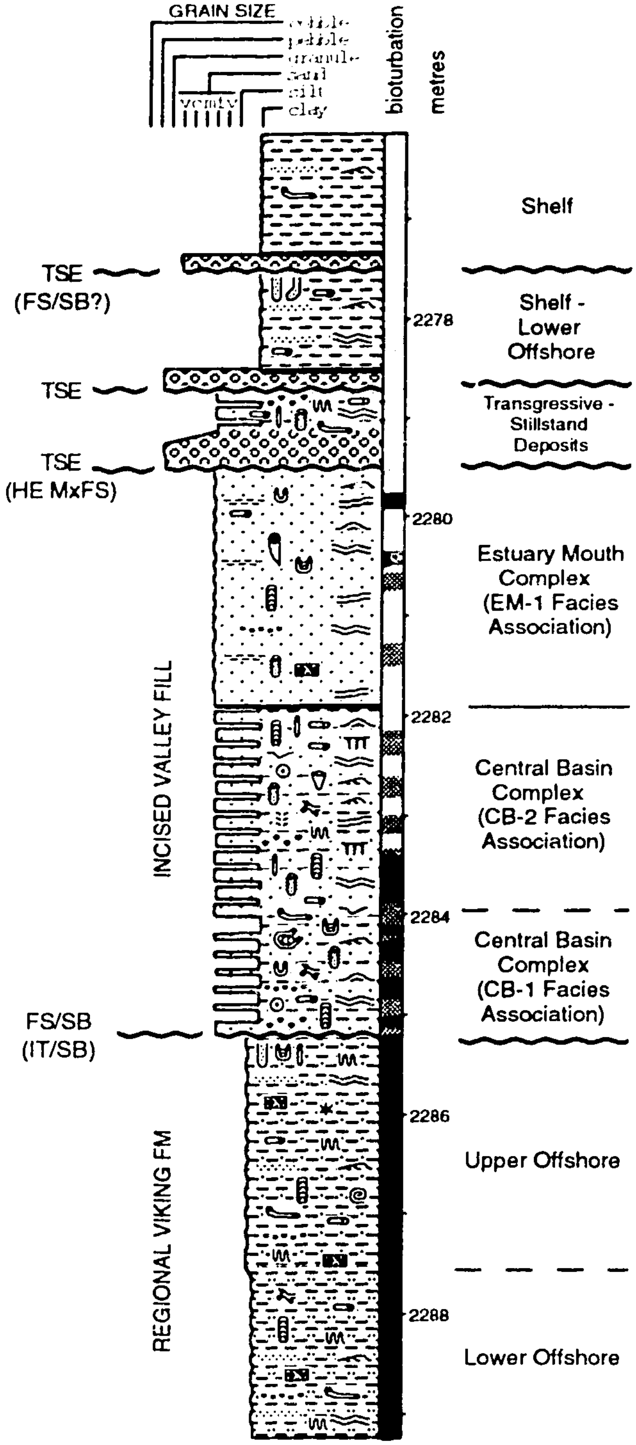


Figure IX-23. Trace Fossil Distribution in Facies of the Sandy CB-2 Facies Association of the Central Basin Complex. The legend of symbols for trace fossils is given in Figure IX-18. An explanation of the chart is given in Figure IX-13. Note the relatively few dominating elements present, most of which are produced by trophic generalists. Specialised structures are present, though uncommon. The suite displays a mixture of deposit feeding and suspension feeding structures, with relatively uncommon grazing structures.

Figure IX-24. Litholog of an incised valley fill, consisting of muddy Central Basin complex deposits (CB-1 Facies Association) with dispersed pebbles, grading upward into the sandy CB-2 Facies Association, and finally, into sandstones of the Estuary Mouth complex. The valley fill truncates an underlying, thoroughly burrowed, regionally extensive Viking Formation parasequence. Note the presence of a *Glossifungites* assemblage demarcating the co-planar surface of lowstand erosion and transgressive erosion (FS/SB) at the base of the valley. The valley fill is erosionally truncated by a ravinement surface (TSE) which possibly corresponds to a high energy maximum flooding surface (HE MxFS), and passes into a series of transgressive-stillstand cycles. The interval occurs in the NW arm of the Willesden Green valley, in well 12-34-42-07W5. The legend of the symbols used in the litholog is given in Figure IX-18.

BP Et Al. Willesden Green12-34-42-07w5



Estuary Mouth (EM) Complex

The Estuary Mouth (EM) complex constitutes the physiographic barrier between the open marine conditions of the coast from the comparatively more restricted and lower energy conditions of the estuary *sensu stricto*. Preserved sediments from the estuarine side (Figure IX-25 A-D) are considerably different from those deposited on the seaward side (Figure IX-25 E,F) and are, therefore, subdivided into two discrete facies associations. Sediments preserved on the estuarine side of the EM complex (EM-1 facies association) are well represented in cores of the Willesden Green valley system, and are comparatively poorly reflected at Crystal and Sundance/Edson. Cores in the Cyn-Pem valley system do not penetrate estuary mouth deposits. This facies association corresponds to FA3 of Pattison (1991a). Sediments deposited on the seaward side of the estuary mouth constitute the EM-2 facies association, and are exclusively represented by cores from the Sundance/Edson and Crystal valley systems.

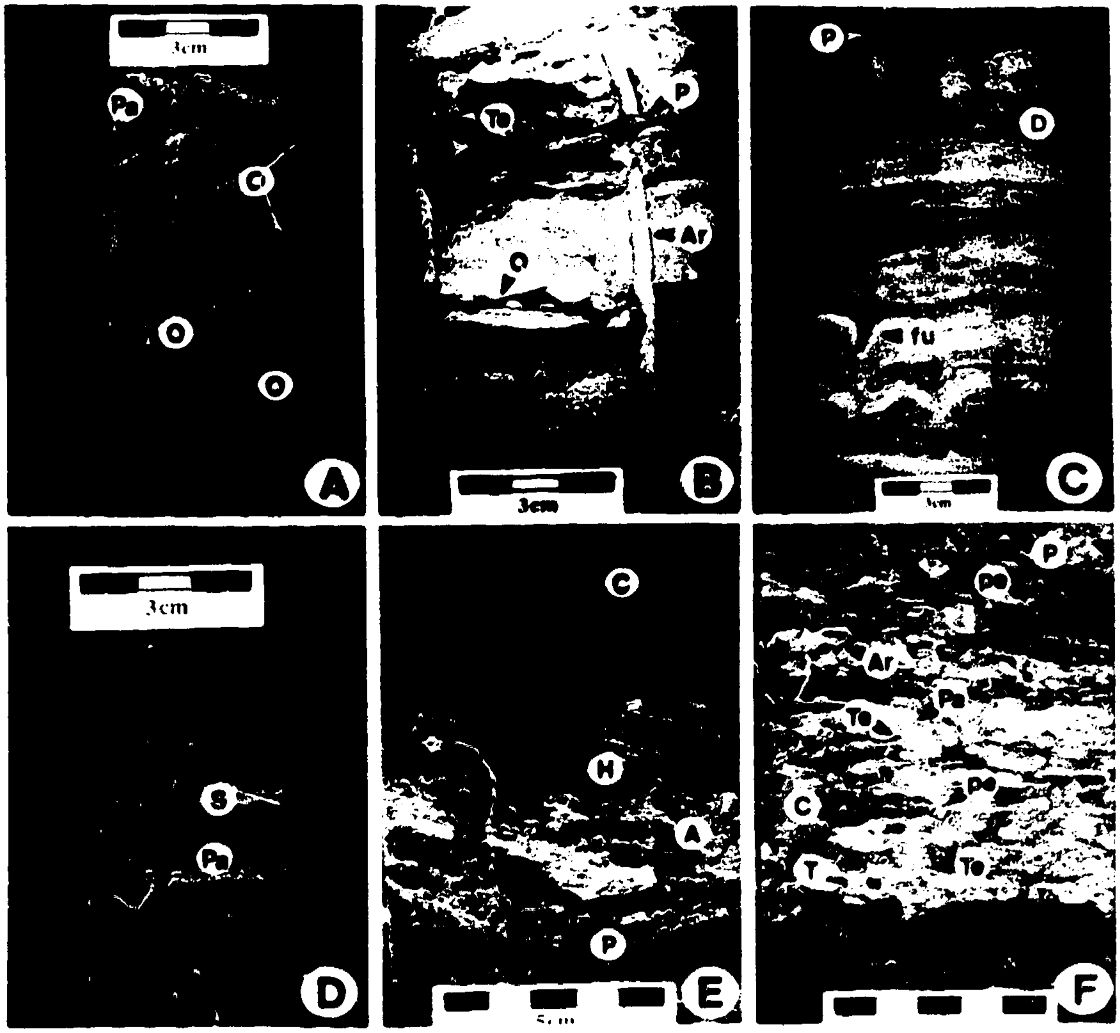
EM-1 Facies Association:

The sediments of the EM-1 facies association pass gradationally from the sandy CB-2 facies association of the CB complex and comprise 4 discrete facies. The main facies consists of vfU-fU grained, wavy to gently undulatory parallel laminated sandstones, in beds 15-25 cm thick (Figure IX-25 A,C). These beds are commonly erosionally amalgamated into bedsets up to 1.5 m thick, but locally have preserved combined flow ripple and oscillation ripple laminated tops. In so far as primary sedimentological features are concerned, the depositional mechanism is identical to that of the sandstone facies of the CB-2 facies association; one of episodic tempestite deposition in relatively shallow water conditions. Burrow intensity is generally uniform and of moderate to high intensity, in marked contrast to equivalent lithofacies in the BHD complex. The observed trace fossils correspond almost exactly to those present in the CB-2 facies association, except that *Helminthopsis*, *Chondrites* and *Anconichnus* occur in far fewer studied intervals (Figure IX-26). This variation probably reflects the overwhelming influence of data from the Willesden Green valley system, in which these particular ichnogenera are rare or absent. As in the CB-2 facies association, the suite records opportunistic colonisation of the tempestite, followed by their subsequent replacement by fairweather communities. In contrast to the CB complex,

Figure IX-25. Depositional Facies of the Estuary Mouth Complex.

A-D: Sediments of the EM-1 Facies Association. **(A)** Wavy parallel laminated to combined flow ripple laminated, storm-generated sandstone bed. Note the robust *Ophiomorpha irregulaire* (O) and *Palaeophycus* (Pa). Willesden Green Field, 11-01-41-07W5, depth 2299.3 m. **(B)** Combined flow ripple laminated sandstone with mud interlaminae, reflecting fairweather deposition. Note the *Ophiomorpha* (O), mud-lined *Arenicolites* (Ar), *Planolites* (P) and *Teichichnus* (Te). Crystal Field, 08-16-48-03W5, depth 1529.1 m. **(C)** Wavy parallel laminated and combined flow rippled fine-grained sandstones with *Diplocraterion* (D), fugichnia (fu) and *Planolites* (P). Willesden Green Field, 14-28-42-07W5, depth 2261.3 m. **(D)** Horizontal to low angle planar lamination passing into current ripple laminated fine-grained sandstone, reflecting washover deposition. *Skolithos* (S) and diminutive *Palaeophycus* (Pa) penetrate the bed. Willesden Green Field, 11-01-41-07W5, depth 2300.9 m.

E and F: Sediments of the EM-2 Facies Association. **(E)** Thoroughly burrowed sandy shale reflecting upper offshore deposition on the barrier bar. *Chondrites* (C), *Helminthopsis* (H), *Planolites* (P) and *Asterosoma* (A) are present. Sundance Field, 01-06-55-20W5, depth 2676.5 m. **(F)** Thoroughly burrowed muddy sandstone reflecting lower shoreface deposition on the barrier bar. *Planolites* (P), *Palaeophycus* (Pa), *Chondrites* (C), *Terebellina* (T), *Teichichnus* (Te), *Arenicolites* (Ar) and dispersed pebbles (pe) are present. Sundance Field, 01-06-55-20W5, depth 2675 m.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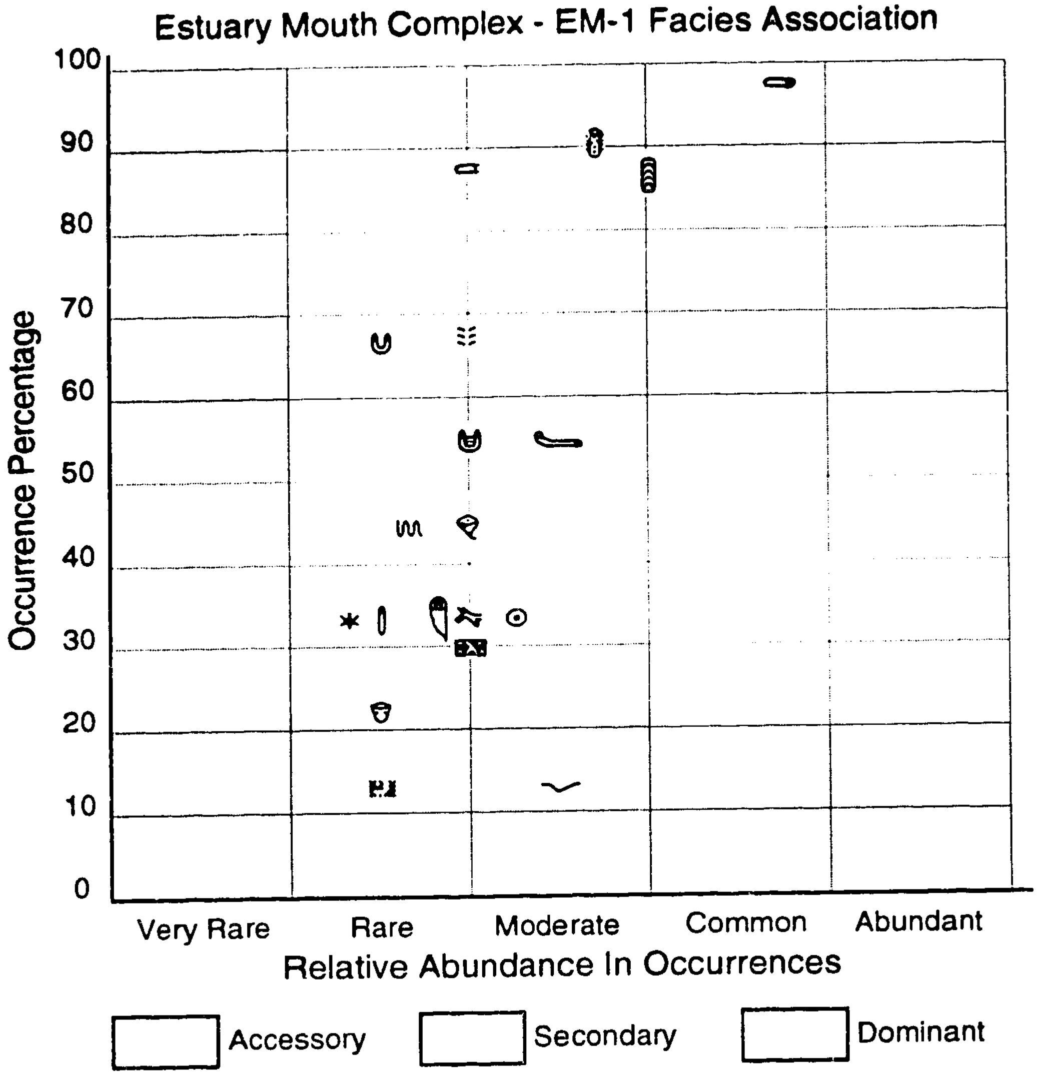


Figure IX-26. Trace Fossil Distribution in Facies of the EM-1 Facies Association of the Estuary Mouth Complex. The legend of symbols for trace fossils is given in Figure IX-18. An explanation of the chart is given in Figure IX-13. The trace fossil suite is dominated by trophic generalists, although burrowing intensities and diversity of the overall suite are fairly high. The suite consists of a mixture of suspension feeding/dwelling structures and deposit feeding structures, with rarer grazing structures.

however, the *Ophiomorpha* tracemaker appears to be the dominant opportunistic coloniser of the storm beds in the EM-1 facies association, with *Diplocraterion* almost as common as *Arenicolites* and *Skolithos*, possibly recording less of a salinity-induced stress on organism type and behaviour. The rarity of syneresis cracks in this and associated facies may support this observation. In addition, the fairweather communities are less well represented than those in the CB complex, probably due to increased erosive amalgamation of individual beds. *Teichichnus, Terebellina, Planolites* and *Palaeophycus* remain the most numerous fairweather traces penetrating into the storm beds, but are less abundant than their counterparts in the CB complex.

Regularly interstratified with the tempestites are stacked oscillation, combined flow and current ripple laminated, fL-fU grained sandstone beds, 5-25 cm thick (Figure IX-25 B). Organic detritus and wood fragments are exceedingly rare. Lithic pebbles, including chert, are locally present, but most common in the south arm of the Willesden Green valley system. Mud interlaminae and thin beds (<5 cm) are abundantly interstratified locally.

Burrow intensity in many of these units is high and physical structures are generally biogenically disturbed or virtually obliterated. Where muddy interlaminae are abundant, high degrees of burrowing imparts a "muddy sandstone" appearance. Dominant ichnogenera are *Ophiomorpha, Skolithos, Teichichnus, Palaeophycus, Planolites* and *Terebellina*, locally with *Rosselia*, fugichnia, *Diplocraterion, Arenicolites, Lockeia*, and rare *Asterosoma, Thalassinoides, Siphonichnus, Bergaueria, Chondrites* and *Helminthopsis*. The latter ichnogenus is confined to Sundance/Edson and Crystal deposits.

This rippled facies is interpreted to reflect general fairweather depositional conditions in the shallow water environments of the EM complex. This facies may also correspond to distal portions of washover lobes or flood-tidal delta deposits, although sediment bodies associated with this latter subenvironment have yet to be documented in Viking Formation EM complexes.

The third facies present within the EM-1 facies association consists of horizontally planar laminated, fL-fU grained sandstones, grading into current ripple lamination, in beds less than 10 cm thick (Figure IX-25 D). This corresponds to the "PR" beds of Pattison (1991a), and like those observed in the BHD complex, are generally unburrowed, except for rare fugichnia, *Skolithos, Palaeophycus, Teichichnus* and *Planolites* near the tops of beds. As in the BHD complex, this facies is interpreted to reflect high current flow conditions and/or shallow water transport with waning flow deposits preserved at the top. Within the EM-1 facies association, the "PR" beds are interpreted to reflect distal washover deposits, generated when storm waves breached the barrier system at the mouth and transported the sand headward into the estuary.

The final facies encountered from the EM-1 facies association is the least common; it was observed in only one cored interval. The 05-34-42-07W5 well in the north arm of the Willesden Green valley contains a four metre thick, moderately- to poorly-sorted, fL-mL grained, low angle planar stratified sandstone body, sharply overlying a sandy CB-2 facies association. The sandstone body consists of multiple, erosionally amalgamated beds, most of which are 20-50 cm in thickness. Carbonaceous detritus is abundant and largely dispersed within the sand beds rather than as thin interlaminae. Siderite-cemented rip-up clasts are present although rare. The unit lacks any evidence of ripple lamination. Burrowing is absent.

The interval is interpreted to reflect rapid deposition of sand under relatively high energy traction transport, possibly subjected to some storm-wave modification following deposition. The erosive amalgamation of beds supports successive depositional events. The absence of burrowing is curious. It may reflect rapid deposition of the individual beds; the poorly-sorted nature of the sand and the abundant dispersed organic detritus may support this. Each successive event may have removed any burrowed zones at the tops of the beds, but more likely, the entire unit, as a whole, may have been deposited in a very short period of time. This enigmatic facies is tentatively interpreted as part of a major washover lobe, deposited when storm waves on the seaward side of the EM complex breached the barrier.

The trace fossil suite for the EM-1 facies association (Figure IX-26) is dominated by *Ophiomorpha, Teichichnus, Palaeophycus* and *Planolites*. *Arenicolites, Diplocraterion, Terebellina, Helminthopsis, Rosselia, Siphonichnus* and fugichnia constitute the secondary elements, while *Asterosoma, Skolithos, Cylindrichnus, Thalassinoides, Chondrites, Bergaueria, Rhizocorallium, Macaronichnus* and *Lockeia* comprise the accessory elements. This trace fossil assemblage shows a close genetic affinity with the CB-2 facies association, consistent with deposition of the EM-1 facies association on the estuary side of the barrier complex.

As in the CB complex, the trace fossil suite shows a high diversity of forms (19 ichnogenera) over the entire EM-1 facies association, but the distribution of individual elements reflects the presence of various environmental stresses. The higher energy nature of fairweather deposition is reflected by the general decrease in importance of grazing and deposit feeding behaviours. Episodic deposition appears to be the main environmental stress indicated by the trace fossil suite, in the form of opportunistic colonisation of the tempestites by simple vertical dwelling structures. As in the CB complex, the dominant fairweather deposit feeding structures correspond to those of trophic generalists. The low abundances and sporadic distributions of grazing and specialised feeding/dwelling structures may suggest the presence of salinity fluctuations, although poor preservation of fairweather deposits and the sandier character of the substrates may easily account for this as well.

EM-2 Facies Association:

The database for the EM-2 facies association is relatively small (7 intervals) and is derived exclusively from the Sundance/Edson and Crystal valley systems. The facies roughly corresponds to FA9 of Pattison (1991a) and comprises two intergradational facies.

The first facies consists of intensely burrowed sandy shale, typically 1.0-1.5 m in thickness (Figure IX-25 E). Sand size is variable, ranging from fL-cL, but generally fU-mU, and is dispersed throughout the facies, presumably biogenically. The mud is silty, dark and locally occurs in discontinuous wisps and stringers. Dispersed pebbles, organic detritus and glauconite are typically present. Remnant wavy parallel laminae are observed in rare sandstone stringers.

Trace fossils are reasonably diverse and consist of abundant *Planolites, Terebellina, Helminthopsis,* common *Chondrites* and *Teichichnus,* moderately abundant *Palaeophycus, Thalassinoides* and rare *Rosselia, Asterosoma, Ophiomorpha* and *Diplocraterion.* This facies is interpreted to reflect upper offshore deposition, similar to the sandy shale facies in the regionally extensive Viking Formation parasequences (*cf.* Figure IX-14).

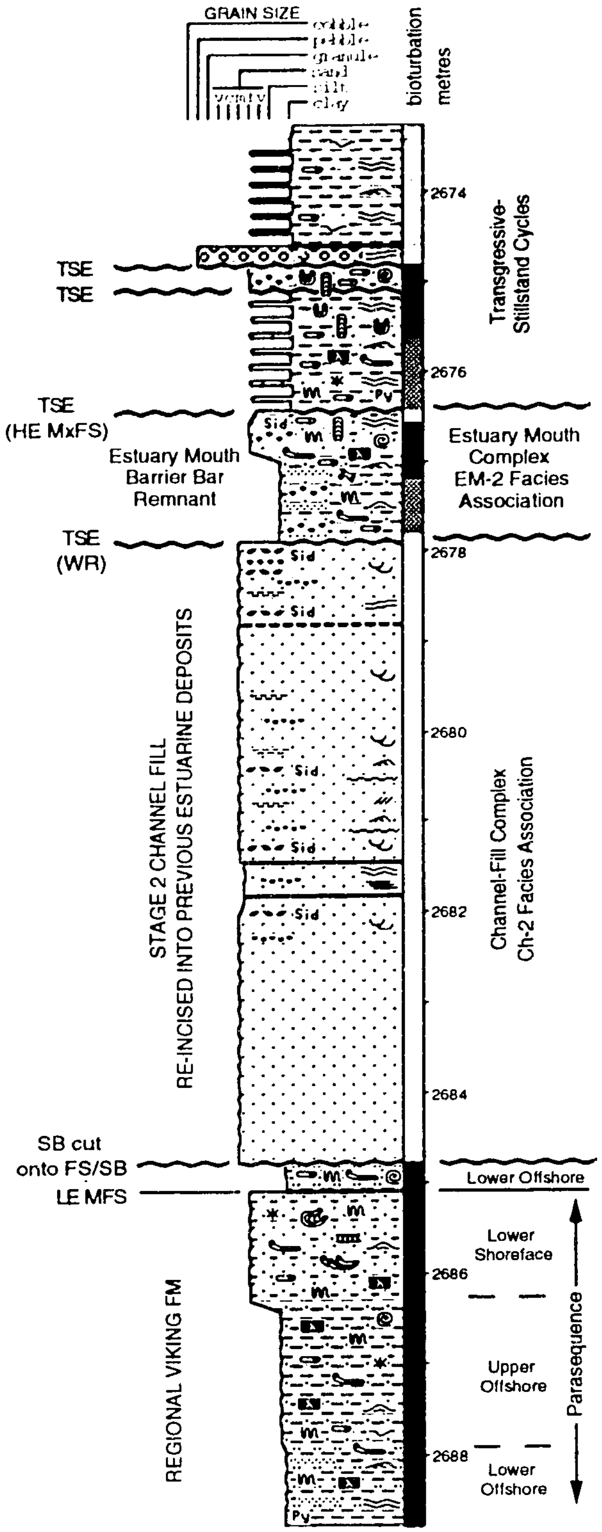
This facies grades upwards into a thoroughly burrowed fL-fU grained, muddy sandstone facies, typically 1.0 m in thickness, containing rare, discrete mudstone interlaminae and stringers (Figure IX-25 F). Pebbles are present, though not abundant, and are dispersed throughout the facies. Burrow intensity is typically intense and, although rare, wavy parallel laminae is locally preserved. The trace fossil suite shows a diverse assemblage, consisting of abundant *Ophiomorpha, Planolites, Skolithos,* and common *Teichichnus, Terebellina, Diplocraterion, Arenicolites* and *Palaeophycus. Helminthopsis, Chondrites, Siphonichnus, Rosselia, Asterosoma* and *Cylindrichnus* comprise moderate to rare elements of the suite. This facies is interpreted to represent distal lower shoreface deposition, similar to the muddy sandstone facies of the regionally extensive Viking parasequences (*cf.* Figure IX-15).

The EM-2 facies association is sharp-based, resting on an erosion surface, locally with a discontinuous granule or pebble lag rarely more than a few clasts thick (Figure IX-27). The succession is interpreted to reflect the progradation of upper offshore to distal lower shoreface environments, on the seaward side of the EM complex. The high degree of burrowing probably indicates slow accumulation or weakly storm-influenced conditions (MacEachern and Pemberton, 1992), corresponding to the deeper water conditions on the seaward side of the barrier system compared to that on the estuarine side. Despite the small database, the intervals studied show both uniform and abundant burrowing, as well as good trace fossil diversity (14 ichnogenera) throughout the intervals. Individual forms are fairly uniformly distributed with little evidence of dominance by a few ichnogenera, in marked contrast to most suites in the estuary proper. The suite is also characterised by a uniform distribution of elaborate and specialised feeding structures. The trace fossil assemblage reflects fully marine, unstressed, K-selected (equilibrium) behaviour (*cf.* Pianka, 1970). The EM-2 facies association is very similar to the Regional Viking Formation cycles, though overall, EM-2 shows a greater proximity to sediment source and lacks the regional distribution of the other.

The sharp base to the succession may locally correspond to an amalgamated FS/SB, reflecting transgressive modification either of the initial valley incision surface or a subsequent period of re-incision. Alternatively, the surface may correspond to a TSE (ravinement surface) or a low energy marine flooding surface, depending on the succession's paleogeographic position and the depositional history of the valley system. The EM-2 facies

Figure IX-27. Litholog of Stage 2 valley fill, reflecting probable deep re-incision through previously deposited estuarine sediments during a subsequent period of relative sea level lowstand (FS/SB). Note the unburrowed nature of the channel sandstones, indicating the presence of possible fluvially-dominated Ch-2 Facies Association. At this locality, the second stage of incision has removed all Stage 1 estuarine fill, and Stage 2 sandstones sit directly upon regionally extensive Viking Formation parasequences. Resumed transgression erosionally truncates the Channel-fill complex (TSE), and is overlain by the lower portion of the estuary mouth barrier bar complex (EM-2 Facies Association). The barrier complex is erosionally truncated by ravinement during renewed transgression (TSE). The interval occurs in the Sundance (NW) arm of the Sundance/Edson valley system (Well 01-06-55-20W5). The legend of the symbols used in the litholog is given in Figure IX-18.

Esso Nosehill 01-06-55-20w5



association is interpreted as the erosional remnant of the barrier bar system at the estuary mouth (Figure IX-27). In the examples studied, the top of the succession is truncated by a TSE, demarcated by the presence of gritty shales or pebble lags (*cf.* MacEachern *et al.*, 1992a), and reflecting erosive shoreface retreat which stripped off the upper portion of the estuary mouth barrier complex and left the upper offshore to lower shoreface deposits as an erosional remnant. The evolutionary model of wave-dominated estuary systems, proposed by Roy *et al.* (1980), predicts the destruction of the barrier under conditions of extreme or prolonged wave attack.

Channel (Ch) Complex

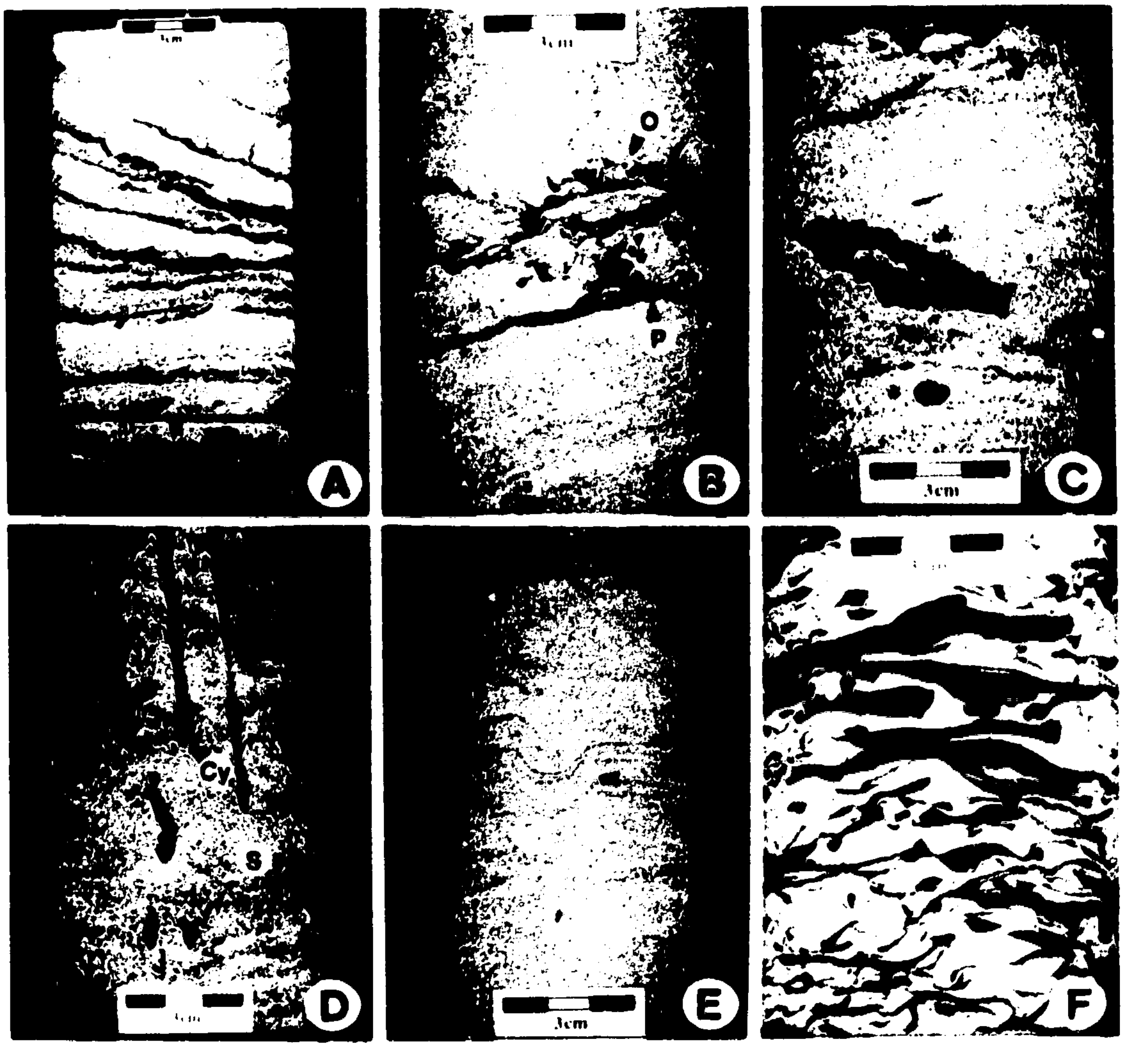
The Channel (Ch) complex facies associations are well-represented in all studied fields. The bulk of the intervals are sandstone-dominated, although pebbly sandstone and interstratified sandstone and conglomerate intervals are also present, particularly in the Willesden Green south field and in the Crystal field. The Crystal field also contains thick conglomerate intervals (FA8 of Pattison, 1991a), as well as thick structureless sandstone bodies (FA7 of Pattison, 1991a). These latter facies associations are largely unburrowed and therefore, are not dealt with in detail here.

The Ch complex corresponds to FA6 of Pattison (1991a), but can be subdivided into two discrete facies associations. Both facies associations are identical with respect to physical sedimentology, but differ in that one is sporadically burrowed (Ch-1) and the other is entirely unburrowed (Ch-2).

Ch-1 Facies Association:

The Ch-1 facies association consists of four facies. The dominant facies comprises mL-cU grained (typically mL-mU), moderately- to poorly-sorted, trough cross-stratified sandstones (Figure IX-28 A-D). Beds are generally 10-25 cm in thickness but may reach 50 cm, and are commonly erosionally amalgamated into bedsets up to 3.0 m in thickness. Current ripple lamination is generally uncommon. The sand is locally quite pebbly and may have intercalated conglomerate beds; clasts consist mainly of intraformationally-derived lithic pebbles, as well as chert pebbles and granules. Siderite-cemented rip-up clasts are common in all examples. Carbonaceous detritus is present, both dispersed and as stringers marking stratification. Glauconite is locally present, but rare. Mud interlaminae and

Figure IX-28. Depositional Facies of the Channel-Fill Complex.
(A) Medium-grained sandstone showing low angle toesets, fanning upward into high angle foresets of a subaqueous dune. Note the siderite-cemented mudstone rip-up clasts near the base of the trough cross-stratified bedset. Stratification is marked by carbonaceous detritus. Sundance Field, 12-13-54-21W5, depth 2723.5 m. **(B)** Moderately well-sorted, medium-grained, trough cross-stratified sandstone. The presence of *Ophiomorpha* (O) and *Planolites* (P) attests to a marine influence on the channel fill. Edson Field, 12-34-52-19W5, depth 2586.5 m. **(C)** Pebbly, trough cross-stratified sandstone, with *Ophiomorpha* (arrows) displaying siderite-cemented wall linings. Crystal Field, 12-20-46-03W5, depth 1725.7 m. **(D)** Trough cross-stratified sandstone, containing elongate *Cylindrichnus* (Cy) and *Skolithos* (S). Crystal Field, 12-20-46-03W5, depth 1726.4 m. **(E)** Medium- to upper fine-grained sandstone, containing horizontal to low angle planar parallel laminations, passing into current ripple lamination. Note the escape trace (*i.e.* fugichnia; arrow). Crystal Field, 16-24-45-04W5, depth 1790.4 m. **(F)** Trough cross-stratified sandstone containing abundant mudstone rip-up clasts, forming a shale-clast breccia. Cyn-Pem Field, 06-12-51-11W5, depth 1945.0 m.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thin (<1 cm) beds are locally intercalated. Rare examples from intervals in Crystal and Edson may possess double mud drapes on some foresets, suggesting subtidally-generated tidal bundling of the bedforms. No unequivocal cyclicity could be documented.

Trace fossils in this facies are sporadically distributed and vary from rare to moderate in abundance. *Ophiomorpha* (Figure IX-28 B,C) and *Skolithos* are the dominant elements of the suite, with *Ophiomorpha* burrows reaching 3 cm in diameter. *Diplocraterion, Arenicolites* and fugichnia occur in lesser numbers. *Teichichnus, Cylindrichnus* (Figure IX-28 D), *Palaeophycus* and *Planolites* are present in most examples and are typically associated with muddy interlaminae and thin beds. *Rosselia* and *Asterosoma* are present, but constitute uncommon elements of the suite. Burrow linings are typically thick.

The second facies consists of 10-50 cm thick beds of low angle (<15°) planar and exceedingly rare, wavy parallel laminated, fL-mL grained sandstones (Figure IX-28 E). These beds are amalgamated into bedsets up to 1.5 m in thickness. Thin, current ripple laminated sandstone beds are also commonly intercalated. Like the trough cross-stratified sandstones, carbonaceous detritus, lithic pebbles, muddy interlaminae, thin mud beds, and mudstone rip-up clasts are locally intercalated. Locally, granule to pebble clast-supported conglomerates are interstratified. The conglomerate units are also low angle planar cross-stratified.

Burrowing in this facies is typically associated with the muddy interlaminae and thin shale beds. This results in sporadic burrowing, largely confined to relatively thin zones. Burrow intensity is generally moderate to weak. Ichnogenera occur in rare numbers and include *Ophiomorpha, Palaeophycus, Cylindrichnus*, lesser *Skolithos* and *Planolites*, and rare *Teichichnus* and *Rosselia*. Single occurrences of *Lockeia, Conichnus* and *Chondrites* are present. Fugichnia (Figure IX-28 E) are relatively common.

The third facies consists of lithic, fU-mL grained, massive (apparently structureless) sandstone, containing organic detritus, muddy stringers, rare mudstone rip-up clasts, and glauconite. Upper and lower contacts are indistinct. Beds range from 50 cm to 2 m in thickness. Burrowing is absent in all examples encountered.

The final facies was only noted from the 06-12-51-11W5 well at Cyn-Pem, and consists of mL-cL grained, moderately-sorted sandstone containing abundant flat mudstone flakes (?desiccated mudstone chips). This 80 cm thick shale-clast breccia possesses low angle planar cross-stratification and is unburrowed (Figure IX-28 F). Several intervals in the Ch complexes of the Crystal valley contain abundant mud flake rip-up clasts, and may be transitional to this facies.

The Ch-1 facies association reflects a predominance of current-generated sediment transport and deposition. The laterally restricted geographic distribution of the facies association supports channelised flow. The bulk of the association reflects relatively small, migrating subaqueous dunes. The amalgamation of the bedforms into thick intervals supports a reasonably high aggradation rate. The interstratified low angle planar laminated sandstones with associated current ripple lamination are interpreted as sheet-flow transport of sand with waning flow conditions locally preserved, possibly reflecting higher flow velocities during flood-stage discharge in the channel, or flow near the channel margins. The apparently structureless sandstone beds may reflect rapid deposition, a lack of lithologic contrast to highlight stratification, or penecontemporaneous liquefaction of the bed, destroying primary structure. The general rarity of the facies precludes discrimination between these possibilities. The shale-clast breccia suggests current transport of intraformational, possibly desiccated, mud flakes from bank settings into the channel environment, presumably under flood conditions.

All ichnogenera in the trace fossil suite of the Ch-1 facies association occur in rare to moderate numbers (Figure IX-29). The suite is "dominated" by *Ophiomorpha* and *Skolithos*, while *Planolites*, *Teichichnus*, *Diplocraterion*, *Cylindrichnus*, *Palaeophycus* and fugichnia comprise the secondary elements. *Asterosoma*, *Rosselia*, *Arenicolites*, *Conichnus* and *Chondrites* constitute accessory elements.

The suite demonstrates that the Ch-1 facies association accumulated in marine or marginal marine conditions, although the degree of salinity stress is difficult to determine. The main environmental stress imposed on the suite appears to be related to migration of subaqueous dunes as well as high energy sheet-flow conditions with rapid deposition. Migrating bedforms pose a severe difficulty to infaunal organisms, since progressive avalanching of sand down the slip face tends to bury the entrance to the dwelling structures, and the non-cohesive shifting nature of the substrate precludes effective deposit feeding or grazing behaviour. Only elongate shafts and deeply

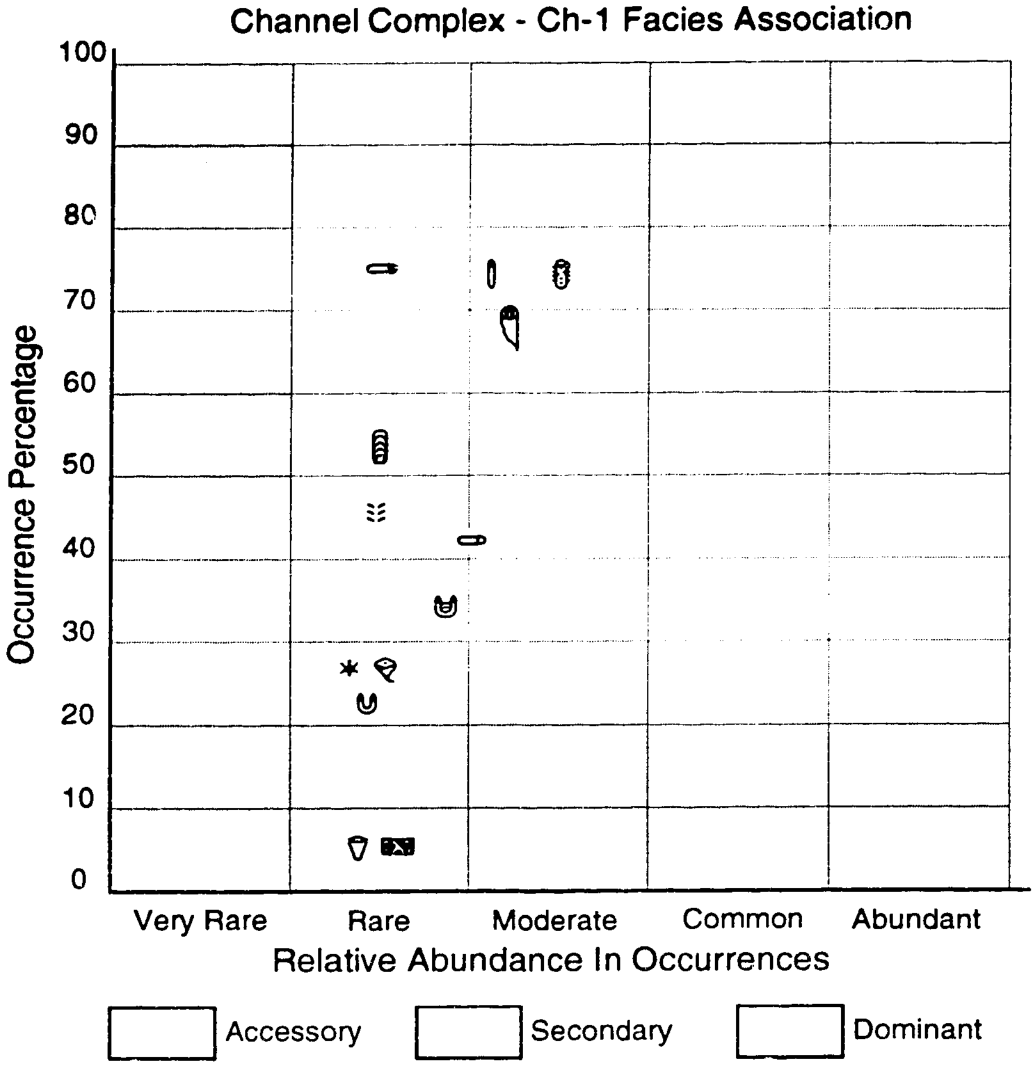


Figure IX-29. Trace Fossil Distribution in Facies of the Ch-1 Facies Association of the Channel-Fill Complex. The legend of symbols for trace fossils is given in Figure IX-18. An explanation of the chart is given in Figure IX-13. Dominating elements of the suite reflect deep suspension feeding/dwelling structures. Other ichnogenera are of low abundance and sporadic in distribution. Most other ichnogenera are associated with muddy interbeds, reflecting pauses in bedform migration.

penetrating and branching networks of heavily-lined dwelling structures are ideally suited to these dynamic settings. Fugichnia record the burial of organisms or their entrainment in flows. The remainder of the suite is associated with muddy interlaminae, recording pauses in bedform migration. Most of the feeding structures associated with these pauses are those of trophic generalists, but this may be related more to a paucity of deposited food than to any presumed salinity fluctuations.

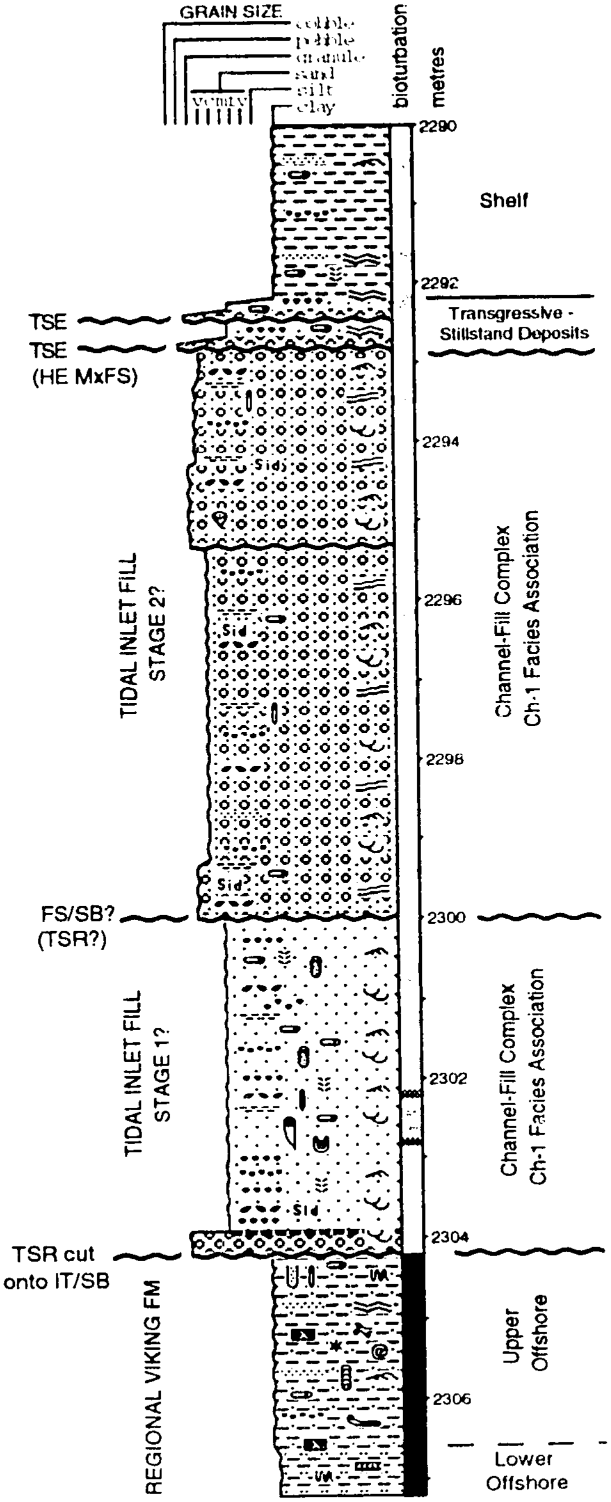
The Ch-1 facies association may reflect a number of possible settings, including tidal channels, tidal inlets or marine-influenced lowstand channels re-incised into previous estuarine deposits. Determining which of these settings are appropriate for a given succession is difficult, particularly with limited well control. Where channels are deeply incised, typically removing all previous estuarine deposits and erosionally overlying regional Viking cycles, a lowstand-induced re-incision interpretation is favoured. Many such intervals may reach 35 m in thickness.

In contrast, good well control in the south arm of the Willesden Green valley system appears to support a tidal inlet interpretation. The 05-06-41-06W5 well (Figure IX-30) intersects a Ch-1 facies association characterised by pebbly trough cross-stratified and low angle planar stratified sandstones containing a sporadic distribution of *Ophiomorpha*, *Skolithos*, *Diplocraterion*, *Arenicolites*, *Cylindrichnus*, *Palaeophycus*, *Planolites* and fugichnia. The intervals show a close lateral association with EM-1 facies associations in surrounding wells, and are deeply scoured, resting on an FS/SB developed on a regionally extensive Viking Formation parasequence. Existing core control is reasonably good, and supports a longitudinally restricted geographic extent to this marine-influenced channel succession; features favouring a tidal inlet interpretation. Several intervals in the Sundance/Edson valley system are suspected to correspond to tidal inlet deposition, but this cannot yet be substantiated.

The 05-06-41-06W5 well indicates a vertical stacking of tidal inlet fill (Figure IX-30). As the entire valley fills, distributary channels typically links up with tidal inlets to drain the valley system. This scenario may produce a channel system which may incise into previous estuarine deposits and locally overly previous channel sediments. Alternatively, however, stacking of channel deposits may reflect initial channel deposition, partially removed by renewed incision during succeeding lowstand conditions. The coarser

Figure IX-30. Litholog of Channel-fill complexes (Ch-1 Facies Association), interpreted as tidal inlet deposits. Note the *Glossifungites* assemblage subtending beneath the initial transgressive fill of the valley (FS/SB). The FS/SB has probably been modified by a later tidal scour ravinement surface (TSR) reflecting the base of the tidal inlet. The interval occurs in the SE arm of the Willesden Green valley system (05-06-41-06W5 well). The coarser-grained channel-fill towards the top may indicate a period of re-incision during a subsequent lowstand. The succession is erosionally truncated at the top by a TSE, reflecting resumed transgression. The legend of the symbols used in the litholog is given in Figure IX-18.

Sicanna Et Al Willesden Green 05-06-41-06w5



conglomeratic channel-fill towards the top of the succession may correspond to rejuvenation of the system during a relative lowstand of sea level. It seems reasonable that just as valley systems themselves become the *loci* of successive periods of re-incision, so too, the existing distributary and tidal inlet channels may also serve as the sites of the re-incision during subsequent lowstand conditions. Partial or complete removal of previous channel deposits may occur, particularly if the lowstand is pronounced and the system becomes a zone of sediment bypass. It follows that in many instances, re-incision surfaces (*i.e.* sequence boundaries) may be picked stratigraphically lower than appropriate, due to the overall similarity between facies in the previous channel and those of the re-incised channel. Without a pronounced grain size change or compositional change in the nature of the fill, the contact between the two systems may be as indistinguishable as the erosional amalgamation of two trough cross-stratified sandstone beds.

Ch-2 Facies Association:

The Ch-2 facies association was encountered in only in two cored intervals within the Sundance/Edson valley system (*cf.* Figure IX-27). The facies association consists of the same lithofacies as the Ch-1 facies association, barring the shale-clast breccia noted from the Cyn-Pem valley system. Neither interval contained conglomerate beds or pebble stringers. In contrast to the Ch-1 facies associations, this association is entirely unburrowed. Where the facies association rests erosionally on regionally extensive Viking parasequences, no *Glossifungites* assemblages were encountered.

The facies association is interpreted to reflect current deposition of sand in a channel setting, similar to that of the Ch-1 facies association. In contrast, it is speculated that the Ch-2 facies association may reflect fluvial- rather than brackish- or marine-influenced channel deposition. These channels may correspond to fluvial, distributary or lowstand-induced re-incision channels, rather than to tidal inlets, tidal channels or transgressively-filled, re-incised channels. Re-incision during a subsequent lowstand of sea level is favoured where channels have incised through all previous estuarine facies and have cut into the underlying regionally extensive Viking Formation parasequences.

CONCLUSIONS

1. The Viking Formation in the Crystal, Willesden Green, Sundance/Edson and Cyn-Pem fields contain estuarine incised valley fill deposits, juxtaposed against regionally extensive, fully marine, highstand progradational cycles.

2. The Viking Formation possesses numerous coarsening upward parasequences of regional extent, reflecting shoreface progradation within fully marine conditions. These successions are informally referred to as the regional Viking cycles. Three thoroughly burrowed and intergradational facies make up a complete coarsening cycle: silty shales, sandy shales and muddy sandstones, reflecting lower offshore, upper offshore and distal lower shoreface environments, respectively. The cycles are characterised by an increase in diversity of ichnogenera reflecting a progressive change from mainly grazing and deposit feeding to predominantly deposit feeding and suspension feeding behaviours. The trace fossil suites display intense burrowing, and are characterised by a high diversity of forms, a lack of dominance by a few forms, presence of significant numbers of specialised feeding/grazing structures, and a uniform distribution of individual ichnogenera, supportive of an equilibrium (K-selected) community within fully marine environments.

3. In marked contrast to the regional Viking cycles, the ichnological record of the valley fill systems displays a variable, though reduced degree of burrowing, a decrease in uniformity of burrowing, a pronounced variability in the distribution of individual ichnogenera, and a dominance by a few forms. Nonetheless, facies associations within the valley fills show a remarkably high trace fossil diversity. The overall suite is best regarded as a slightly impoverished marine assemblage, and is most distinctive in its marked variability. Many intervals show a mixed *Skolithos-Cruziana* ichnofacies. The dominant elements are ubiquitous in distribution and reflect the simple structures of trophic generalists. Such r-selected (opportunistic) behaviours are characteristic of stressed environmental settings, particularly those subjected to salinity fluctuations, episodic deposition, and variability in substrate consistency.

Many of the secondary and accessory elements of the trace fossil assemblage are not opportunistic and record more specialised and elaborate feeding or grazing behaviours which are uncommon in stressful environmental settings. Their sporadic distribution and variable abundances in the facies associations are interpreted to reflect salinity fluctuations within the estuary which may have repeatedly ranged from brackish to fully marine. In addition, the reduced size of some ichnogenera compared with their fully marine counterparts are also characteristic of brackish water conditions.

4. Recognition of the valley base or valley margins is facilitated by an integration of stratigraphy, sedimentology and ichnology. Erosional truncation of underlying regional Viking parasequences may locally be highlighted by the presence of anomalous dispersed pebbles, conglomeratic lags, or anomalous lithofacies. In most of the incised valley systems, the valley margins are demarcated by a *Glossifungites* assemblage. The presence of this trace fossil suite demonstrates that initial preserved valley fill was marine-influenced, indicating that the valley probably did not fill until the ensuing transgression. The erosional discontinuity demarcating the incised valley systems therefore corresponds to a co-planar (amalgamated) surface of lowstand erosion and transgressive erosion or marine flooding (*i.e.* FS/SB).

5. The observed facies associations and their distributions within the valley systems indicate that they accumulated in a wave-dominated embayed estuary (barrier estuary) setting. The valley fill deposits demonstrate a tripartite zonation of facies associations, defining three major depositional zones within the estuary: the Bay Head Delta complex, the Central Basin complex, and the Estuary Mouth complex. A fourth depositional complex reflects channel fill.

6. The Bay Head Delta complex is characterised by weakly and sporadically burrowed delta front storm bed sandstones with highly subordinate delta slope sediment-gravity flows and distal portions of distributary channels. The tempestites are relatively thin, reflecting the relatively low energy nature of storm events within the estuary compared with those which operate on open coasts. The facies association possesses one of the weakest degrees of burrowing, the most sporadic distribution of burrowing and dominantly only

structures generated by trophic generalists. This reflects high aggradation rates, episodic deposition and, possibly, reduced salinity as the main controls on the trace fossil suite.

7. The Central Basin complex consists of two interbedded facies. The most distinctive facies comprises fairweather deposition of sands and muds within the lagoon or bay environment of the central basin. This facies is dominated by structures reflecting r-selected opportunistic behaviour, commonly associated with variable, but generally reduced salinity. Reduced size of many structures and presence of syneresis cracks supports brackish water conditions. The sporadic distribution of secondary and accessory elements, reflecting more elaborate and specialised feeding and grazing behaviour indicates, however, that salinity ranged repeatedly from brackish to fully marine. Salinity fluctuations may have been seasonal, related to variations in river discharge, rainfall, and/or storm washovers of the barrier complex at the estuary mouth.

The other main facies consists of thin, storm-generated wavy parallel to combined flow and oscillation ripple laminated sandstone beds. In this facies, the dominant ichnological elements reflect rapid colonisation of the event bed by opportunistic organisms, in response to episodic deposition. The alternation between fairweather and storm deposits produces a mixed *Skolithos-Cruziana* ichnofacies. Detailed inspection of the suite, however, demonstrates that the assemblage is quite complicated and records highly variable depositional conditions. Salinity fluctuations, episodic deposition and variable substrate consistency appear to be the dominant stresses imparted on the tracemaking organisms.

8. The Estuary Mouth complex consists of two facies associations. The dominant facies association (EM-1) reflects deposition on the estuary side of the mouth, and is manifest by moderately to abundantly burrowed fairweather ripple laminated sandstones, interbedded with storm-generated sandstones, washover sandstones and possible tidal inlet sandstones. The trace fossil suite shows a high diversity of forms over the entire facies association, but the distribution of individual elements reflects opportunistic behaviour related to episodic deposition. Salinity stresses may have also occurred, but are difficult to resolve.

The facies association deposited on the seaward side of the estuary mouth (EM-2) is erosionally-bound and interpreted as the basal portion of the estuary mouth barrier bar complex itself. Resting on a co-planar FS/SB, or locally, a marine flooding surface, and erosionally truncated by an overlying TSE, the facies association coarsens upward from intensely burrowed sandy shales to muddy sandstones. These facies are interpreted to reflect the upper offshore to distal lower shoreface erosional remnant of the barrier complex. The trace fossil suite shows a uniform distribution of individual forms, a high degree of burrowing, a reasonable diversity of elements, a lack of dominance by a few ichnogenera, and the presence of moderate numbers of elaborate and specialised grazing and feeding/dwelling structures. The overall assemblage is consistent with fully marine, largely unstressed, equilibrium (K-selected) communities, and shows a closer genetic affinity with the regional Viking parasequences than to the incised valley fill assemblages.

9. Channel-fill facies associations are dominated by amalgamated subaqueous dunes, interstratified with flood-induced sheet-flow sandstones. The trace fossil suite demonstrates that most channel complexes accumulated in marine or marginal marine conditions, although the degree of salinity-induced stress is difficult to determine. The main stress illustrated by the trace fossil suite appears to be related to migration of subaqueous dunes, with a subordinate influence imparted by high energy sheet-flows with associated rapid deposition. The trace fossil suite reflects this by a predominance of deeply penetrating, branching and thickly-lined dwelling structures. The facies associations may locally reflect fluvial channels, distributary channels, tidal channels, tidal inlets, or lowstand-generated channels re-incised into earlier estuarine deposits.

10. The ichnology of estuarine valley systems in the Viking Formation are distinguished from fully marine regional Viking Formation successions only through careful analysis of the entire assemblage, including uniformity of burrowing, intensity of burrowing, the distribution of individual elements, the character of dominant elements, ethological interpretation of the organism behaviours, and assessment of trace fossil size, in addition to the cataloguing of the ichnogenera present. The wide range of environmental stresses imposed on organisms occupying Viking Formation estuaries results

in a highly complicated ichnological record, but detailed analysis of the preserved suite permits a much enhanced interpretation of the depositional subenvironments comprising the incised valley systems.

11. The complex nature of incised valley systems requires the full integration of stratigraphy, sedimentology and ichnology, in order to recognise the depositional complexes and ultimately, to resolve the depositional history of the successions. To date, ichnology has been under-utilised in such analyses, although its careful employment is currently proving to be invaluable.

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CHAPTER X

ICHNOLOGY AND SEDIMENTOLOGY OF TRANSGRESSIVE DEPOSITS, TRANSGRESSIVELY-RELATED DEPOSITS AND TRANSGRESSIVE SYSTEMS TRACTS, UPPER VIKING FORMATION, CENTRAL ALBERTA[6]

INTRODUCTION

Cretaceous strata of the Western Canada Sedimentary Basin, Alberta contain abundant transgressive deposits and transgressively-related deposits, owing to the additive effects of global (eustatic) rises of sea level during this time period (Haq *et al.*, 1987), and relatively rapid tectonic subsidence of the foreland basin (Stockmal and Beaumont, 1987; Cant and Stockmal, 1989). Transgressive surfaces and their associated deposits are widespread and well-developed in many stratigraphic intervals, including the Albian Bluesky Formation (Oppelt, 1988), the Falher members and Notikewin Member of the Spirit River Formation (Smith *et al.*, 1984; Jackson, 1984), the Paddy Member of the Peace River Formation (Leckie, 1991a,b), the Viking Formation (Boreen, 1989, Raychaudhuri, 1989; Davies, 1990; Pattison, 1991a; MacEachern *et al.*, 1992a; Raychaudhuri *et al.*, 1992), the Bow Island Formation (Cox, 1991; Raychaudhuri and Pemberton, 1992), the Cenomanian Dunvegan Formation (Bhattacharya, 1989; Bhattacharya and Walker, 1991), the Turonian Cardium Formation (Plint *et al.*, 1988; Vossler and Pemberton, 1988), and the Campanian Bearpaw-Horseshoe Canyon Formation transition (Saunders and Pemberton, 1986; Saunders, 1989).

With the notable exceptions of Nummedal and Swift (1987) and Pattison (1991a), sequence stratigraphers have routinely regarded transgressions, their erosion surfaces, and their deposits to be relatively uncomplicated and rapidly generated. In contrast, Pattison (1991a) demonstrated the wide diversity of

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[6] A version of this chapter has been published. MacEachern, J.A., D.J. Bechtel and S.G. Pemberton. 1992. *In*: S.G. Pemberton (ed.), Applications of ichnology to petroleum exploration- a core workshop. Society of Economic Paleontologists and Mineralogists, Core Workshop 17: 251-290.

surfaces and deposits produced when small-scale stillstand cycles are superimposed on an overall transgression. Transgressive surfaces are discontinuities across which a landward shift of facies can be demonstrated. Transgressive surfaces can be separated into largely non-erosive low energy marine flooding surfaces and low relief, high energy (erosive) flooding surfaces. The low energy flooding surfaces (LE FS) correspond to the flooding surfaces or marine flooding surfaces of others (*e.g.* Bhattacharya and Walker, 1991; Beynon and Pemberton, 1992). In the Viking Formation, most of the well-developed LE FS occur in the regionally extensive highstand parasequences near the base of the succession, and are dealt with in detail in Chapter III. High energy flooding surfaces (HE FS) are manifest as low relief erosion surfaces cut by wave and/or current processes, associated with erosional shoreface retreat during transgression. Nummedal and Swift (1987) identified two subcategories of HE FS: the higher energy ravinement surfaces (*cf.* Stamp, 1921) and the lower energy (distal) offshore marine erosion surfaces. The HE FS are also analogous to the transgressive surfaces of erosion (TSE) of others (*e.g.* Bhattacharya and Walker, 1991; MacEachern *et al.*, 1992a). Basinward, high energy flooding surfaces pass into low energy, non-erosional flooding surfaces. The upper part of the Viking Formation is dominated by HE FS surfaces and their associated deposits, and are the concern of this paper.

Within incised valley systems of the Viking Formation, several HE FS can be differentiated (*e.g.* MacEachern and Pemberton, in press; Zaitlin, in press; Chapter IX). The main surfaces correspond to the transgressive surface (equivalent to the initial transgressive surface), the wave ravinement surface associated with erosive shoreface retreat of the barrier complex near the mouth of the incised valley, the tidal scour ravinement surface reflecting tidal inlet generation and migration, and the maximum flooding surface, particularly in the vicinity of the interfluves and valley margins. Seaward of the valley margins and interfluves, the maximum flooding surface becomes an LE FS. Valley systems, despite constituting important elements of the transgressive systems tract, are highly complex and lie beyond the scope of this paper to address properly. They are dealt with in more detail by Reinson *et al.* (1988), Boreen and Walker (1991), Pattison (1991a,b,c; 1992), Dalrymple *et al.* (1992), Pemberton *et al.* (1992c), MacEachern and Pemberton (in press), and Zaitlin *et al.* (in press), as well as in Chapter IX.

This paper concentrates on the character of the HE FS and the associated deposits of the transgressive systems tract within the upper portion of the Viking Formation. The study area is regional in extent (Figure X-1), ranging from Township 18-66, Range 16W4-21W5. Detailed analyses of the ichnology and sedimentology from selected cores in the Judy Creek, Joarcam, Joffre, Gilby A and B, Chigwell, Willesden Green, Crystal, Sundance, Edson, Kaybob, Fox Creek, Waskahigan, Giroux Lake, Caroline, Garrington, and Blood (Bow Island Fm) fields were integrated with facies observations published by other workers. In addition, core data from Fenn, Mikwan and Chain were made available by I. Raychaudhuri (pers. comm., 1992). The study seeks to integrate ichnology with sedimentology in order to develop regionally consistent criteria for the recognition of HE FS in the subsurface, as well as for the differentiation between deposits directly associated with active ravinement and those associated with progradational cycles during intervening stillstand cycles.

REGIONAL STRATIGRAPHY

The Viking Formation is upper Albian (Lower Cretaceous) in age, passes upwards out of the marine shales of the Joli Fou Formation, and is overlain by Lower Colorado marine shales. Slipper (1918) informally gave the name "Viking" to gas-producing sandstones of the Viking-Kinsella field near Viking, Alberta. Wickenden (1949) first referred to the black shales at the base of the Colorado Group, overlying the Mannville Group, as the Joli Fou shale. Stelck (1958) later formally raised both the Viking and the Joli Fou to formation status.

The general stratigraphic equivalents of the Viking and Joli Fou are given in Figure X-2. Rough equivalents of the Joli Fou Formation include the Skull Creek shale in Montana and the Thermopolis shale in Wyoming (McGookey *et al.*, 1972; Weimer, 1984). The Viking Formation is roughly equivalent to the Paddy Member of the Peace River Formation (Koke and Stelck, 1985; Stelck and Leckie, 1990; Leckie and Singh, 1991), the upper part of the Bow Island Formation (Glaister, 1959; Cox, 1991; Raychaudhuri and Pemberton, 1992), as well as the Muddy Sandstone, Newcastle Formation and J-Sandstone

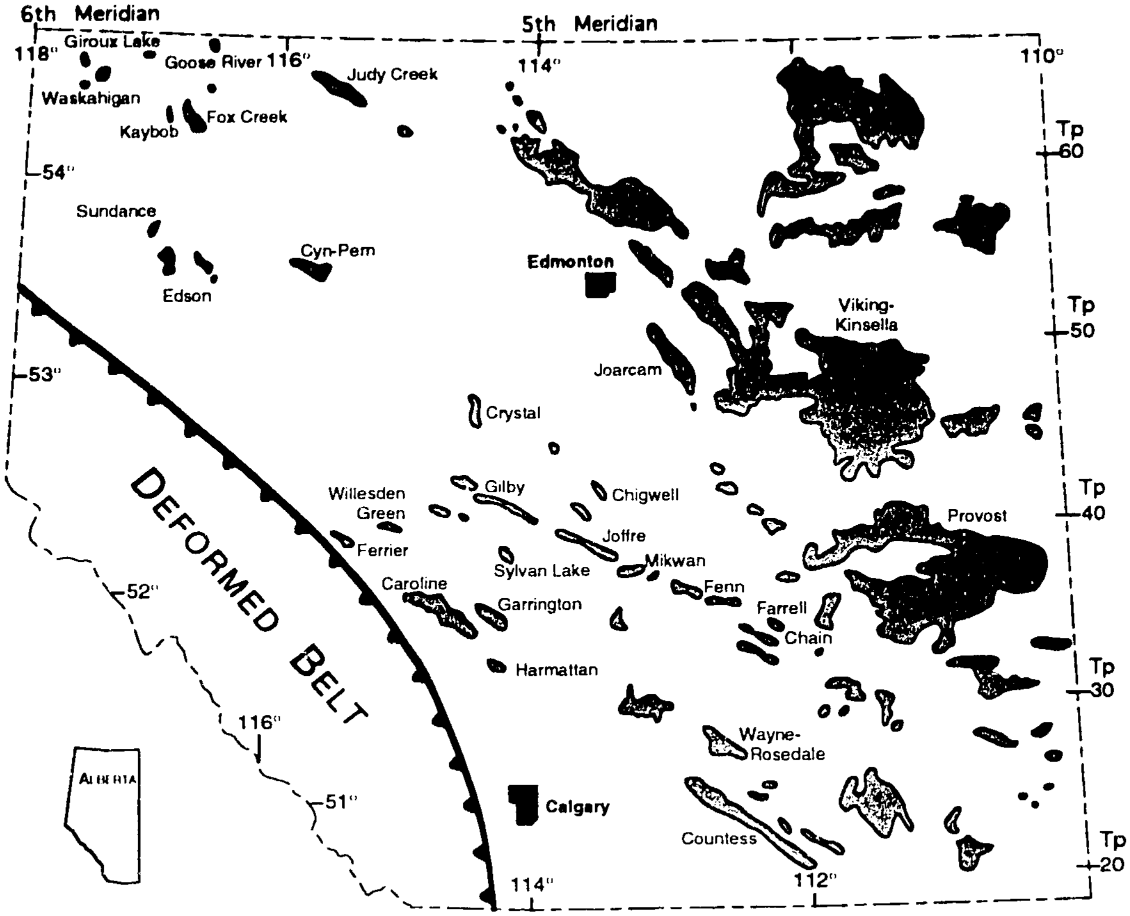


Figure X-1. Study area map, showing Viking Formation fields of central and south-central Alberta.

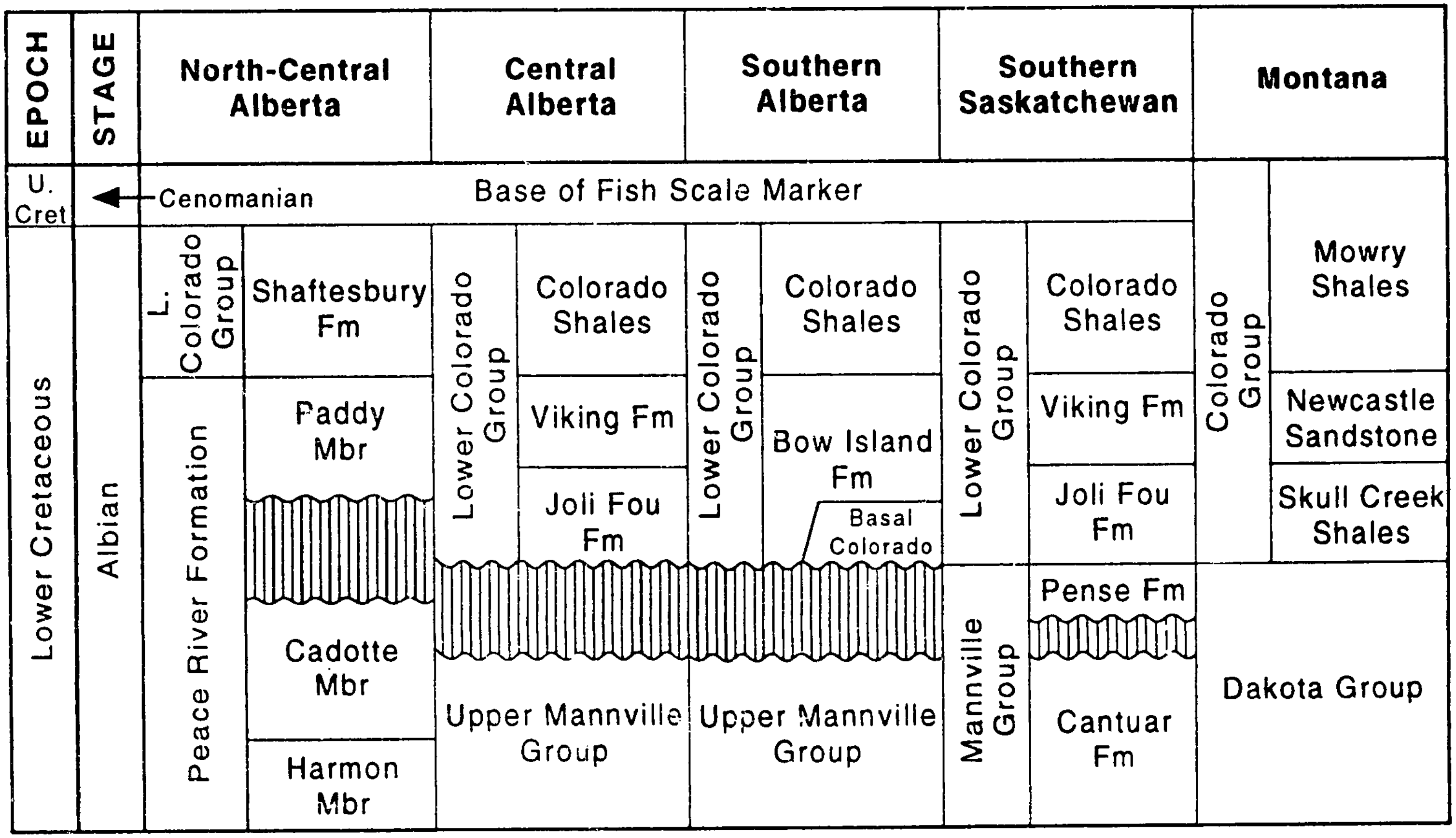


Figure X-2. Stratigraphic correlation chart for the Viking Formation and equivalents.

in Montana, Wyoming and Colorado, respectively (McGookey *et al.*, 1972; Beaumont, 1984; Weimer, 1984).

The overlying marine shales are typically referred to as the lower Colorado shales (Stelck, 1958), the Lloydminster shale (Tizzard and Lerbekmo, 1975) or the unnamed shale member of the Colorado Group (Evans, 1970; Downing and Walker, 1988). These shales are stratigraphically equivalent to the lower part of the Shaftesbury Formation, overlying the Peace River Formation (Stelck and Leckie, 1990; Leckie *et al.*, 1990; Bloch *et al.*, 1993), and to part of the Hasler Formation, Goodrich, and the lower part of the Cruiser Formation in N.E. British Columbia (Stelck and Koke, 1987; Stelck and Leckie, 1990). In the United States, the shales are equivalent to the Mowry shale in Montana and North Dakota (McGookey *et al.*, 1972).

A formal biostratigraphy using arenaceous foraminiferal assemblages has been established for the upper Albian Hasler Formation in N.E. British Columbia and its equivalents (Figure X-3), largely based on the work of Stelck (1975), Caldwell *et al.* (1978), Stelck and Hedinger (1983), Koke and Stelck (1985), Stelck and Koke (1987), Stelck and Leckie (1990) and Stelck (1991). The Joli Fou and Viking formations occupy the *Haplophragmoides gigas* Zone, overlying the *Ammobaculites wenonahae* subzone of the *Gaudryina nanushukensis* Zone. The zone is, in turn, overlain by the *Verneuilina canadensis* subzone of the *Miliammina manitobensis* Zone. Detailed studies of the Hasler Formation shales has led to the subdivision of the *H. gigas* Zone into seven discrete subzones. Unfortunately, this subdivision has not yet been carried south into central Alberta.

The upper portion of the Viking Formation of the Western Canada Sedimentary Basin, originally regarded as the "Viking grit" (Stelck, 1958) is an excellent interval in which to study the ichnology, sedimentology and stratigraphy of transgressive deposits, their bounding erosive discontinuities and the interstratified stillstand intervals. Much attention has been afforded the Viking Formation and its equivalents with regard to sequence stratigraphy (*e.g.* Leckie, 1988; 1991a,b,c; MacEachern *et al.*, 1990; 1991a,b; 1992a; Cox, 1991; Pattison, 1991b,c; Posamentier and Chamberlain, 1991a,b, 1993; Weimer, 1991; MacEachern and Pemberton, in press; Pemberton and MacEachern, in press) and the less interpretatively constrained allostratigraphy (Downing and Walker, 1988; Raddysh, 1988; Raychaudhuri, 1989, Boreen, 1989; Davies, 1990; Pozzobon and Walker, 1990; Boreen and

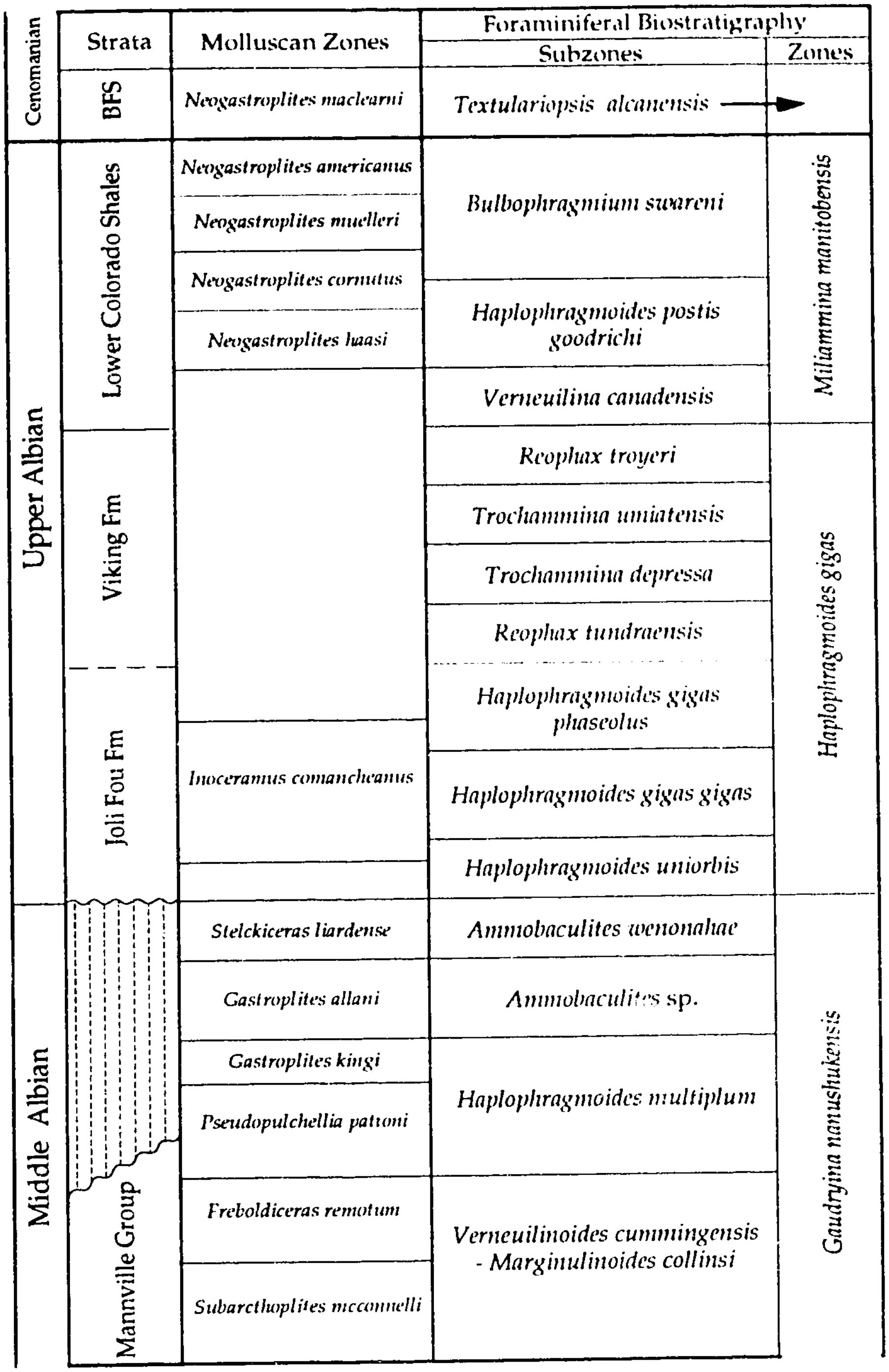


Figure X-3. Correlation of Molluscan Zones and Foraminiferal Zones/ Subzones within the Albian, and its relationship to the Joli Fou and Viking formations. BFS refers to the Base of Fish Scales Marker [modified from Stelck (1991) and Stelck (pers. comm., 1993)].

Walker, 1991; Pattison, 1991a; Walker and Davies, 1991; Walker and Boreen, 1991; MacEachern *et al.*, 1992b; Pemberton *et al.*, 1992a; Raychaudhuri *et al.*, 1992). Boreen and Walker (1991) and Pattison (1991a,b) have proposed a formal allostratigraphic framework for the Viking Formation (Figures X-4 and X-5, respectively), according to the rules of the North American Code of Stratigraphic Nomenclature (NACSN, 1983).

VIKING FORMATION TRANSGRESSIVE SYSTEMS TRACTS

A regional study of facies overlying the first major HE FS of the Viking Formation (VE3 of Boreen, 1989; *cf.* Figure X-4; VE3-1a of Pattison, 1991a; *cf.* Figure X-5) was undertaken to characterise the variety of deposits contained within an overall transgressive setting. Lags associated with the transgressive surfaces as well as sediments which accumulated under conditions of relative rising sea level are herein considered to be "transgressive deposits". These deposits are commonly interstratified with the distal equivalents of stillstand progradational deposits herein referred to as "transgressively-related deposits". Separation of the actual transgressive deposits from the interstratified transgressively-related intervals is not always practical and these related deposits are dealt with as part of the overall transgressive systems tract. Landward, these transgressively-related deposits may merge into stacked high energy parasequences (*e.g.* Giroux Lake; *cf.* Chapter VIII).

In this context, the facies successions observed in the upper Viking, although varying considerably between the different fields and locally within the same field, comprise a limited number of facies types (Facies A-F; *cf.* Tables X-1 to X-6), some of which are markedly intergradational. For the purposes of this paper, the thicker transgressive-stillstand parasequences are not discussed in this paper, although they are clearly elements of some transgressive systems tracts. Such deposits possess the characteristics of typical shorefaces and the reader is referred to MacEachern and Pemberton (1992), Pemberton and MacEachern (in press), and to Chapters IV and VIII. The integration of ichnology with sedimentology and sequence stratigraphy provides numerous insights into the nature of transgressive modification and subsequent depositional responses. Utilising ichnology aids in the recognition and delineation of the HE FS as well as differentiating active

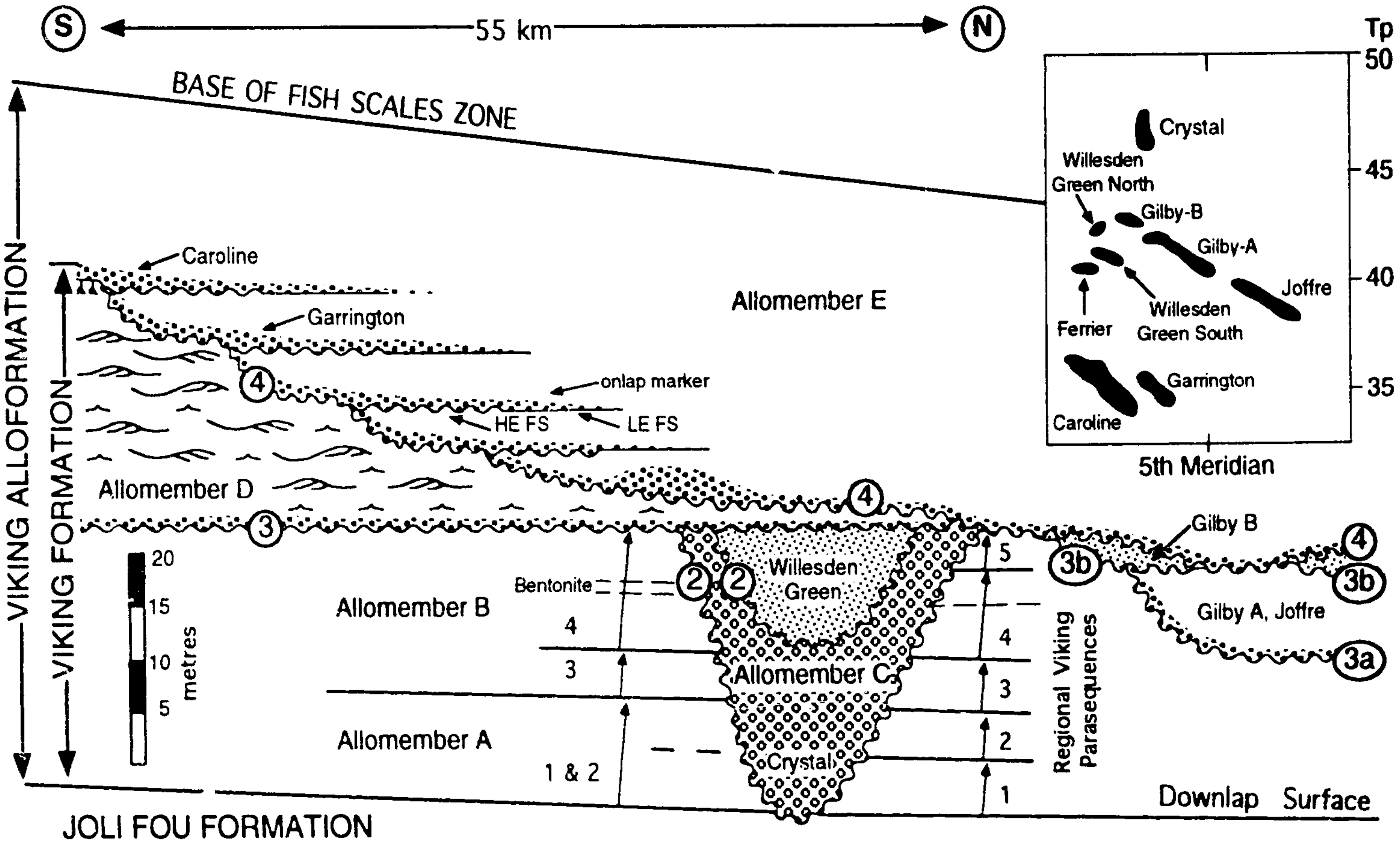


Figure X-4. Allostratigraphic framework proposed for the Viking Formation. The Viking Alloformation contains 5 Allomembers (A-E), separated from one another by regional discontinuities. The main discontinuities are VE2 (2), VE3 (3) and VE4 (4), with secondary erosion surfaces present as well. Figure modified after Boreen and Walker (1991).

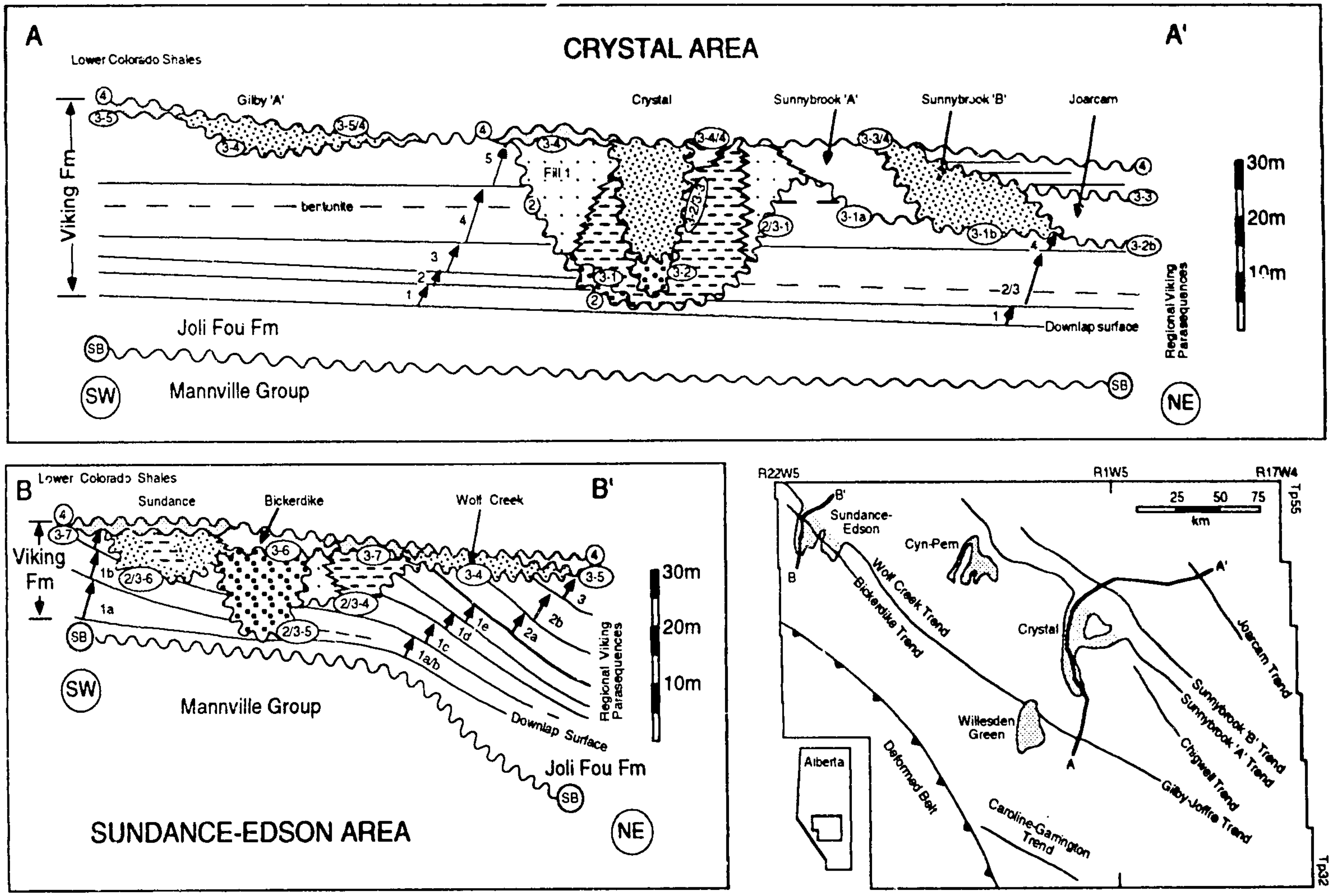


Figure X-5. Revised allostratigraphic framework for the Viking Formation by Pattison (1991a). The VE3 surface has been subdivided into 7 discrete surfaces (3-1 to 3-7). In addition, surfaces are locally amalgamated, designated by a backslash (*i.e.* 2/3-5). This second generation allostratigraphy highlights the complexity of the VE3 transgression in central Alberta. Figure modified after Pattison (1991a).

transgressive deposition from subsequent stillstand conditions. Ultimately, it may be possible to more accurately resolve the basin expressions of transgressive systems tracts from subsequent highstand systems tracts.

FACIES DESCRIPTIONS AND INTERPRETATIONS

Facies A: Moderately- to Poorly-Sorted, Polymictic Conglomerate Facies

Sedimentology

Facies A (Table X-1; Figure X-6) dominantly consists of an erosionally-based, clast-supported pebble conglomerate, but may locally occur as an intraformational rip-up clast-rich, coarse sandstone with rare chert pebbles. The conglomerate beds are generally 10-50 cm thick, although they may also occur as 1 cm thick veneers on erosion surfaces. Boreen (1989) and Boreen and Walker (1991) noted that some conglomerates in the Willesden Green area may occur up to 2.9 m thick, commonly localised into E-W trending bodies.

Clasts are of a variety of types, including chert (dominant) and other lithic fragments, mudstone (locally sideritic) rip-up clasts, winnowed intraformational siderite nodules, and rarer wood fragments, probably coalified *in situ*. B-axis imbrication is present locally, but is rare overall. Normal and inverse grading have been observed, although the former dominates (*e.g.* Hein *et al.*, 1986; Downing and Walker, 1988). Grain sizes range from granules to pebbles, commonly varying along the same mappable surface, and are typically 0.5-1.0 cm along the C-axis, although exceptionally large clasts reach 7 cm. Locally, the conglomerate contains shale interbeds (*e.g.* at Gilby, Raddysh, 1988; at Caroline-Garrington, Hein *et al.*, 1986; and at Crystal, Figure X-6 D, E).

The texture and sorting of the matrix is variable. It generally consists of moderately well-sorted, fine- to coarse-grained sand at the base, but commonly grades upwards into poorly-sorted muddy sand (Figure X-6 A,B). In many cases, Facies A grades upwards into Facies B (Figure X-6 F). Stratification is exceedingly rare except in thicker intervals, which typically show low to moderate angle (<20°) planar laminations.

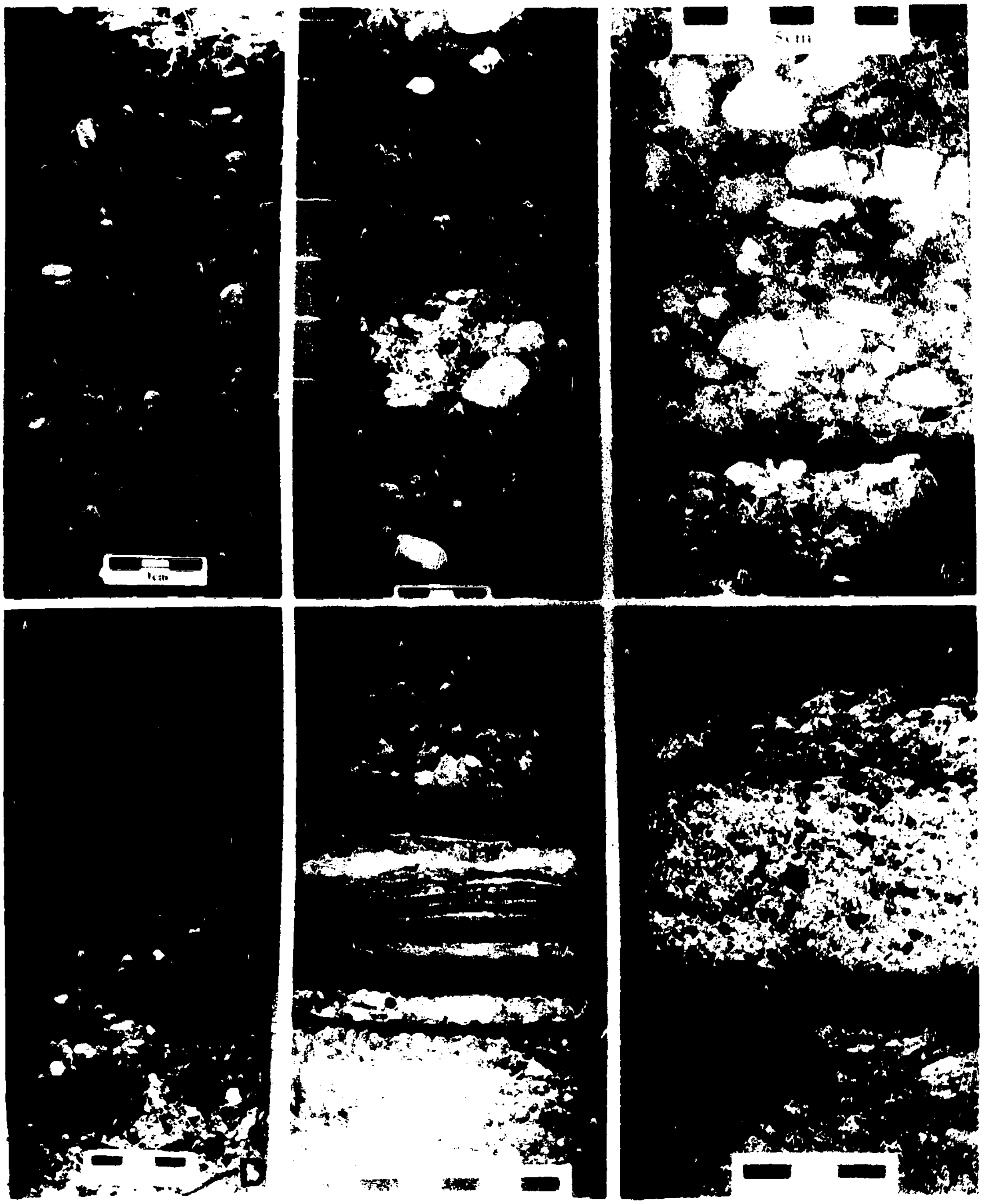
More rarely, the facies consists of medium- to coarse-grained sandstones with abundant subangular to subrounded sideritic shale fragments, coalified

Facies A: Moderately- to Poorly-Sorted, Polymictic Conglomerate Facies: Transgressive Lag

Reference	Field	Facies Designation
Power, 1988	Joarcam	No lag developed.
Posamentier and Chamberlain, 1991	Joarcam	No designation.
Reinson *et al.*, 1988	Crystal	Conglomeratic or granule layer.
Raychaudhuri, 1989	Chigwell	Facies 6c.
Pattison, 1991a	Crystal, Sundance, Edson, Cyn-Pem	Massive conglomerate of FA 10.
Downing and Walker, 1988	Joffre	Pebbles veneering CM5, E1, and E3.
Raddysh, 1988	Gilby A+B	Facies J; some Facies I.
Cox, 1991	Blood (Bow Island)	Conglomerate at base of Transgressive FA.
Boreen and Walker, 1991	Willesden Green	Lags mantle VE3, + VE4.
Hein *et al.*, 1986	Caroline, Garrington, Harmattan East	Mainly Facies 7; minor Facies 3, 4, 5 + 6.
Leckie, 1986	Caroline	Facies 3, Facies 5.
Davies, 1990	Caroline, Garrington	Some Facies 6, especially above VE3 and VE4.

Table X-1. Facies A: Equivalents of other workers.

Figure X-6. Facies A: Moderately- to Poorly-Sorted Polymictic Conglomerate Facies. (A) Conglomerate, with a sandy matrix grading into a muddy sand matrix. Willesden Green Field, 14-20-40-06W5, depth 2249 m. **(B)** Conglomerate, with a sandy matrix at the base passing into muddy matrix upwards. Joffre Field, 02-21-38-26W4, depth 1582.6 m. **(C)** Well-sorted, coarse polymictic pebble conglomerate. Bow Island Formation, Blood Field, 06-16-06-22W4, depth 987.2 m. **(D)** Conglomerate with a muddy Facies B interbed, containing medium-grained sand-filled *Skolithos*. Kaybob Field, 10-24-61-19W5, depth 1776.2 m. **(E)** Facies C interbedded with conglomerate. Crystal Field, 10-06-46-03W5, depth 1736.7 m. **(F)** Conglomerate grading upward into pebbly sandy shale (Facies B). Windfall Field, 07-03-60-15W5, depth 1652 m.


1cm
5cm
b

wood fragments, abundant carbonaceous detritus and dispersed subrounded to rounded chert pebbles. These units display vague low angle to horizontal stratification.

Ichnology

The conglomerates themselves are devoid of trace fossils; where the matrix becomes muddy, *Terebellina*, *Planolites*, *Teichichnus*, *Palaeophycus*, and *Thalassinoides* are locally visible in low abundances (Figure X-6 D). Raddysh (1988) also noted vertical shafts (*Skolithos*?) associated with laminated mudstones interstratified with the conglomerates of the Gilby field area.

Interpretation of Facies A

The conglomerate facies is interpreted as a transgressive lag, reflecting transgressive excavation or transgressive reworking of a discontinuity (*cf.* Table X-1). The facies typically mantles major VE3 and VE4 discontinuities, as well as many of the less regional intra-Viking Formation HE FS within virtually every field area. Well-sorted pebble conglomerate layers indicate well-developed winnowing. Where thicker conglomerates occur, waning energy conditions are reflected by progressively poorer sorting of the matrix upwards. The presence of intraformationally-derived material supports a genetic affinity between erosion of the substrate and emplacement of the conglomerate.

The gradational transition into muddy conglomerates as well as into the pebbly and sandy shale of Facies B, suggests a progressive decrease in energy operating near the sediment-water interface. The presence of firmground trace fossil assemblages (*i.e.* the *Glossifungites* ichnofacies) colonising the erosional discontinuity beneath the conglomerate veneers at some localities (*e.g.* Kaybob, Joffre, Gilby, Willesden Green, Fox Creek, *etc.*) demonstrates the existence of a depositional hiatus between the eroding event and final lag emplacement as well as the existence of marine conditions prior to final lag emplacement (*cf.* MacEachern *et al.*, 1990; 1991a,b; 1992b; Pemberton *et al.*, 1992a).

The mechanism of supplying the pebbles to the depositional site remains highly conjectural, posing considerable difficulties in the interpretation of the genesis of the discontinuity. The widespread nature of the lags and the locally large clast sizes imposes serious constraints on the nature of the transport mechanism, particularly where deposition occurred seaward of fairweather wave base. One possibility is that the lags are the result of winnowing of upper shoreface, foreshore and backshore deposits of the Viking shoreline systems during erosive shoreface retreat. The facies of these environments are rarely preserved in the Viking and as a result, the character of the deposits are unknown. Nonetheless, the sediments of the lower and middle shoreface are considerably finer-grained, and this would imply a profound increase in sediment grain size in the nearshore zone. A winnowing mechanism also does not explain the presence of conglomerate lags overlying discontinuities excavated into facies deposited seaward of fairweather wave base. Purely transgressive erosion surfaces generated in open marine settings are associated with wave ravinement, limited to depths above fairweather wave base. The presence of lags seaward of this would require subsequent basinward transport of the pebbles by storm events or sediment gravity flows.

A second possibility is that the most substantial lags may have initially been deposited during lowstand conditions, and hence, demonstrates the presence of a sequence boundary (SB). The pebble-filled ichnogenera of the *Glossifungites* ichnofacies indicates that either the SB was excavated under marine conditions (*e.g.* a forced regression; *cf.* Plint, 1988; Posamentier *et al.*, 1992; Chapters III and VIII), or that lowstand conglomerates were subsequently reworked during transgression, producing an amalgamated sequence boundary and marine flooding surface (FS/SB). Firmground colonisation of the FS/SB would have to have occurred during transgressive modification of the lowstand lag in order for the discontinuity to be exposed to the tracemakers.

The scenario of a transgressively-modified sequence boundary is the most favoured interpretation, due to the combination of such features as the widespread distribution of the lags, the large clast sizes, the well-winnowed character of the basal portions of the lags, and the genetic association (gradational contacts) with transgressive deposits (*e.g.* Facies B). Whether the pebbles are transported basinward by lowstand-induced mechanisms or not, the final emplacement of the conglomerate mantling the discontinuity reflects a transgressive lag, independent of the genesis of the erosion surface.

Facies B: Pebbly Muddy Sandstones and Sandy Shale Facies

Sedimentology

The basal contact of Facies B (Table X-2; Figure X-7) is typically sharp and erosional, unless it overlies Facies A with which it is generally gradational (Figure X-6 F). Sharp-based Facies B units commonly contain relatively abundant dispersed pebbles along the erosional contact.

The main body of the facies consists of fine- to very fine-grained sandstones, siltstones and shales, interstratified on a millimetre to centimetre scale. The proportion of sand, silt and shale is highly variable. Sandstone and siltstone interbeds display wavy (undulatory) low angle (<15°) parallel laminations and combined flow ripple laminae. Rare current ripple lamination has also been documented (*e.g.* Raychaudhuri, 1989). Most primary stratification is preserved as remnants within a moderately to intensely burrowed fabric.

Lower medium- (mL) to upper very coarse-grained (vcU) sands, granules, and chert and lithic pebbles are disseminated throughout the interstratified portion of the facies, giving it a speckled or gritty "salt and pepper" appearance. Dispersed pebbles may reach 5.5 cm in diameter, but are typically <3 cm. Such pebbles appear to be matrix-supported, but this may be an artifact of biogenic activity. Leckie (1986), however, recognised some mud-supported clasts with preserved imbrication at Caroline, suggesting some intervals are primary. Bentonite beds and sideritic shale horizons are commonly intercalated as well.

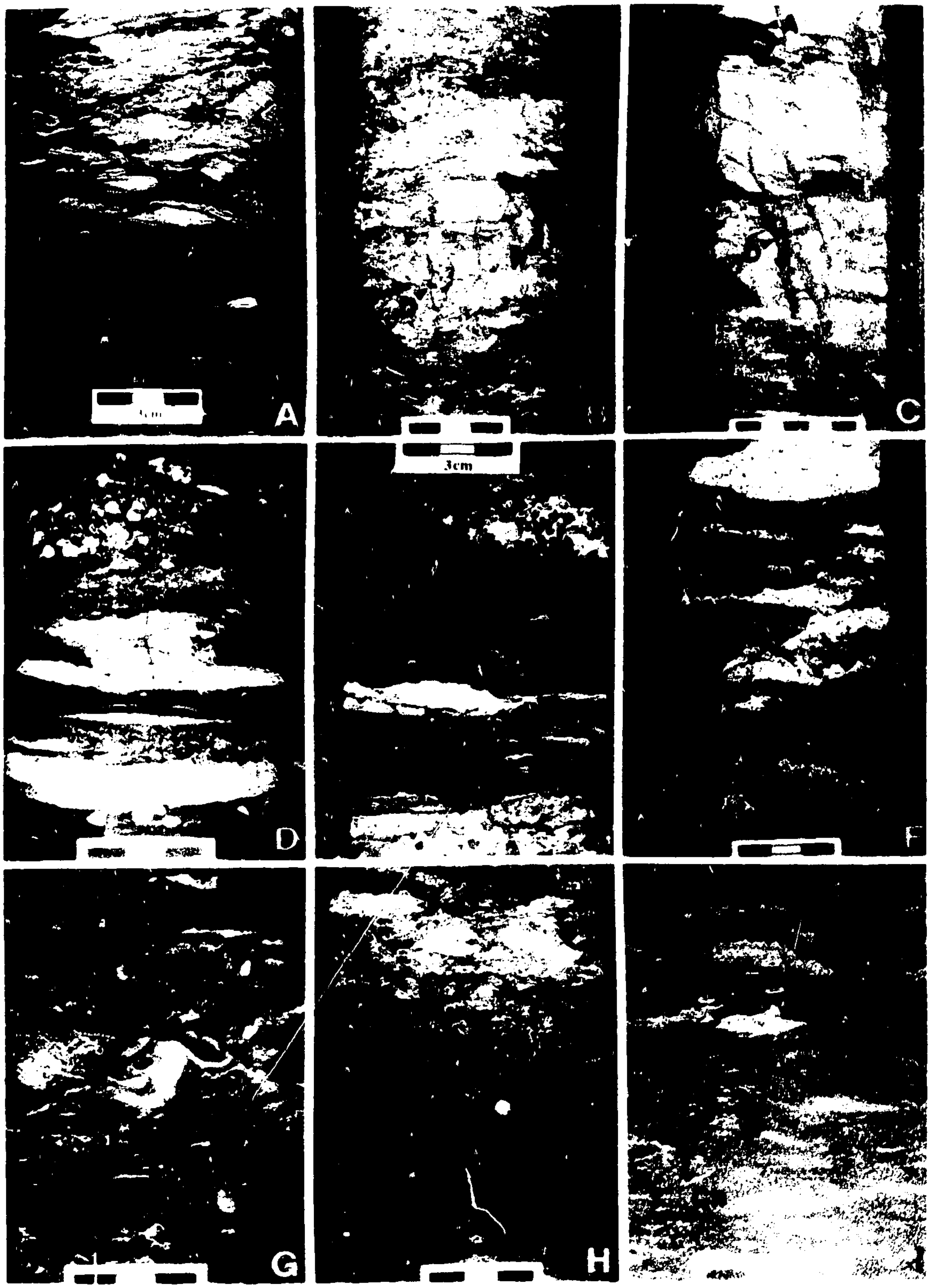
Interbedded with the main body of the facies are sharp-based, thin (10-20 cm), lower to upper medium-grained (mL-mU), "salt and pepper" sandstone beds with allochthonous vitrinitic coal fragments, sideritic shale rip-up clasts, and organic detritus (finely comminuted plant debris). Pyrite and glauconite are present as minor constituents. Primary structures are dominated by trough cross-stratification, with lesser massive (apparently structureless) intervals and low angle parallel laminated beds. More rarely, thin conglomerates are also intercalated. These beds are typically <5 cm in thickness, although in the Caroline area, they are 5-30 cm thick (Leckie, 1986; Hein *et al.*, 1986). Some beds are normally graded and show very rare B-axis imbrication. These units are interbedded within Facies B on a decimetre to metre scale and may reflect an affinity with Facies F.

Facies B: Pebbly Muddy Sandstone and Sandy Shale Facies: Distal Ravinement Deposits

Reference	Field	Facies Designation
Power, 1988	Joarcam	Bioturbated muddy sandstone and interbedded mudstone and coarse sandstone of Member D.
Posamentier and Chamberlain, 1991	Joarcam	No designation, included in FA Member C.
Reinson *et al.*, 1988	Crystal	No designation.
Raychaudhuri, 1989	Chigwell	Facies 7c.
Pattison, 1991a	Crystal, Sundance, Edson, Cyn-Pem	Bioturbated sandy mudstones of FA 10.
Downing and Walker, 1988	Joffre	Upper portions of CM5 and E3.
Raddysh, 1988	Gilby A+B	Facies G; Facies J.
Cox, 1991	Blood (Bow Island)	No designation.
Boreen and Walker, 1991	Willesden Green	Bioturbated gritty mudstone facies and pebbly mudstone facies of FA5.
Hein *et al.*, 1986	Caroline, Garrington, Harmattan East	Included in Facies 10A.
Leckie, 1986	Caroline	Facies 3.
Davies, 1990	Caroline, Garrington	Some Facies 8 of Allomember E.

Table X-2. Facies B: Equivalents of other workers.

Figure X-7. Facies B: Pebbly Muddy Sandstone and Sandy Shale Facies. **(A)** Thoroughly burrowed muddy sandstone with *Zoophycos* (Z) and *Subphyllochorda* (Su). Giroux Lake Field, 10-05-66-21W5, depth 1368.3 m. **(B)** Pebbly and muddy sandstone with abundant *Diplocraterion* (D) and *Rosselia* (R). Joffre Field, 12-26-38-26W4, depth 1541.0 m. **(C)** Thoroughly burrowed muddy sandstone with *Diplocraterion* (D), *Asterosoma* (A), *Rosselia* (R) and *Planolites*. Kaybob South Field, 07-19-62-19W5, depth 1654 m. **(D)** Pebbly sandy shale with a few distal storm sandstone beds. Interval is largely unburrowed, atypical of other Facies B intervals. Caroline Field, 16-28-33-5W5, depth 2530 m. **(E)** Pebble stringers in weakly burrowed sandy shale. *Planolites* (P) and *Chondrites* are present. Kaybob South Field, 07-19-62-19W5, depth 1653.3 m. **(F)** Intensely burrowed sandy shale with dispersed pebbles. Traces include *Teichichnus* (Te), *Palaeophycus* (Pa), *Thalassinoides*, *Terebellina* (T) and *Planolites*. Windfall Field, 07-03-60-15W5, depth 1652.4 m. **(G)** Thoroughly burrowed sandy shale with dispersed pebbles, and *Planolites*, *Helminthopsis* (H), *Zoophycos*, *Terebellina*, *Chondrites* (Ch), *Rosselia* (R), *Diplocraterion* (D), and *Palaeophycus* (Pa). Kaybob South Field, 07-19-62-19W5, depth 1652.8 m. **(H)** Gritty sandy shale, thoroughly burrowed with *Planolites* (P), *Asterosoma* (A), *Helminthopsis* (H) and *Zoophycos* (Z). Kaybob South Field, 11-27-62-20W5, depth 1662.4 m. **(I)** Sand-poor shale with *Terebellina* (T), *Chondrites* (Ch), *Thalassinoides* (Th) (reburrowed), *Planolites* and *Helminthopsis* (H). Note the dispersed medium to coarse sand grains. Kaybob South Field, 11-27-62-20W5, depth 1658.0 m.



A
3cm
B
C
D
E
F
G
H

Facies B units may be subdivided into two subfacies, largely reflecting the degree of burrowing. The pebbly mudstone facies of Boreen and Walker (1991) appears to be predominantly unburrowed and is characterised by pebble stringers within a dark shale (Figure X-7 D, E). This "subfacies" is rare, except in the Willesden Green, Caroline, Garrington, Harmattan East areas, where it overlies VE4. It is possible that this subfacies of Facies B may be more genetically related to Facies E than with the more typical Facies B.

The dominant aspect of Facies B is pervasive burrowing. It is widespread throughout the Viking Formation in the northeast and southeast portion of the study area (Figure X-1), though relatively uncommon in the southwest portion of Alberta, where it occurs as thin units (<20 cm) in Allomember E (above VE4; *cf.* Figures X-4 and X-5). In these localities, it contrasts markedly with the largely unburrowed appearance of the associated facies (*cf.* Boreen and Walker, 1991). To the north and east (*e.g.* Sundance, Edson, Kaybob, Fox Creek, Giroux Lake, Judy Creek, and Waskahigan areas), Facies B is a common element to the facies associations above VE3, and is typically interstratified with all other facies; it possesses erosional basal contacts with all other facies except Facies A. Commonly, Facies B also grades upwards into Facies C. Less commonly, the sand content is such that the facies is a bioturbated muddy sandstone containing dispersed pebbles, rip-up clasts and intraformationally-derived siderite nodules (Figure X-7 A-C).

Ichnology

The burrowed version of the facies shows an ichnofabric index of 4 to 5 (*i.e.* ii4-ii5; Figure X-8; *cf.* Droser and Bottjer, 1986, 1989, 1991). The high degree of bioturbation commonly obscures the individual biogenic structures, making identification of ichnogenera difficult (Figure X-7 A-H). Several units, particularly thin intervals, are pervasively bioturbated, producing a mottled sandy shale lacking discrete biogenic structures.

The softground suite is dominated by deposit-feeding structures, containing abundant *Terebellina* and *Planolites*, common *Chondrites*, small *Asterosoma*, common to rare *Teichichnus*, *Cylindrichnus*, small, but locally robust *Rosselia* and *Siphonichnus*. The assemblage also contains subordinate amounts of grazing/foraging structures, such as *Helminthopsis* and *Zoophycos*, which become more abundant as the facies becomes shalier (Figure X-7 G-I). The assemblage reflects the *Cruziana* ichnofacies.

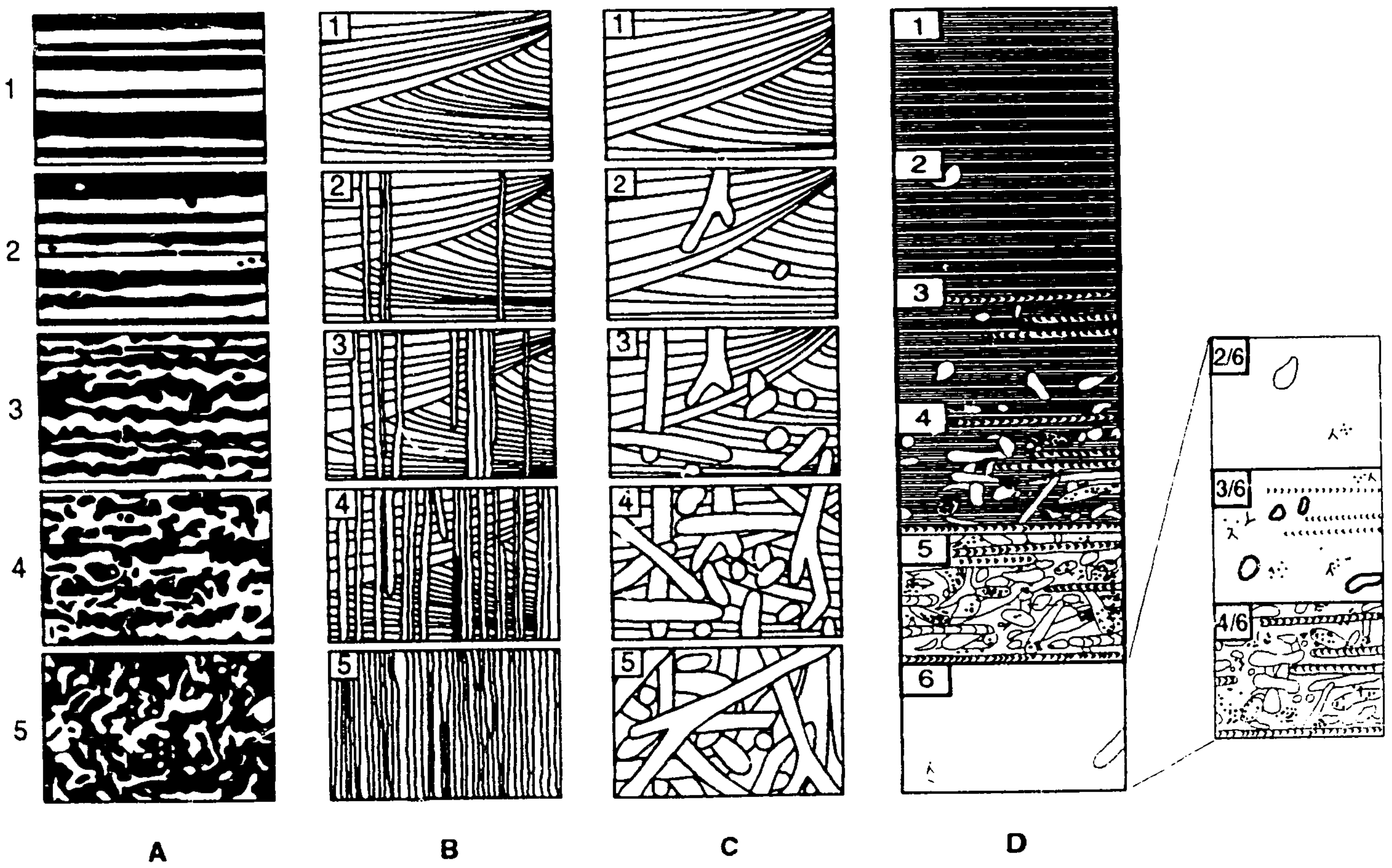


Figure X-8. Quantified ichnofabric indices of bioturbation. **(A)** for thin-bedded strata. **(B)** for thick-bedded strata dominated by *Skolithos*. **(C)** for thick-bedded strata dominated by *Ophiomorpha*. **(D)** for fine-grained, deep-water environments. (Modified from Droser and Bottjer, 1986, 1989, 1991).

Softground suspension feeding *Diplocraterion* burrows are present in small numbers, as are passive carnivore dwelling structures such as *Palaeophycus*.

The relatively rarer muddy sandstone version of Facies B is generally pervasively burrowed, and contains abundant *Ophiomorpha, Palaeophycus, Subphyllochorda, Rosselia* and *Planolites*, with rarer *Teichichnus* and *Terebellina* (Figure X-7 A-C). For the most part, the muddy sandstone reflects opportunistic colonisation (mainly with *Ophiomorpha* and *Diplocraterion*), succeeded by a resident community (*cf.* Pemberton *et al.*, 1992b).

Interpretation of Facies B

Facies B is interpreted to have been deposited in a lower to upper offshore setting, associated with distal storm events and perhaps weak rotary tidal currents (*cf.* Facies F). The fully marine character is indicated by the high diversity of ichnogenera. The intensity of bioturbation may partly reflect the overall wave climate (*cf.* MacEachern and Pemberton, 1992); low wave energy with infrequent storm events favours more thorough biogenic reworking of the interbedded sandstone, siltstone and shale portion of the facies.

The gradational relationship between Facies B and the transgressive lag (Facies A), the erosional basal relationship with all other facies, and the common association of *Glossifungites* suites with the erosional contact, supports a genetic, possibly waning energy and/or distal association with the transgressive ravinement process. Coarse material is presumably transported basinward by storms, submarine debris flows and/or sediment gravity flows during erosive shoreface retreat. The greater abundance of pebbles near the base of Facies B is consistent with this interpretation. The "salt and pepper" speckled or gritty appearance of the unit, caused by dispersed coarse sand, granules and pebbles, reflects biogenic homogenization of thin stringers of this material. Few deposit feeding organisms are capable of manipulating pebbles, but such material can be disturbed and shifted sideways, downwards and, to a lesser degree, upwards, by virtually all infaunal organisms (Hanor and Marshall, 1971). Nonetheless, the presence of some pebbles and granules throughout Facies B suggests a continued, though upward diminishing supply of such material, consistent with a progressively more distal position from the zone of active transgressive erosion. The common gradational transition from Facies B to Facies C, and more rarely, Facies D and E, supports this relationship. Original emplacement of pebbles may reflect initial lowstand conditions as in Facies A, but the final deposition of the facies corresponds to transgressive reworking of this material.

Discrete sandstone and conglomerate beds, interstratified with Facies B are interpreted as storm-related event deposits (tempestites), cannibalised from the landward pebble lag veneering the transgressive discontinuity and transported basinward to the lower and upper offshore in the northeast and the shelf in the southwest. Reworking by tidal currents, possibly storm-enhanced, may account for the current-generated structures observed in the coarse sandstone beds. Relatively thick units or rapid burial may have served to protect these beds from the more intense biogenic reworking in the finer sandstone and siltstone layers of the facies.

Leckie (1986) and Hein *et al.* (1986) favoured submarine debris flows as a means of transporting this coarse detritus basinward in the Caroline-Garrington-Harmattan East area. The initiating mechanism of the debris flows required to transport the conglomeratic and granule sandstones into the shelf environment is problematic, although a storm influence or tectonic influence cannot be ruled out.

Facies C: Interbedded Fine-Grained Sandstone and Shale Facies

Sedimentology

Facies C (Table X-3; Figures X-9 and X-10) is a highly variable interval and commonly grades from Facies B, and into Facies D. Locally, it may be erosionally overlain by Facies A or Facies B.

The sandstone content of Facies C varies considerably. The facies consists of fine- to very fine-grained sandstones, siltstones and shales, interbedded on a variety of scales. The sandstone beds are sharp-based, commonly show normal grading and/or burrowed tops, and are typically <5 cm thick. Locally, they constitute up to 30 cm thick sets of erosionally amalgamated sandstone beds. Sandier intervals contain more abundant and thicker amalgamated beds than shalier intervals.

Preserved primary sedimentary structures are dominated by wavy, undulatory parallel laminae of low angle (<15° and generally <10°) (Figure 9A-D), although subordinate amounts of combined flow ripple laminae, oscillation ripple laminae and rarer current ripple laminae are also present, and dominate in shalier Facies C (Figure X-10). Wavy parallel laminae,

Facies C: Fine-Grained Sandstone and Shale Facies: Stillstand Progradation Deposits

Reference	Field	Facies Designation
Power, 1988	Joarcam	Interbedded siltstone and mudstone facies of Member C+D.
Posamentier and Chamberlain, 1991	Joarcam	FA Member C.
Reinson *et al.*, 1988	Crystal	Interlaminated sandstone and mudstone facies.
Raychaudhuri, 1989	Chigwell	Facies 7a.
Pattison, 1991a	Crystal, Sundance, Edson, Cyn-Pem	Striped mudstone facies of FA10.
Downing and Walker, 1988	Joffre	Some Facies 4 of FA4 and FA5.
Raddysh, 1988	Gilby A+B	Facies D.
Cox, 1991	Blood (Bow Island)	Included in dark grey shale facies of Transgressive FA.
Boreen and Walker, 1991	Willesden Green	Burrowed/laminated sandstone and mudstone facies of FA4.
Hein *et al.*, 1986	Caroline, Garrington, Harmattan East	Facies 8a and 8b in FA1; associated with facies 10a.
Leckie, 1986	Caroline	No designation- not present.
Davies, 1990	Caroline, Garrington	Facies 2 of Allomember D.

Table X-3. Facies C: Equivalents of other workers.

Figure X-9. Facies C: Interbedded Fine-Grained Sandstone and Shale Facies - Sandy Subfacies. (A) Weakly burrowed, wavy parallel and combined flow rippled sandstone, with fugichnia (fu), *Planolites* (P) and *Zoophycos* (Z). Joarcam Field, 16-12-48-21W4, depth 972.5 m. **(B)** Largely unburrowed, oscillation and combined flow rippled sandstone with *Siphonichnus* (Si), interbedded with biogenically-mottled sandstone and shale containing *Planolites, Palaeophycus, Zoophycos* (Z) and *Teichichnus* (Te). Kaybob Field, 02-28-63-20W5, depth 1560 m. **(C)** Combined flow ripple laminated sandstone bed, interstratified with thoroughly burrowed sandy shale containing *Siphonichnus, Planolites* (P), *Zoophycos* (Z) and *Teichichnus* (Te). Joarcam Field, 10-04-48-20W4, depth 974.3 m. **(D)** Amalgamated oscillation ripple and combined flow ripple laminated sandstone bed with escape traces (f), lined *Skolithos* (Sk) and *Palaeophycus* (Pa). Joarcam Field, 16-12-48-21W4, depth 972.2 m. **(E)** Intensely burrowed muddy sandstone with *Terebellina* (T), *Siphonichnus* (Si), *Planolites, Teichichnus* (Te) and *Palaeophycus* (Pa). Waskahigan Field, 10-30-65-22W5, depth 1440.8 m. **(F)** Intensely burrowed muddy sandstone with *Terebellina* (T), *Planolites, Subphyllochorda* (Su), *Zoophycos* (Z), *Teichichnus* (Te) and *Chondrites*. Waskahigan Field, 10-30-65-22W5, depth 1440.1 m.

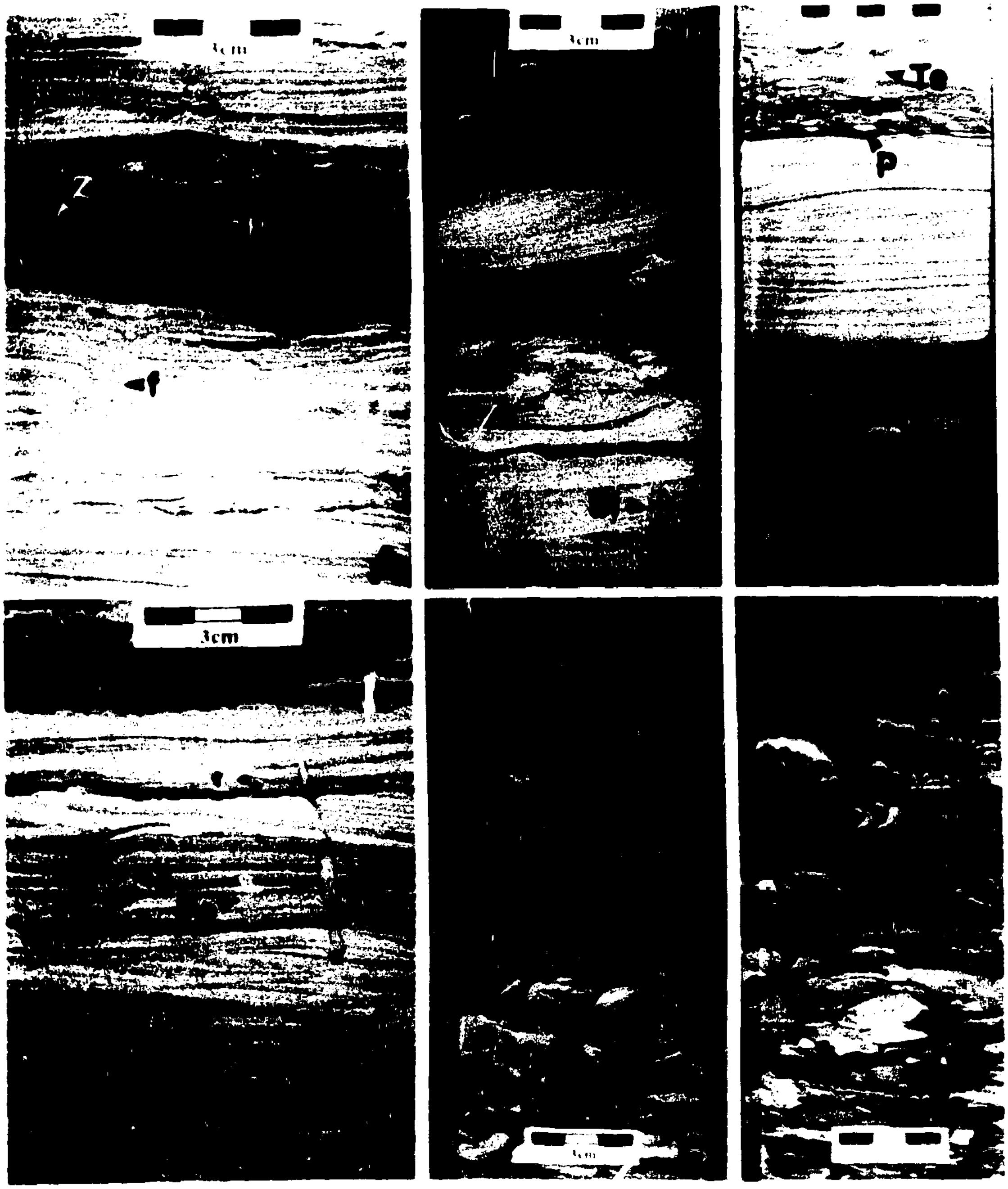
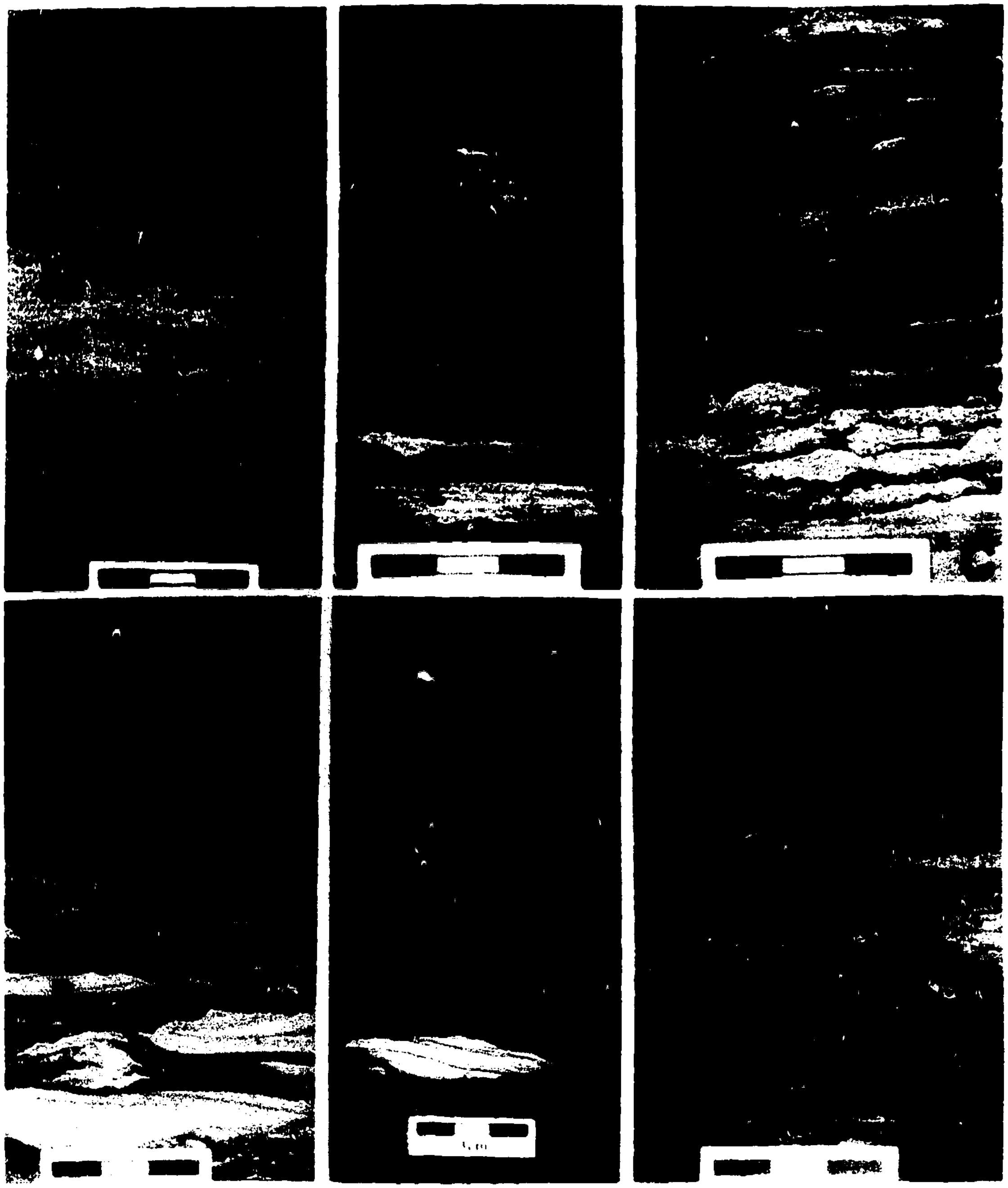

3cm
Z
f
3cm
Te
P
3cm
3cm

Figure X-10. Facies C: Interbedded Fine-Grained Sandstone and Shale Facies - Shaly Subfacies. **(A)** Moderately burrowed, oscillation rippled sandstone containing *Palaeophycus* (Pa) and *Siphonichnus* (Si). Joarcam Field, 16-12-48-21W4, depth 972.7 m. **(B)** Weakly burrowed, wavy parallel laminated sandstones and silty shales with *Lockeia* (L) and *Siphonichnus* (Si). Kaybob North Field, 02-28-63-20W5, depth 1552.5 m. **(C)** Weakly to moderately burrowed interval, with *Planolites* (P), *Siphonichnus* (Si). Kaybob South Field 02-28-63-20W5, depth 1552.5 m. **(D)** Moderately to intensely burrowed interval, with *Teichichnus* (Te), *Zoophycos* (Z), *Terebellina, Siphonichnus* and *Planolites* (P). Joarcam Field, 16-12-48-21W4, depth 973.9 m. **(E)** Intensely burrowed sandy shale, with remnant oscillation ripple laminated sandstones. Trace fossils are *Planolites, Siphonichnus, Helminthopsis* (H), *Chondrites* (Ch) and *Terebellina* (T). Waskahigan Field, 10-30-65-22W5, depth 1442.1 m. **(F)** Intensely burrowed sandy shale, with distal, normally graded storm beds. Trace fossils are *Zoophycos* (Z), *Teichichnus* (Te), *Planolites, Chondrites* and *Helminthopsis* (H). Kaybob South Field, 07-19-62-19W5, depth 1651.5 m.



particularly those that contain upward convex laminations, are interpreted to reflect distal hummocky cross-stratification (HCS); amalgamated intervals are dominated by upward concave laminae infilling scours and are interpreted to reflect thin swaley cross-stratified (SCS) beds. The sandstones are interstratified on a centimetre to decimetre scale, whereas the amalgamated beds are more commonly intercalated on a decimetre to metre scale.

As in Facies B, very coarse-grained sandstones and pebbly sandstone beds, typically <5 cm but locally up to 30 cm, are intercalated on a decimetre to metre scale. Chert pebble conglomerates are rare and <15 cm in thickness. These coarse-grained units are commonly massive (apparently structureless) but may show small-scale trough cross-stratification and low angle parallel stratification locally. Rip-up clasts, sideritic shale bands (typically <10 cm in thickness), pyrite nodules, sideritic nodules, organic detritus, allochthonous wood fragments (coalified *in situ*), shell fragments, glauconite and very rare syneresis cracks are all notable constituents of this facies. Bentonites are locally interbedded as well. Dispersed pebbles and granules are locally present, but far less common than in Facies B; these are more abundant in Facies C units which grade out of Facies B.

Ichnology

Facies C is generally less intensely burrowed than Facies B, and has an ichnofabric index ranging from 2 - 4 (Figure X-8; *cf.* Droser and Bottjer, 1986, 1989, 1991), although rare intervals reach ii5 (Figure X-9 E, F). As a result of this lowered degree of burrowing, individual ichnogenera are readily recognised. Softground trace fossils are dominated by deposit-feeding and related structures, typified by abundant *Planolites*, *Teichichnus*, common to moderately abundant *Asterosoma*, *Chondrites*, *Terebellina*, and moderately abundant to rare *Cylindrichnus*, *Siphonichnus*, *Rhizocorallium*, *Subphyllochorda* and *Thalassinoides* (Figure X-10). Grazing/foraging structures are also associated, and consist of abundant *Helminthopsis*, moderate numbers of *Zoophycos* and rare occurrences of *Anconichnus horizontalis* (Figure X-10 D-F). Suspension feeding behaviour is reflected by relatively rare, lined *Diplocraterion* and *Skolithos*, although a single example of *Arenicolites* was also noted; these structures are largely restricted to the thicker sandstone beds. Thicker storm beds commonly contain escape traces (fugichnia), recording the attempt of organisms entrained within the flow or buried by the tempestite, to reach the new sediment-water interface (Figure X-9 A, D). *Lockeia*, a pelecypod resting trace and *Palaeophycus*, the dwelling structure of a passively predaceous annelid, are moderately abundant. The suite corresponds to the *Cruziana* ichnofacies, with some elements of the *Skolithos* ichnofacies recording opportunistic colonisation of the HCS beds (*cf.* Pemberton and Frey, 1984; Frey, 1990; Pemberton *et al.*, 1992b; Chapter IV).

The softground suite does not vary significantly with changes in the burrowing intensity, numbers of individual forms may be lower, but the observed diversity remains reasonably high. Exceptions are Facies C units which are encased in thick Facies D or E, lying above VE4. These units typically show low burrow intensities and mainly contain *Planolites, Asterosoma, Teichichnus, Lockeia, Siphonichnus* and rare *Skolithos. Chondrites, Helminthopsis, Cylindrichnus* and *Terebellina* are rare or absent.

In contrast, sandy intervals of Facies C (Figure X-9) typically contain the abundant suspension-feeding, passive carnivore dwelling, and escape structures, reflecting their affinity for the colonisation of storm beds (*cf.* Frey, 1990; Pemberton *et al.*, 1992a,b). Shaly intervals of Facies C (Figure X-10) are dominated by deposit-feeding structures, such as *Planolites, Terebellina, Chondrites* and rare *Asterosoma. Helminthopsis* comprises the main foraging/grazing element in these units although *Zoophycos* and *Anconichnus horizontalis* remain minor constituents.

In addition to the softground assemblage, many Facies C intervals contain a cross-cutting firmground assemblage of trace fossils (the *Glossifungites* ichnofacies), related to the development and colonisation of overlying erosional discontinuities (*cf.* Pemberton and Frey, 1985; MacEachern *et al.*, 1990; 1991a,b, 1992b; Pemberton *et al.*, 1992a). These structures have been identified by other researchers, but predominantly ascribed to the softground suite (*e.g.* Downing and Walker, 1988; Boreen, 1989; Boreen and Walker, 1991; Davies, 1990). The trace fossils of the *Glossifungites* assemblage are robust, largely suspension-feeding structures, which are passively infilled with medium- to coarse-grained sandstone from the overlying units. The main ichnogenera are *Diplocraterion* (*D. habichi* routinely misidentified as *Arenicolites*), *Skolithos* and *Arenicolites*. In addition, robust firmground *Thalassinoides* are locally present. These structures clearly post-date the deposition of Facies C and record conditions at the time of erosional exhumation along a discontinuity, such as a transgressive erosion surface or an FS/SB (see below). As such, these structures should not be employed in the environmental interpretation of Facies C (*cf.* MacEachern *et al.*, 1990; 1991a,b; 1992b).

Interpretation of Facies C

Facies C is interpreted to record deposition in open marine offshore to distal lower shoreface conditions, in a moderately to highly storm-dominated setting (*cf.* MacEachern and Pemberton, 1992; Chapters IV and V). Most sandstone beds are interpreted to reflect fairly distal storm event beds and their waning flow deposits. Sand-dominated Facies C intervals, containing thicker amalgamated tempestites record distal lower shoreface conditions, whereas shalier portions correspond to more distal upper offshore conditions.

The intensity of burrowing is interpreted to reflect a combination of enhanced storm intensity, storm frequency and sedimentation rate, rather than a change in water chemistry, distance from shore, or nature/abundance of infauna (*cf.* Pemberton and Frey, 1984; Pemberton *et al.*, 1992b; MacEachern and Pemberton, 1992). The maintained diversity in less intensely burrowed intervals supports this interpretation. Thicker storm beds are generally less burrowed internally, commonly possess burrowed tops, and are encased in more intensely burrowed interbedded sandstone and shale. This "laminated to burrowed" (Howard, 1971) or "Lam-Scram" (Frey, pers. comm., 1991) aspect is a characteristic feature of tempestite deposition in shallow marine settings (*cf.* Chapter VII), reflecting storm bed emplacement, opportunistic colonisation, and progressive replacement by fairweather resident assemblages (*cf.* Pemberton *et al.*, 1992b; Chapter IV).

Davies (1990) described a virtually identical facies (his Facies 2 of Allomember D) in the Caroline-Garrington area, which grades upwards into a storm-dominated lower to middle shoreface, consisting of HCS beds overlain by erosionally amalgamated SCS beds. This close association supports the upper offshore to distal lower shoreface interpretation in the comparable Facies C.

The presence of coarse clastic beds and the rare dispersed pebbles are assigned the same interpretation as those in Facies B; the decrease in abundance and thickness and abundance may reflect increased distance from, or decreased rate of transgressive erosion. Storm events and/or sediment gravity flows(?) may also serve to shift these coarse clastics basinward (Leckie, 1986; Hein *et al.*, 1986; Boreen, 1989) although the initiating mechanism(s) remains problematic.

Facies C is an exceedingly common facies in the northeast and southeast portion of the study area, where they probably correspond to the distal portions of short-lived stillstand shorefaces developed on the various VE3 transgressive erosion surfaces (Pattison, pers. comm., 1992). Fining upward of the facies, and particularly, the gradation into Facies D and E, record progressive deepening and transgression of the stillstand shoreface. Facies C is rare to the southwest, except where it constitutes the base of Allomember D, above VE3 (Davies, 1990). It is largely absent above VE4; post-VE4 sediments form the bulk of the preserved transgressive deposits in the Caroline-Garrington-Harmattan East area.

Facies D: Pinstripe-Bedded Sandstone, Siltstone and Shale Facies

Sedimentology

Facies D (Table X-4; Figure X-11) is intergradational between Facies C and Facies E, making the delineation of the boundaries subjective. The facies records a regular interbedding of very fine- to fine-grained (vf-f) sandstones and siltstones, encased in shales of variable silt content. This interbedding occurs on a millimetre to centimetre scale.

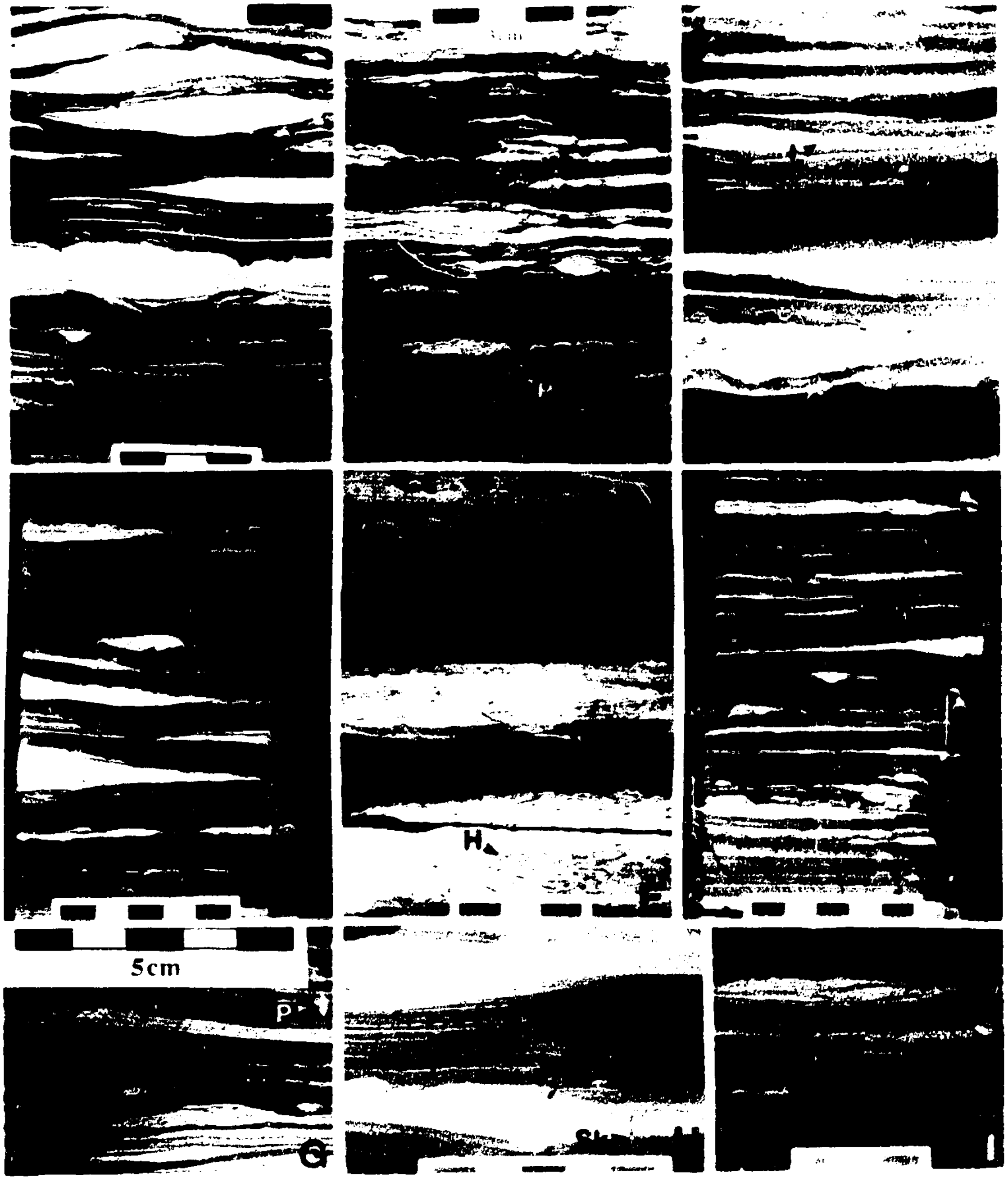
The sandstones and siltstones are sharp-based, show well-developed normal grading, and range from 0.5-5.0 cm in thickness, though typically <1.0 cm. Low angle parallel lamination, and starved combined flow and oscillation ripple laminae dominate the physical sedimentary structures of these units.

Fine- to medium-grained, 5-10 cm thick sandstones, contain similar structures to the above, and are intercalated on a decimetre scale with intraformationally-derived rip-up clasts, organic detritus, and rare glauconite. The shales are fissile, locally with siderite-cemented bands, and contain pyrite and fish scales on bedding planes. Pebble stringers are locally intercalated, though more common in the Willesden Green-Caroline-Garrington-Harmattan East area (*cf.* Leckie, 1986; Hein *et al.*, 1986; Boreen, 1989).

Facies D: Pinstripe-Bedded Sandstone, Siltstone and Shale Facies: Distal Stillstand Progradation Deposits		
Reference	Field	Facies Designation
Power, 1988	Joarcam	Included in interbedded mudstone and siltstone facies of Member C+D.
Posamentier and Chamberlain, 1991	Joarcam	No designation.
Reinson *et al.*, 1988	Crystal	No designation.
Raychaudhuri, 1989	Chigwell	Some Facies 7a.
Pattison, 1991a	Crystal, Sundance, Edson, Cyn-Pem	Included in dark mudstone facies of FA10.
Downing and Walker, 1988	Joffre	Some Facies 4 of FA4; mainly FA5.
Raddysh, 1988	Gilby A+B	Some Facies K.
Cox, 1991	Blood (Bow Island)	Included in dark grey shale facies of Transgressive FA.
Boreen and Walker, 1991	Willesden Green	Included in silty shale facies of FA E.
Hein *et al.*, 1986	Caroline, Garrington, Harmattan East	Included in Facies 10a of FA1.
Leckie, 1986	Caroline	Included in Facies 1.
Davies, 1990	Caroline, Garrington	Included in Facies 9 of Allomember E.

Table X-4. Facies D: Equivalents of other workers.

Figure X-11. Facies D: Pinstripe-Bedded Sandstone, Siltstone and Shale Facies. (A) Weakly burrowed wavy parallel, current ripple and combined flow ripple laminated sandstone beds. *Planolites, Lockeia* (L), *Helminthopsis* and escape traces are present. Joffre Field, 03-31-36-22W4, depth 1397.9 m. Scale in centimetres. **(B)** Weakly to moderately burrowed interval, with sediment-starved, combined flow ripples and wavy parallel laminae. *Planolites* (P) and *Palaeophycus* are present. Fox Creek Field, 10-36-61-19W5, depth 1744 m. **(C)** Largely unburrowed, pinstripe-bedded unit with a conglomeratic stringer near the base. *Planolites* (P) and *Lockeia* (L) are present. Joarcam Field, 16-12-48-21W4, depth 976.9 m. **(D)** Largely unburrowed interval with wavy parallel and oscillation rippled sandstone beds. *Planolites*, fugichnia and *Lockeia* (L) are present. Bow Island Formation, Blood Field, 06-16-06-22W4, depth 984.4 m. Scale in centimetres. **(E)** Wavy parallel and combined flow ripple laminated sandstone beds, with abundant *Helminthopsis/Anconichnus* (H) and escape traces (f). Crystal Field, 13-05-46-03W5, depth 1745.8 m. Scale in centimetres. **(F)** Largely unburrowed, pinstripe-bedded interval with *Planolites* (P) and *Lockeia*. Bow Island Formation, Blood Field, 06-16-06-22W4, depth 977.7 m. Scale in centimetres. **(G)** Sandy interval with oscillation ripple lamination and wavy parallel lamination. *Planolites* (P) is present. Bow Island Formation, Blood Field, 06-16-06-22W4, depth 979.8 m. **(H)** Combined flow rippled sandstones and silty shales. Small *Skolithos* (Sk), *Helminthopsis/Anconichnus* (H), *Planolites, Lockeia* and fugichnia (f) are present. Chigwell Field, 10-28-41-25W4, depth 1453.8 m. Scale in centimetres. **(I)** Largely unburrowed interval. *Planolites* are visible. Fox Creek Field, 10-15-62-19W5, depth 1656.4 m.


P
H
5cm
P
G
Sk

Ichnology

The ichnology of the facies is problematic. Most of the shale interbeds are characterised by minimal bioturbation, while some are entirely devoid of visible trace fossils. In contrast, many of the sandstones possess a low abundance of discrete burrows, as well as subtle disturbances within the laminae and irregularities along the bases of the beds, which may reflect casts of grazing structures, resting traces or surface trails (Figure X-11 A, B). The overall burrow intensity ranges from ii2 - ii3 (Figure X-8; *cf.* Droser and Bottjer, 1986, 1989, 1991), and generally decreases as the facies fines upwards.

All visible ichnogenera are deposit feeding structures such as *Planolites, Teichichnus* and rare *Asterosoma*, or grazing structures such as *Helminthopsis, Anconichnus horizontalis* and rare *Zoophycos*. Some irregularities on the bases of the siltstone and sandstone beds may reflect *Lockeia, Scolicia, Aulichnites* or other surface trails. Some of the thicker sand beds contain escape traces, but the tops do not appear to have been colonised by opportunistic organisms. No firmground suites have been recognised in this facies to date, but may be locally developed, likely associated with siderite-cemented horizons (see Facies E).

Interpretation of Facies D

Facies D is interpreted to lie basinward of Facies C and landward of Facies E, occupying the lower offshore realm. The thin sandstone and siltstone beds reflect the most distal portions of storm beds, possibly associated with stillstand shorefaces. This facies is more common in the northeast and southeast portions of the study area, where it probably represents the distal equivalents of shoreface progradation associated with short-lived stillstands within the overall VE3 transgression. The coarser sandstone and pebble beds and stringers are problematic, and are interpreted to represent similar, though more distal equivalents of comparable layers in Facies C.

The paucity of visible burrowing is also problematic, but consistent with similar shaly successions in the Albian Harmon Member of the Peace River Formation (*cf.* Chapter IV), the Joli Fou Formation, and the Wilrich Member of the Spirit River Formation. The interpreted significance of the minimal, and basinward declining visible biogenic reworking is addressed in the interpretation of Facies E.

Facies E: Dark, Fissile Shale Facies

Sedimentology

Facies E (Table X-5; Figure X-12) consists of dense, fissile, black or dark gray coloured shale, with variable silt content. Locally, the shale is siderite-cemented in 2-20 cm thick bands. Irregularly interspersed throughout the facies are thin (<2 cm) siltstone and very fine-grained sandstone beds, showing sediment-starved, combined flow ripple (Figure X-12 G) and low angle wavy parallel laminations. These laminated beds comprise less than 10% and typically less than 5% of the facies, becoming less common upwards; Facies E commonly grades out of Facies D (Figure X-12 A-C). The shale contains abundant fish scales on bedding planes. The facies is the dominant element of the unnamed Colorado shales. Bentonite beds are locally intercalated.

In the southwest portion of the study area, particularly in the Willesden Green, Caroline, Garrington and Harmattan East fields, Facies E also contains sharp-based, thin conglomerate beds and medium- to coarse-grained sandstone beds and stringers (*e.g.* Leckie, 1986; Hein *et al.*, 1986; Boreen, 1989; Davies, 1990). Such beds are virtually absent from equivalent facies to the northeast and southeast, possibly reflecting greater distance from the sediment source. Locally, thin (<10 cm), biogenically mottled, sandy shales, reminiscent of Facies B, erosionally overlie sideritised zones of Facies E. In the Caroline-Garrington-Harmattan East area, Facies E is routinely interbedded with thick packages of coarse-grained, cross-stratified pebbly sandstones (Facies F).

Ichnology

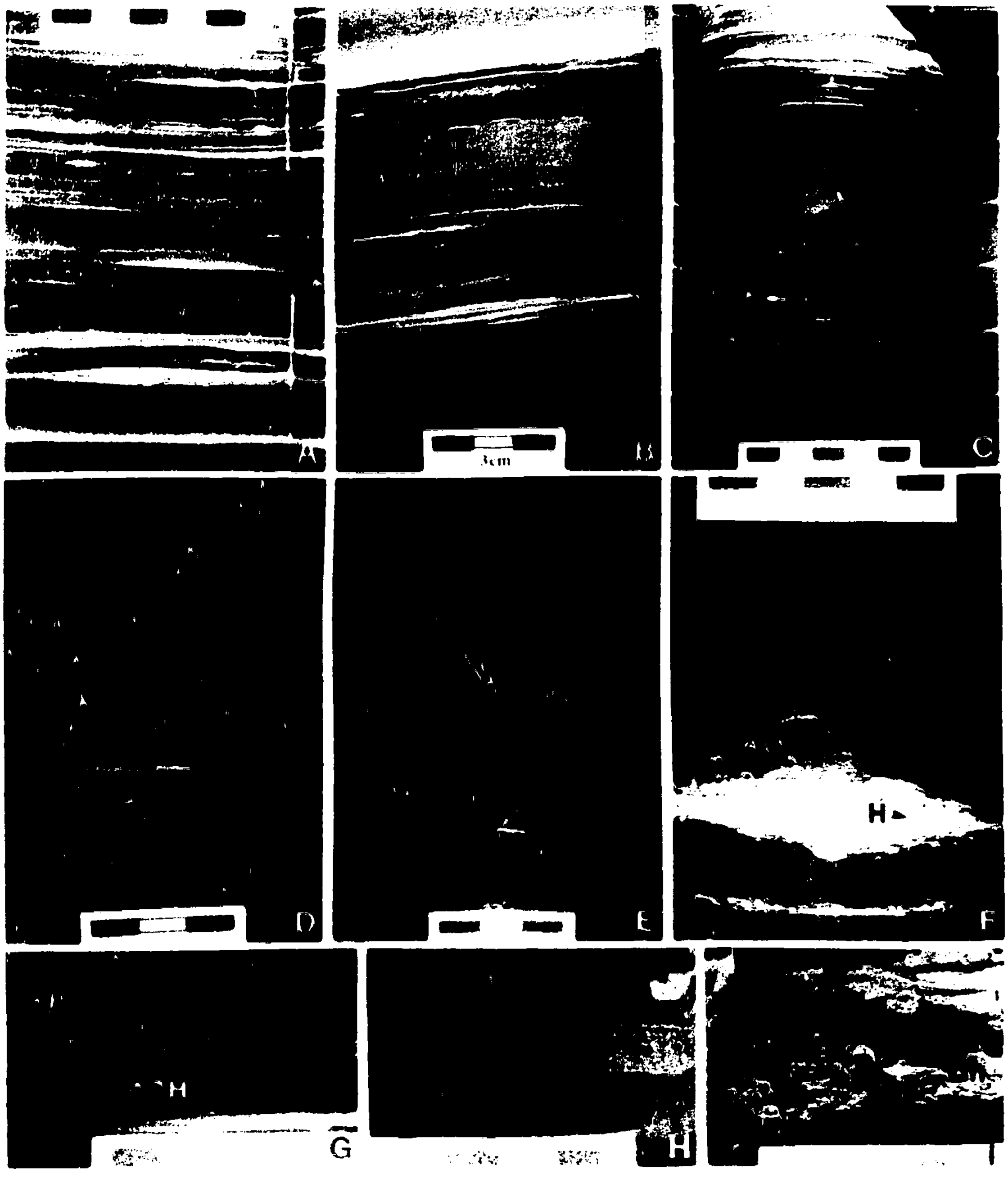
The ichnology of Facies E is problematic. For the most part, the shales appear to be unburrowed, except for a few enigmatic discontinuities in the thin siltstone interlaminae (ii2; Figure X-8; Droser and Bottjer, 1986, 1989, 1991). The thin siltstone and very fine- to fine-grained sandstone beds, on the other hand, are weakly burrowed, showing *Planolites*, rare *Terebellina*, *Helminthopsis* (Figure X-12 F, I), *Siphonichnus* and possible casts of surface grazing and crawling/resting traces. A single example of *Zoophycos* was observed in Facies E above VE4 in the Crystal field (Figure X-12 H). These appear to reflect a distal *Cruziana* ichnofacies although these same elements

Facies E: Dark, Fissile Shale Facies: Maximum Flooding Deposits

Reference	Field	Facies Designation
Power, 1988	Joarcam	Black marine shale facies above Member D.
Posamentier and Chamberlain, 1991	Joarcam	No designation.
Reinson *et al.*, 1988	Crystal	Dark mudstone facies.
Raychaudhuri, 1989	Chigwell	Facies 1.
Pattison, 1991a	Crystal, Sundance, Edson, Cyn-Pem	Dark mudstone facies of FA10.
Downing and Walker, 1988	Joffre	Facies 14 of FA6.
Raddysh, 1988	Gilby A+B	Some Facies K.
Cox, 1991	Blood (Bow Island)	Included in dark grey shale facies of Transgressive FA.
Boreen and Walker, 1991	Willesden Green	Silty shale facies of FA5, Allomember E.
Hein *et al.*, 1986	Caroline, Garrington, Harmattan East	Facies 10a, locally with Facies 1b and 8b-c of FA1.
Leckie, 1986	Caroline	Facies 1.
Davies, 1990	Caroline, Garrington	Facies 9 of Allomember E.

Table X-5. Facies E: Equivalents of other workers.

Figure X-12. Facies E: Dark, Fissile Shale Facies. (A) Thin siltstone and sandstone stringers in silty shale. A few *Planolites* (P) are present. Unit is gradational with Facies D. Bow Island Formation, Blood Field, 06-16-06-22W4, depth 977.1 m. **(B)** Silty shale with thin sandstone stringers. A few *Planolites* (P) are visible. Goose River Field, 07-03-68-18W5, depth 1228.8 m. **(C)** Shale interval gradational with Facies D, showing thin sandstone stringers interpreted as distal tempestites. *Planolites* (P) are present. Edson/Cyn-Pem Area, 10-08-50-14W5, depth 2390 m. Scale in centimetres. **(D)** Silt-poor, fissile shale with rare siltstone and sandstone stringers. *Planolites* and rare *Helminthopsis* (H) are present. Chigwell Field, 06-28-43-26W4, depth 1401.7 m. Scale in centimetres. **(E)** Largely unburrowed fissile shale. Chigwell Field, 06-28-43-26W4, depth 1401.0 m. Scale in centimetres. **(F)** Shale, containing thin, distal sandstone beds with combined flow ripple laminae. *Helminthopsis* (H) and *Planolites* (P) are visible. Edson/Cyn-Pem area, 10-08-50-14W5, depth 2388 m. **(G)** Sediment-starved, combined flow ripple laminated sandstone bed. *Helminthopsis* (H) and *Planolites* (P) are present. Chigwell Field, 10-28-41-25W4, depth 1451.3 m. Scale in centimetres. **(H)** Thin sandstone bed with *Zoophycos* (Z), *Helminthopsis/Anconichnus* (H) and small fugichnia (f). Crystal Field, 11-12-46-03W5, depth 1699.3 m. Scale in centimetres. **(I)** Thin sandstone bed, with fairly intense burrowing consisting of *Helminthopsis* (H), *Planolites* and *Chondrites* (Ch). Crystal Field, 11-12-46-03W5, depth 1699 m. Scale in centimetres.


A
3cm
B
C
D
E
H
F
H
G
H
I

may also occur within the *Zoophycos* ichnofacies. The distinction ultimately rests with the relative dominance of grazing/foraging structures, which are poorly preserved in the shales, relative to deposit feeding structures. The intercalated thin "Facies B"-type layers reflect pervasive bioturbation and individual structures are not discernible. The coarse-grained, trough cross-stratified sandstones of Facies F, encased in Facies E shales, also show moderate amounts of burrowing (*cf.* below).

In addition to these softground suites, *Glossifungites* assemblages, typically excavated into sideritised horizons in the shale beneath the erosional bases of "Facies B"-type horizons or pebble stringers, are locally present in the Caroline-Garrington areas, and consist of *Diplocraterion habichi* and *Skolithos* (see below). These ichnological suites correspond to the higher energy conditions associated with the excavation of the substrate (reflecting the generation of an FS/SB), rather than the quiet water conditions associated with Facies E shale accumulation.

Interpretation of Facies E

The black shales of Facies E are interpreted to have been deposited in relatively deep, quiet waters, corresponding to shelfal conditions. The siltstone and sandstone beds are interpreted as the distal equivalents of storm deposits which accumulated in the offshore and lower shoreface (Facies D and C respectively). The origin of the coarse-grained sandstone and conglomeratic stringers are less clear, and are regarded to reflect similar depositional processes as those assigned for comparable units in Facies C. The presence of these coarse stringers in Facies D and E is restricted to the Willesden Green-Caroline-Garrington-Harmattan East area, and lie above VE4; to the southeast and northeast, these coarse layers are exceedingly rare. Their greater abundance in the southwest may reflect a greater proximity to sediment source.

Several authors have noted the apparent paucity of biogenic structures in this and the associated Facies D (*e.g.* Leckie, 1986; Hein, *et al.*, 1986; Davies, 1990; Pattison, 1991a, *etc.*) and have attributed this to environmentally unfavourable conditions for infaunal organisms. Leckie (1986) collected microfossils from the shales and had the analyses performed by P. Sherrington, who interpreted the assemblage, occupying the *Miliammina manitobensis* Zone, as reflecting restricted marine conditions, somewhat reduced with respect to salinity and in part, euxinic. Nonetheless, the assemblage cited consisted of reasonable numbers of fourteen genera, at least as diverse as most other samples collected from the subzones of the *Haplophragmoides gigas* Zone. These facies of the Viking Formation show abundant and diverse trace fossil assemblages in contrast to Facies E.

A similar fauna collected from the roughly equivalent strata of the basal Sunkay Member, Blackstone Formation in the central Rocky Mountains, was interpreted to reflect shallow, cool, probably somewhat turbid waters, with slightly reduced salinities as compared to fully marine conditions (Wall, 1967). The paleoecology of the *Miliammina manitobensis* Zone from equivalent strata in northeastern British Columbia, although not ruling out euxinic stratification, does not support it, owing to the wide diversity of benthic foraminiferal genera (Stelck, 1975). Such restriction in the basin should be expected to reflect a similar restriction in the diversity and abundance of the benthic microfauna. Microfossils collected from numerous Viking Formation fields in the study area also show diverse arenaceous foraminiferal suites. The paucity of visible burrows in the Joli Fou Formation belies the abundance and diversity of arenaceous benthic foraminifera recovered from samples in core.

The paucity of visible traces in Facies E and associated units may be explained in two main ways. The first is that relatively few organisms actually occupied that particular ecologic niche, possibly due to the cooler, turbid water, reduced salinity and localised or periodic euxinic conditions suggested above. The trace fossils associated with the coarser-grained units may therefore correspond to episodic storm or sediment gravity flow emplacement of marine, fully oxygenated and nontoxic waters which transported the event bed into shelfal areas that were generally stressful to organisms. Presumably, most of the colonisers of the substrate would have been entrained in the flow from the offshore and lower shoreface, or reflect larval settling by opportunistic organisms (*cf.* Pemberton *et al.*, 1992b). With time, the shelfal area would progressively return to stagnant conditions, resulting in the demise of the colonisers. As such, the scenario corresponds to the "doomed pioneers" of Föllmi and Grimm (1990). This does not, however, explain the local presence of grazing structures in the sandstones, particularly near their tops; these are more typical of the traces of a resident population associated with the shelfal setting itself (Ekdale *et al.*, 1984). This scenario also fails to address the high abundance and diversity of benthic foraminifera recovered from the samples.

A more likely possibility is that relatively abundant burrows are (or were) present throughout the shales, but are either essentially invisible due to a lack of lithologic contrast, or have been subsequently destroyed. Both causes are probable and are not mutually exclusive. Traces are visible where silt or sand stringers are present, due more to the existence of lithologic contrast between the shales and the sandstones or siltstones than to the sudden appearance of opportunistic colonisers. *Planolites* is relatively common within these shales, highlighted by its contrasting fill. This is comparable to the apparent absence of burrowing in the Joli Fou Formation shales, while the abundant grazing and shallow deposit feeding structures of the distal *Cruziana* ichnofacies dominate the siltier shales of the downlapping, regionally extensive lower Viking Formation parasequences (the "regional" Viking). The minimal disturbance of the thin siltstone horizons in Facies E largely reflects the shallow nature of the grazing structures, the diminutive size of infaunal tracemakers, and the predominance of surface trails, characteristic of the shelf setting. Few biogenic structures are deeply penetrative.

Irregularities on the bases of beds locally reflect hypichnia, preserved in hyporelief (*cf.* Ekdale *et al.*, 1984), of grazing structures and surface trails, rather than loading. A detailed study of the bases of siltstone and sandstone beds in the Facies E and D units may yield a more complete assemblage of traces for these shelfal settings. Much of the understanding of resident trace fossil communities in neritic and bathyal water depths come not from visible traces in the flysch, but from the bases of turbidite beds, which contain abundant casts of complicated grazing structures (*e.g.* Crimes and Crossely, 1991; McCann and Pickerill, 1988). A similar approach to the Colorado shales may prove useful, however, it should be kept in mind that storm bed emplacement tends to be more strongly erosive than many of the distal turbidites, and the preservation potential of delicate surface structures is correspondingly lower.

In addition, trace fossils may not be visible in Facies E because the substrate may be more of a soupground than a softground in these shelf environments (*cf.* shelf chalks; Ekdale and Bromley, 1984). Although shallow grazers and foragers may be abundant in the shale, upon compaction and dewatering, these structures are unlikely to be preserved. Much of the fill of these structures are fecal casts, rather than sand or silt which would contrast with the shales of Facies E. As a result, essentially no record of the biogenic activity of the organisms may be preserved, except in association with siltstone and sandstone beds which are less susceptible of compaction. Also, inhabitants of soupgrounds and watery softgrounds tend to cause diffusive turbulence by their passage through the substrate and thus, tend to produce a structureless fabric (Bromley, 1990). No doubt, lack of contrasting fill and soupground conditions have acted in concert to obscure the ichnological assemblage of the shales. This is a more plausible scenario than the appeal for toxic bottom water conditions, given the relative diversity of the benthic microfossil suites collected, and the traces observed in the associated facies.

Facies F: Cross-Stratified Sandstone, Pebbly Sandstone and Conglomerate Facies

Sedimentology

Facies F (Table X-6; Figure X-13) possesses erosional lower contacts, locally loaded into the underlying facies (typically Facies E), and sharp upper contacts with all other facies; in most localities, the facies is interbedded with Facies E, and to a lesser degree, Facies D. In the Willesden Green area, the cross-bedded pebbly sandstones are also interbedded with the weakly burrowed version of Facies B (*cf.* Boreen and Walker, 1989).

Facies F consists mainly of sandstones, pebbly sandstones and clast-supported conglomerates. In the northeast and southeast, the sandstones are medium- to coarse-grained, becoming coarser towards the southwest, where they are typically coarse- to very coarse-grained. Granules and pebbles of chert, as well as other lithic fragments, are common as stringers within the pebbly sandstones. Clast-supported, chert granule and pebble conglomerates contain a medium- to coarse-grained sandstone matrix, locally poorly-sorted and relatively muddy. The pebbly sandstones and conglomerates are coarser-grained (pebbles up to 5 cm in diameter) and more abundant towards the southwest (*cf.* Leckie, 1986; Hein, *et al.*, 1986; Davies, 1990). The facies possesses a "salt and pepper" appearance.

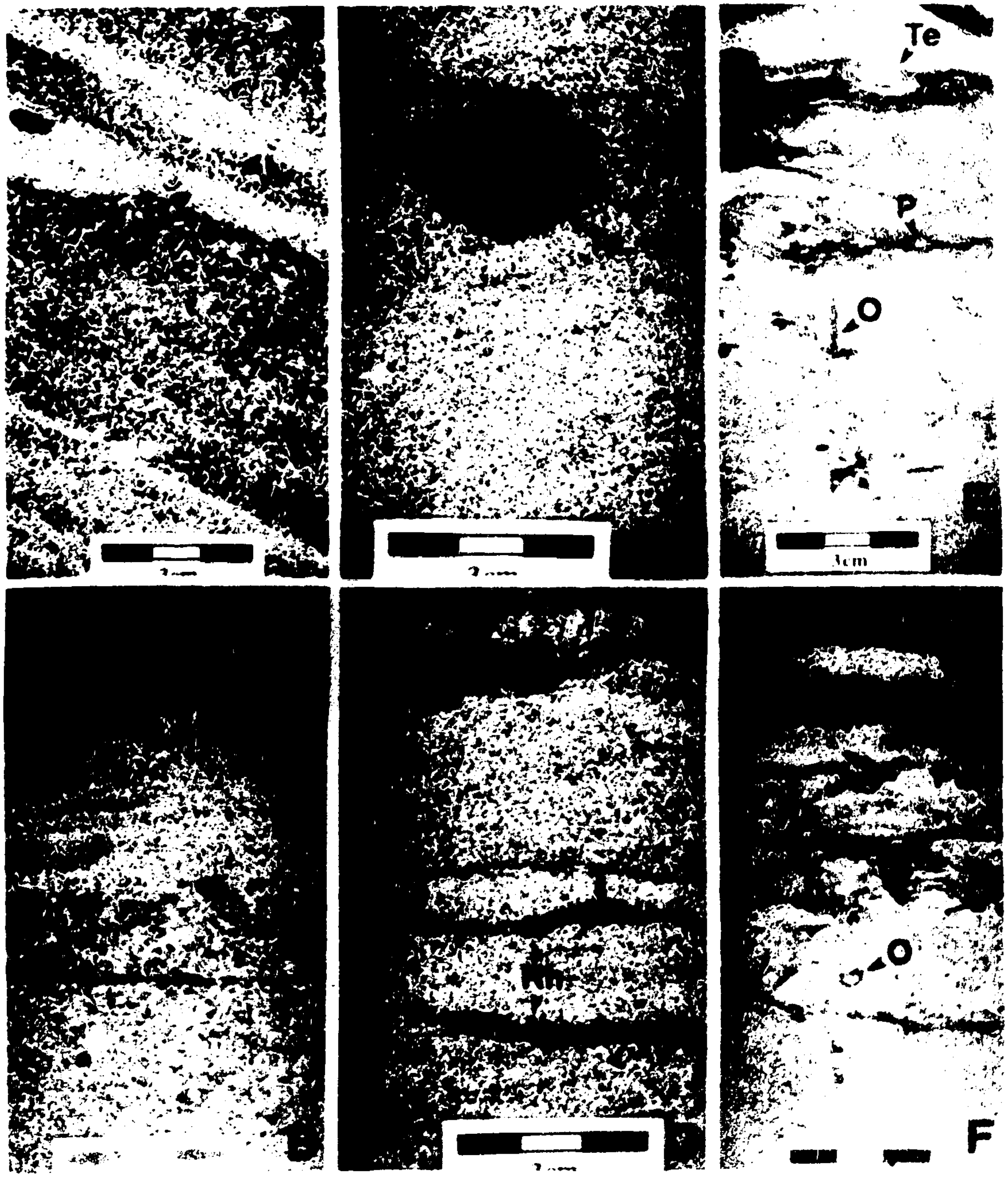
The coarse-grained units generally occur in <50 cm thick sets, but are commonly stacked in 1-2 m thick amalgamated beds. Sets may be separated by reactivation surfaces, mud laminae on a millimetre scale and partings 1-

Facies F: Cross-stratified Sandstone, Pebbly Sandstone & Conglomerate Facies: Tidal Ridge Deposits?

Reference	Field	Facies Designation
Power, 1988	Joarcam	Fine to coarse sandstone facies Member C, coarse sandstone facies Member of D.
Posamentier and Chamberlain, 1991	Joarcam	Medium to coarse sandstone beds in FA Member C.
Reinson *et al.*, 1988	Crystal	Coarse-grained granular sandstone of Upper Transgressive Facies.
Raychaudhuri, 1989	Chigwell	Thin cross-bedded sandstones in Facies 7b.
Pattison, 1991a	Crystal, Sundance, Edson, Cyn-Pem	Cross-bedded sandstone facies of FA10.
Downing and Walker, 1988	Joffre	Some Facies 7+8, possible Facies 5+6 in FA3.
Raddysh, 1988	Gilby A+B	Facies E and F.
Cox, 1991	Blood (Bow Island)	No designation.
Boreen and Walker, 1991	Willesden Green	Cross-bedded sandstone facies of FA5.
Hein *et al.*, 1986	Caroline, Garrington, Harmattan East	Facies 9 of FA2, interbedded with FA3.
Leckie, 1986	Caroline	Facies 4.
Davies, 1990	Caroline, Garrington	Facies 7 and some Facies 6 in Allomember E.

Table X-6. Facies F: Equivalents of other workers.

Figure X-13. Facies F: Cross-Stratified Sandstone, Pebbly Sandstone and Conglomerate Facies. All photos are from the Caroline Field, 16-28-33-05W5. **(A)** High-angle trough cross-stratified coarse-grained pebbly sandstone. Depth 2524.2 m. Scale in centimetres. **(B)** Trough cross-stratified pebbly sandstone and conglomerate, abruptly capped by black, silt-poor shale. Depth 2523.7 m. Scale in centimetres. **(C)** Trough cross-stratified, medium- to coarse-grained sandstone, with robust *Teichichnus* (Te). Depth 2529.5 m. Scale in centimetres. **(D)** Medium- to coarse-grained sandstone with *Rhizocorallium* (Rh). Depth 2528.9 m. Scale in centimetres. **(E)** Trough cross-stratified, medium-grained sandstone with muddy interlaminae. *Teichichnus* (Te), *Planolites* (P) and small *Ophiomorpha* (O) are present. Depth 2526.3 m. **(F)** Trough cross-stratified, medium-to coarse-grained sandstone with muddy interlaminae. *Ophiomorpha* (O), *Rhizocorallium* (Rh), *Palaeophycus* (Pa) and *Planolites* (P) are present. Depth 2526.3 m. Scale in centimetres.


Te
P
O
3cm
Kh
O
F

10 cm thick. Sideritised rip-up clasts up to 11 cm across, abundant carbonaceous detritus, and carbonised wood fragments are common constituents.

Leckie (1986) identified five main types of stratification in the coarse-grained units of the Caroline area, which seem to adequately characterise the facies throughout the study area (*e.g.* Boreen, 1989; Davies, 1990; Pattison, 1991a; MacEachern *et al.*, 1992a). The observed stratification types are: 1) high angle cross-stratification, with inclinations up to 30°, interpreted as trough and planar tabular cross-bedding; 2) low angle bedding, with dip angles of <12°; 3) crudely-developed, horizontal parallel stratification, in sets 1-3 cm thick; 4) apparently structureless (massive) bedding; 5) compound cross-bedding, where low angle (4°-6°, up to 12°) master bounding sets bracket smaller-scale, trough cross-stratified sets with foreset inclinations of 20°-26°.

Ichnology

The facies is dominated by physical sedimentary structures, although a low degree of biogenic reworking (ii2; Figure X-8; *cf.* Droser and Bottjer, 1986, 1989, 1991) is associated with the mud laminae and thinner shale partings. As in Facies E, little or no burrowing is visible within the thicker mudstone partings and in the intervening shale beds.

Virtually all biogenic structures can be assigned to the *Cruziana* ichnofacies, corresponding mainly to deposit feeding behaviour. Ichnogenera are represented by relatively robust *Planolites* and *Teichichnus* (Figure X-13 B, C), as well as *Rhizocorallium* (Figure X-13 E), *Asterosoma*, and small *Ophiomorpha* (Figure X-13 C, F). *Palaeophycus* (Figure X-13 F) and rare *Skolithos*, constitute minor elements of the assemblage.

Interpretation of Facies F

The overall setting of Facies F is ascribed to a shallow marine, tidally influenced shelf (Leckie, 1986; Boreen, 1989; Davies, 1990). Leckie (1986) interpreted the facies to reflect storm-enhanced tidal sand ridges and sand waves, similar to those observed on modern continental shelves (Stride, 1982; *cf.* Table X-7). The shale partings, commonly observed between sandstone sets, are characteristic of tidal sand ridges (Houboult, 1968; Stride, 1982), although their origin has been regarded as problematic (*e.g.* Hein *et al.*, 1986; 1991). They are not interpreted to reflect slackwater between flood and ebb

Tide-Generated Ridges	Storm-Generated Ridges	Viking Transgressive Sandstone
	coarsening-upward sequences	an over-all fining-upward sequence
no record of HCS, high-angle cross-beds with dip angles greater than 20°, master-bedding with dip angles of 6° to 14°	abundance of HCS, symmetrical wave ripple lamination, and unidirectional current ripple lamination	crossbedding on two scales: high-angle (greater than 20°) and low-angle (less than 10°; no record of HCS in facies 3, 4 and 5
	heavily bioturbated intervals reflecting long periods of time between storms, which allows extensive bioturbation of some beds; common trace fossils are *Asterosoma* and *Teichichnus*	thin zones of moderately abundant burrowing with *Rhizocorallium*, *Palaeophycus*, *Planolites*, *Ophiomorpha*, *Teichichnus*, and *Asterosoma*
	separated from (paleo) shoreline by mudstone (*i.e.* shoreline detached)	shoreline detached
	oriented 15°-30° to shoreline	shoreline trend unknown
transgressive	transgressive	transgressive
mud layers commonly present		mud layers, draping cross-bedded sandstone
mud clasts present		mud clasts present

Table X-7. Comparison of Viking Formation transgressive sandstones with tide-generated and storm-generated ridges. (Modified after Leckie, 1986).

tide, nor related to neap-spring cyclicity. The nature of tidal flow on the shelf is rotary, because the tidal "wave" is not deformed as it is in the inshore areas. Hence, tidal flow on the shelf is quasisteady and predominantly unidirectional (Johnston and Baldwin, 1986). Leckie (1986) suggested that the shale partings are a result of seasonal cycles, speculating that during the winter months, intense winter storms enhanced erosion in the inshore areas and augmented the tidal currents, facilitating transport of coarse material in a basinward direction. During these energetic periods, mud was held in suspension. In contrast, the summer months were characterised by overall lower energy conditions, favouring deposition of the mud from suspension onto and between the tidal sand ridges. The presence of large shale rip-up clasts and the poorly-sorted nature of the conglomerates were regarded to support rapid deposition with minimal reworking of the tidal sand ridges themselves. The observed compound stratification reflects superimposition of small scale current-generated bedforms onto larger scale ones, a feature characteristic of bedforms in a shelf setting (Johnston and Baldwin, 1986).

The controversy surrounding the appropriateness of a tidal origin for these coarse clastics has been discussed at length by Leckie (1986). The apparent switch from wave/storm domination, noted in the lower portion of the transgressive deposits (VE3-related), to tidal domination in the upper part (VE4-related), may reflect a more widespread and rapid transgression, producing a wide expansive shelf and embayment of the shoreline, features believed to be conducive to increasing tidal range (D.J.P. Swift, pers. comm., 1985, referenced in Leckie, 1986). These conditions may have been met by the VE4 transgression; VE3 appears to have been more incremental.

The ichnological signature of the coarse clastics appears to reflect predominantly penetrative deposit feeding structures. This may indicate the preference of the tracemakers for the noncohesive or semicohesive substrate of the tidal sand ridge over the soupy or cohesive substrate of the shelf muds. The infauna may also have favoured the higher energy conditions associated with the sand ridge. In this sense, these ichnological elements demonstrate a basinward displacement of organism behaviours consistent with *Cruziana* and *Skolithos* ichnofacies into the distal *Cruziana* or ?*Zoophycos* ichnofacies. The existence of these tracemakers within the tidal shelf sand ridges, while the intervening shale beds and thicker partings retain the unburrowed appearance of Facies E and D, may support the contention that the absence of visible resident trace fossil suites in shelf mudstones is a purely taphonomic phenomenon.

In contrast, Walker and Davies (1991) and Davies and Walker (1991) have proposed that the coarse-grained onlap markers (*i.e.* Facies F) in Allomember E in the vicinity of the Caroline and Garrington fields (Figure X-4) reflect high frequency forced regressions within an overall transgression. In this model, the bases of the onlap markers or tongues correspond to sequence boundaries or their correlative conformities, produced during minor falls in relative sea level. The coarse-grained sandstone tongues themselves are interpreted to reflect the basinal extensions of forced regression shorefaces. During lowered sea level, the coarse-grained sandstone was transported basinward by storms and/or tidal currents and deposited on the overlying black mudstones (Facies E). Rapid resumed transgression subsequently blanketed these coarse clastics in shelfal mudstones. The absence of documented forced regression shoreface deposits landward of the coarse tongues detracts from this model. The cores studied from Caroline lack *Glossifungites* suites demarcating the base of Facies F units, despite the erosional contact reflected by the rip-up clasts and the marine affinity of the coarse clastics demonstrated by the trace fossil suites. Nonetheless, this may reflect autocyclic deposition of the clastics on a correlative conformity of the forced regression sequence boundary, precluding firmground colonisation. In addition, Davies and Walker (1993) have reported several intervals where the coarse onlap tongues overlie erosional discontinuities penetrated by pebble-filled *Skolithos* and *Diplocraterion*, possibly reflecting a *Glossifungites* suite.

The model proposed by Davies and Walker (1993) and the tidal sand ridge model of Leckie (1986) are not mutually exclusive, however. The high frequency forced regression model affords a convenient mechanism for supplying coarse detritus to the basin. The sediments then become stranded on the shelf during resumed transgression, favouring their subsequent remobilisation into tidal sand ridges. In any case, the nature of Facies F intervals remains enigmatic. Clearly, further research into the character of VE4 is essential in order to resolve the surfaces' sequence stratigraphic significance and the genesis of its overlying deposits.

HIGH ENERGY (EROSIVE) FLOODING SURFACES (HE FS)

Closely tied to the transgressive deposits themselves, are the HE FS or ravinement surfaces. The abundance of these surfaces in the upper portion of the Viking Formation suggests a complex history of transgression, culminating in the maximum flooding of the North American Interior Seaway and deposition of the widespread Colorado shales and their equivalents.

Careful stratigraphic correlations across the east and northeast portions of the study area by Pattison (1991a) have admirably demonstrated the complexity of the "VE3" transgression, where higher frequency minor falls in relative sea level, stillstand periods and enhanced rates of relative sea level rise have produced at least seven discrete transgressively-modified surfaces (VE3-1 to VE3-7; *cf.* Figure X-5). The widespread presence of Facies A pebble lags suggests that the regional VE3 surface may initially have been excavated during lowstand conditions and subsequently modified during transgression, which generated this composite of "VE3"-related FS/SB surfaces (Pemberton and MacEachern, in press; Chapter III).

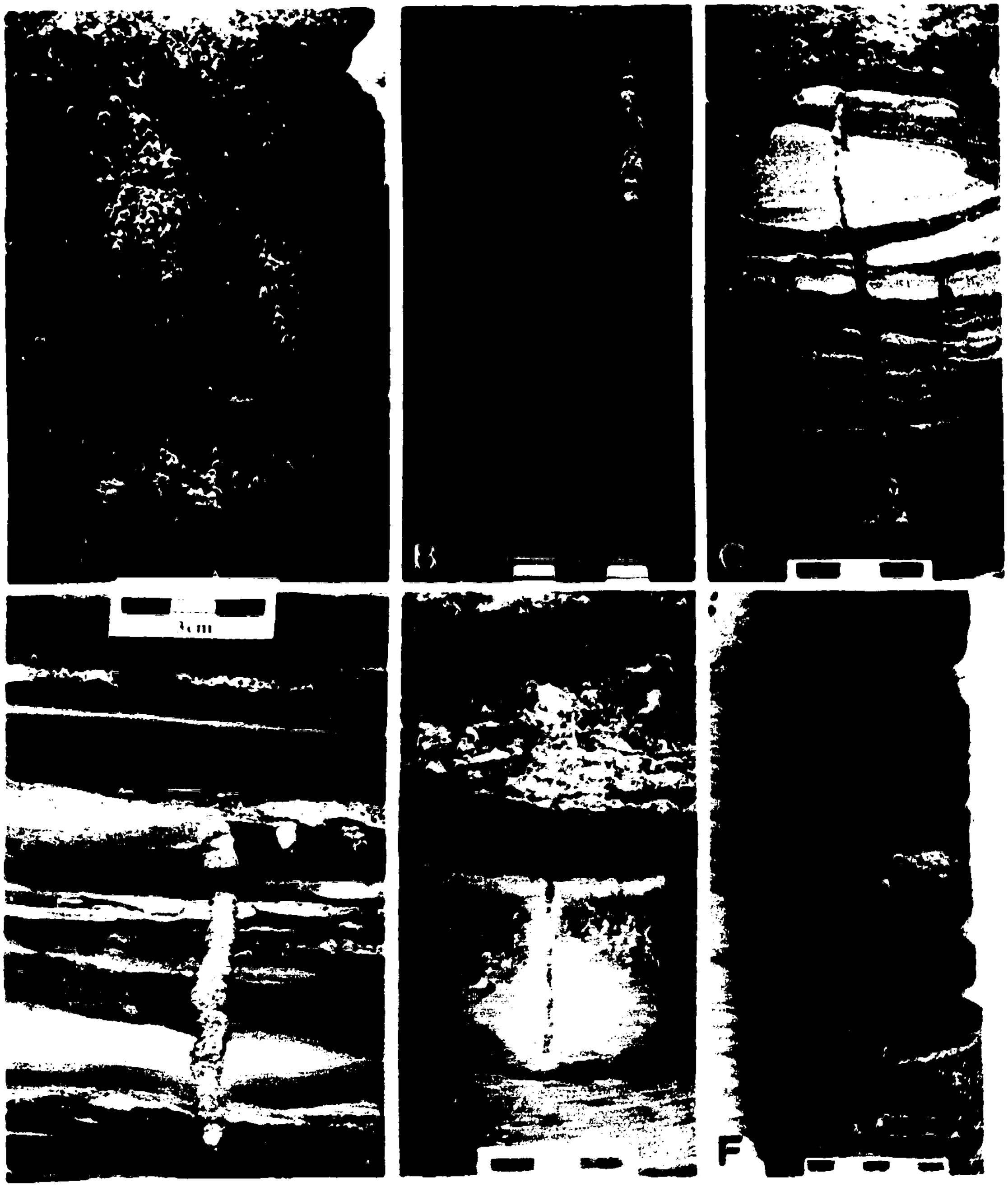
Walker and Davies (1991) and Davies and Walker (1993) have suggested that the "VE4" surface (Figures X-4 and X-5) also reflects an initial lowstand event, which produced a regionally extensive sequence boundary with an associated pebble lag. Subsequent transgression substantially modified the sequence boundary, manifest by stillstand-induced wave-cut notches which rise stratigraphically to the southwest in steps due to progressive, though incremental ravinement. As a result, the "VE4" surface also corresponds to a composite of discrete FS/SB surfaces. Walker and Davies (1991) have also suggested that these VE4 FS/SB surfaces were also modified by higher frequency falls in relative sea level, producing lower-order sequence boundaries. This has not been substantiated, as the VE4 surface(s) have yet to be documented in the detail accorded the VE3 surface(s). Successions associated with the VE4 transgression contrast sharply with those of VE3, suggesting their depositional histories are profoundly different.

The presence of discrete HE FS is difficult to determine on the basis of sedimentology alone, particularly when dealing with the upper Viking Formation, where there exist abundant sharp-based pebble stringers and thin, trough cross-stratified, coarse-grained sandstones within the interbedded sandstones, siltstones and shales. These coarse stringers may reflect a veneer on transgressive erosion surfaces, but due to their abundance in Facies B, C, D, and E, picking which ones have regional stratigraphic significance is highly problematic.

A means of delineating these surfaces is the recognition of the substrate-controlled *Glossifungites* ichnofacies that mark many of the Viking erosional discontinuities (Figure X-14; *cf.* MacEachern *et al.*, 1990; 1991a,b; 1992b; Pemberton *et al.*, 1992a). The subject of the *Glossifungites* ichnofacies and its sequence stratigraphic significance is dealt with in considerable detail in MacEachern *et al.* (1992b) and Pemberton and MacEachern (in press) (*cf.* Chapters II and III). The key points are that they consist of robust, unlined and sharp-walled, dominantly vertical dwelling and suspension feeding structures which are predominantly excavated into erosionally exhumed, dewatered and stiff shaly substrates. Soft muds are unable to support the robust vertical shafts which characterise the suite. The overwhelming majority of such structures in the Cretaceous are produced by infauna occupying marine to marginal marine settings. The presence of such structures also demonstrates that erosional exhumation of the substrate was not immediately followed by preserved depositional cover; colonisation of the exhumed substrate must predate significant depositional cover. The stiff nature of the substrate permits the dwelling structures to remain open after they are vacated by the tracemakers and therefore, they are passively filled during deposition of the next unit. These assemblages demarcate erosional discontinuities associated with a depositional hiatus. High energy (erosive) flooding surfaces (HE FS) afford an elegant means of generating substrate-controlled trace fossil suites, because the surfaces are erosionally exhumed within a marine or marginal marine environment. This favours colonisation by firmground-dwelling organisms after the surface is cut, and prior to deposition of significant thicknesses of overlying sediment. It is not surprising, therefore, that the upper portion of the Viking Formation contains a large number of *Glossifungites* assemblages that cross-cut softground suites (Figures X-14, X-15, X-16, X-17 and X-18).

The characteristic trace fossil assemblage consists predominantly of *Diplocraterion* (particularly *D. habichi*), *Skolithos*, *Arenicolites* and firmground *Thalassinoides* (Figure X-14). These suites are dominated by suspension feeding behaviours and record the more energetic conditions

Figure X-14. Ichnologically-Demarcated Transgressive Surfaces of Erosion (TSE). **(A)** Thoroughly burrowed Facies C, cross-cut by a robust, medium- to coarse-grained sand-filled *Arenicolites* of the *Glossifungites* ichnofacies, which subtends from a TSE. Kaybob South Field, 07-19-62-19W5, depth 1652 m. Bar at base is 3 cm. **(B)** Thoroughly burrowed Facies C with *Planolites* (P), *Teichichnus* (Te) and *Palaeophycus*, cross-cut by a *Skolithos* (Sk) of the *Glossifungites* ichnofacies, marking a TSE. Kaybob South Field, 07-19-62-19W5, depth 1780.2 m. Scale in centimetres. **(C)** Largely unburrowed Facies C. Unit is cross-cut by a *Diplocraterion* of the *Glossifungites* ichnofacies, subtending from a TSE (VE4). The VE4 surface is overlain by a Facies B interval. Chigwell Field, 04-02-42-26W4, depth 1439.3 m. Scale in centimetres. **(D)** Weakly burrowed Facies C, cross-cut by *Diplocraterion habichi* of the *Glossifungites* ichnofacies, which subtends from a probable TSE. A thin, gritty sandstone layer overlies the surface. Joarcam Field, 16-12-48-21W4, depth 978.3 m. **(E)** Siderite-cemented Facies E, penetrated by a *Skolithos* shaft of the *Glossifungites* ichnofacies, marking a TSE. The surface is overlain by thoroughly burrowed muddy sandstones of Facies B. Garrington Field, 16-13-34-03W5, depth 2066.2 m. Scale in centimetres. **(F)** Moderately burrowed, shaly Facies C, cross-cut by robust *Diplocraterion habichi* of the *Glossifungites* ichnofacies, marking a TSE. Kaybob Field, 07-30-61-18W5, depth 1651.3 m. Scale in centimetres.


B
C
3cm
F

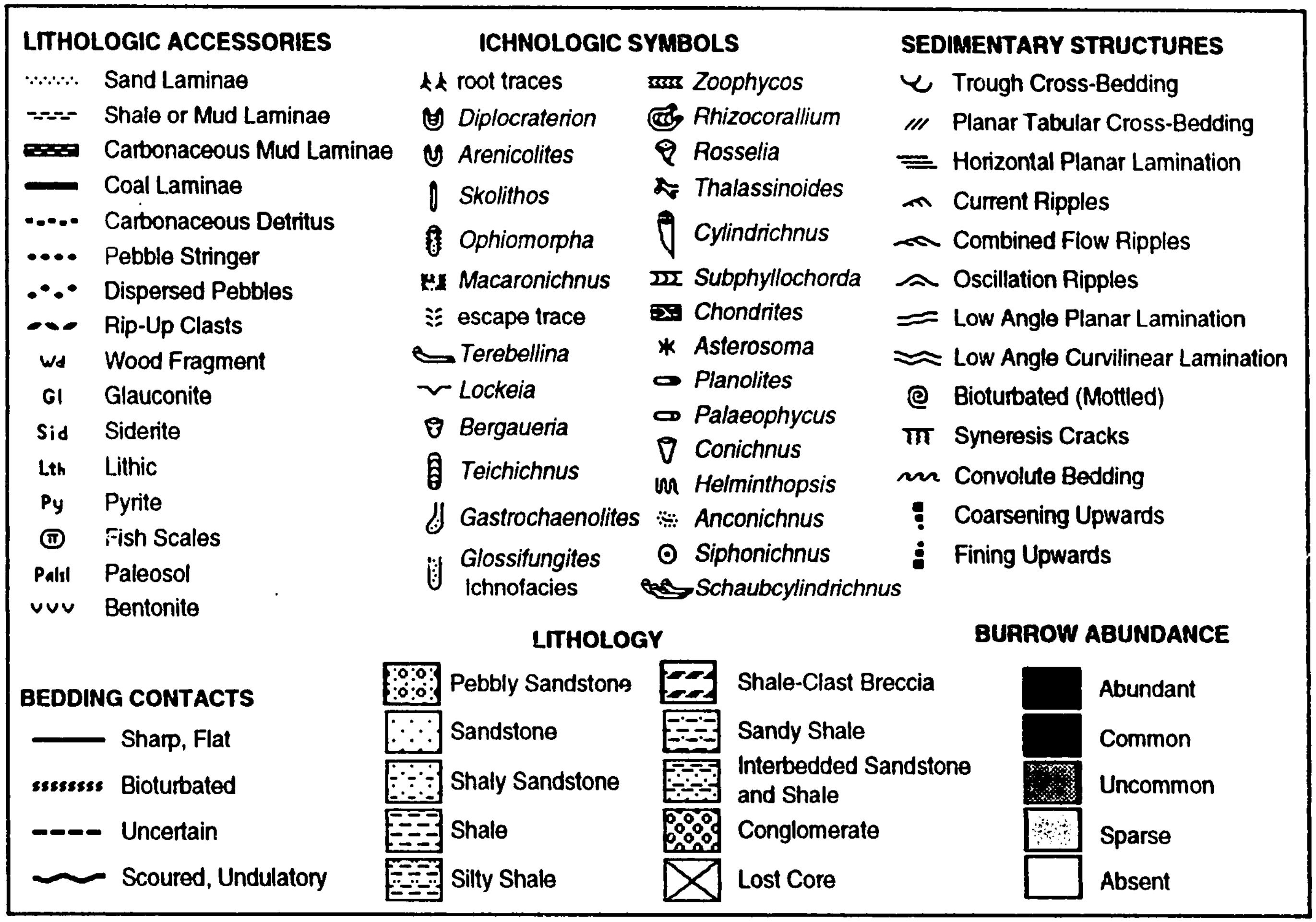


Figure X-15. Legend of Symbols used in Lithologs.

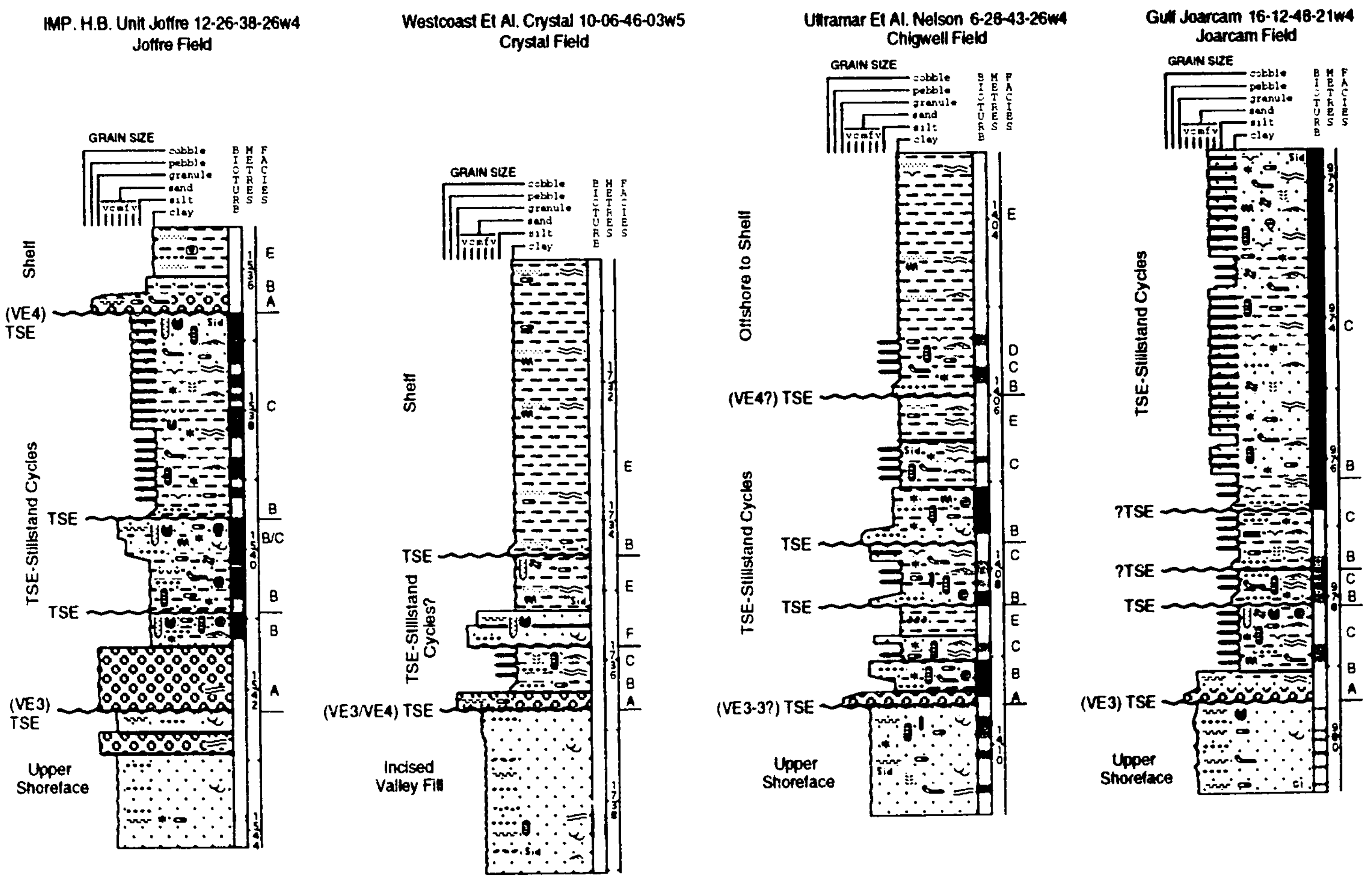


Figure X-16. Lithologs of transgressive systems tract facies, lying above initial TSE (VE3), with facies designations discussed in the text. Note the high degree of vertical and lateral variability in the successions. Lithologs reflect the successions in the northeast portion of the study area The legend of symbols used in lithologs is given in Figure X-15.

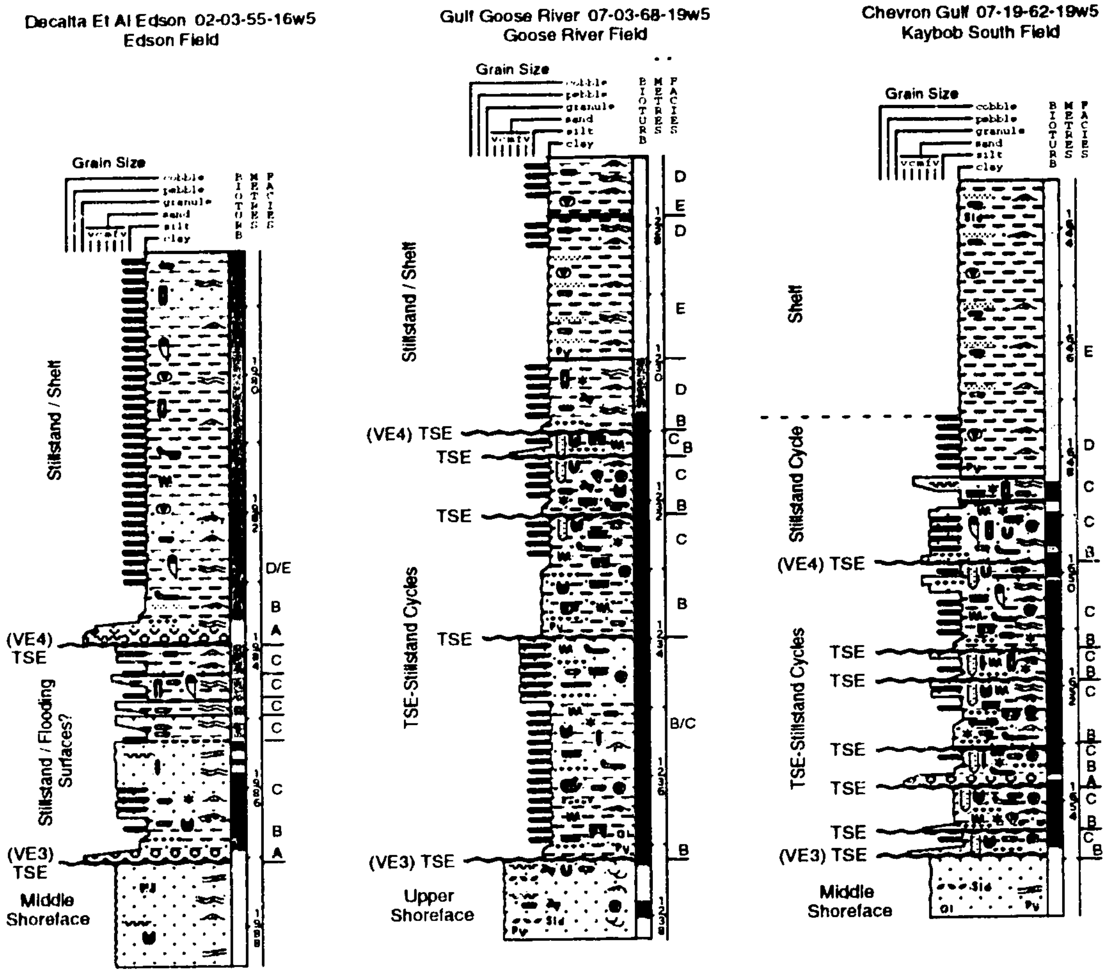


Figure X-17. Lithologs of transgressive systems tract facies lying above initial TSE (VE3) in the northwest portion of the study area. The complexity of the succession is consistent with observations most of central Alberta. The legend of symbols used in the lithologs is given in Figure X-15.

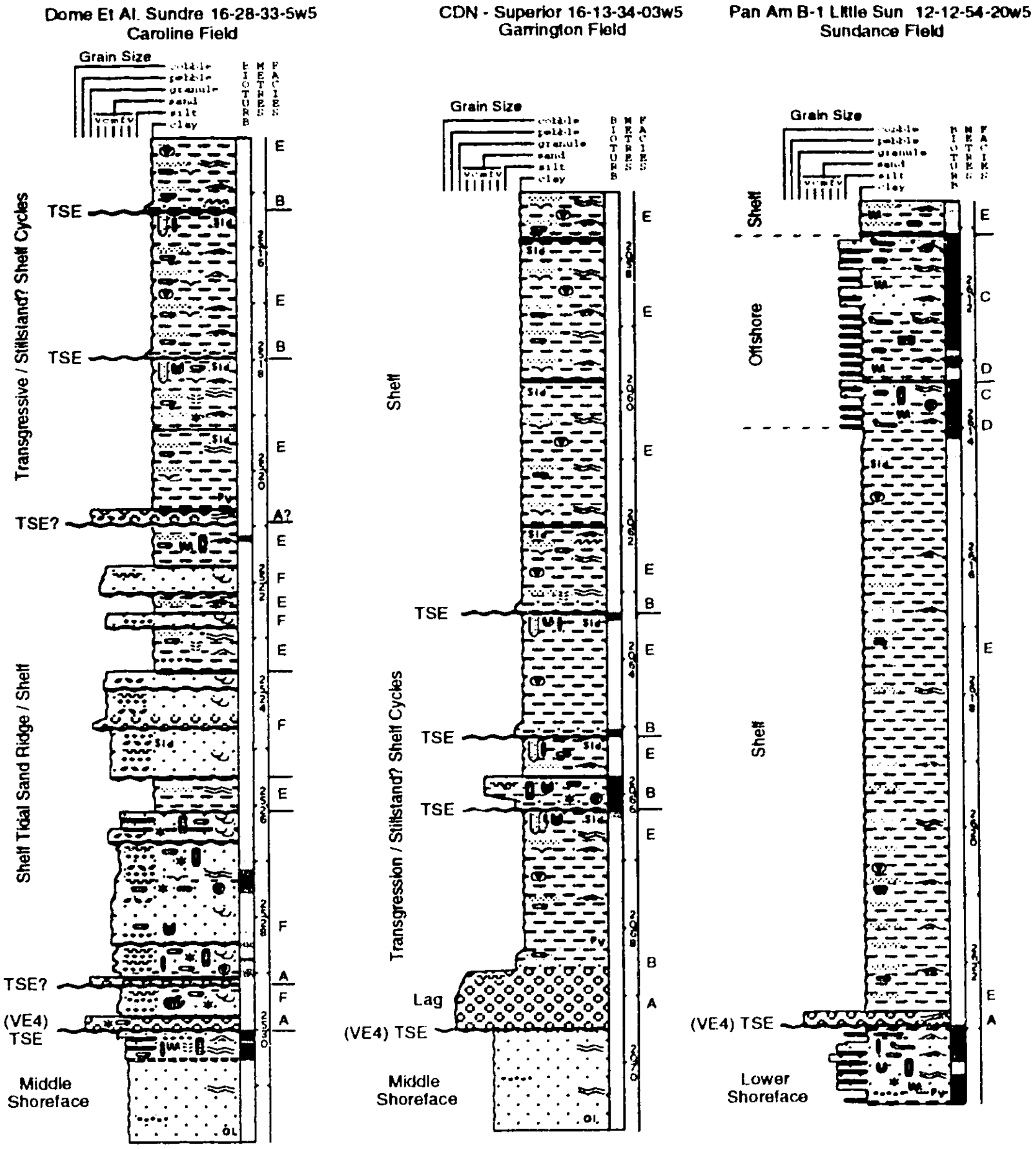


Figure X-18. Lithologs of transgressive systems tract facies lying above the VE4 surface in the southwest portion of the study area. Caroline Field successions shows well-developed tidal sand ridges. The legend of symbols used in lithologs is given in Figure X-15.

associated with transgressive excavation of the substrate. This contrasts markedly with the lower energy softground assemblage associated with muddy facies deposition. Previously, most authors have included these firmground structures with the softground suite, obscuring the true, original depositional conditions of the facies. The *Glossifungites* suite reflects conditions at, or soon after, the process of transgressive erosion.

The *Glossifungites* suites are characteristically overlain by Facies A or B, which are interpreted as the proximal and distal facies, respectively, of the transgressive erosion process. Virtually every VE3 surface and VE4 surface, where incised into or ravined across shaly sediments, show a firmground suite (*cf.* Figures X-16, X-17 and X-18). The suites are most abundantly developed in the central and northeastern portions of the study area, where they are associated with the complex development of several discrete VE3-related surfaces (Pattison, 1991a; Figure X-5). Many firmgrounds appear to have been developed on siderite-cemented portions of the shales (*e.g.* Gilby Field; *cf.* Raddysh, 1988), but whether the siderite is a function of wave ravinement, a chemical response related to deep penetration by the tracemakers of the *Glossifungites* suite, or that pre-existing siderite-cemented bands formed resistant layers which the HE FS could not incise through, is uncertain, although in the latter case, soft bodied fauna would find it difficult to penetrate such a layer. In the southwest portion of the study area, firmground suites are also associated with siderite horizons within the Facies E shales, sharply overlain by thin "Facies B"-like intervals (Figure X-14 E), lying above VE4.

The regional significance of these ichnologically-demarcated erosional discontinuity surfaces requires careful mapping and correlation. Surfaces appear localised or amalgamated (co-planar) in several localities, making delineation difficult. The character of the overlying transgressive deposits also tends to vary considerably, even across short distances, complicating the process of determining surface equivalence. In addition, some *Glossifungites*-demarcated surfaces may be autocyclically-generated (*cf.* Chapter II), applying a moderating influence on the direct stratigraphic applications of such breaks in the rock record. Regardless, the presence of a substrate-controlled ichnofacies overlain by Facies A or B, provides a more distinctive and reliable means of identifying an erosional discontinuity of **more likely** sequence stratigraphic significance, than merely choosing any one of a number of pebble stringers or gritty shales with dispersed pebbles. The integration of ichnologically-demarcated erosional discontinuities with softground ichnology and sedimentology will undoubtedly enhance and refine developing sequence stratigraphic paradigms for the Viking Formation.

DISCUSSION

Previously, sequence stratigraphers, with the exception of Nummedal and Swift (1987) have afforded comparatively little attention to transgressive deposits and their associated facies (*cf.* Posamentier and Vail, 1988; van Wagoner, *et al.*, 1990). The overriding interest has been with sequence boundaries and their associated lowstand deposits. Transgressions have routinely been regarded as rapidly accomplished, relatively uncomplicated, and commonly characterised by fairly minimal deposition. Pattison (1991a), MacEachern *et al.* (1992a) and Pemberton and MacEachern (in press), among others, have clearly demonstrated that, if anything, transgressive erosion surfaces are at least as complex as, and may be associated with a wider variety of facies associations, than the lowstand surfaces which have dominated the attention of sequence stratigraphers. Transgressive systems tracts may consist of HE FS deposits, stillstand shorefaces and their distal equivalents (transgressively-related deposits), and incised valley fills.

Transgressive and transgressively-related deposits, excluding incised valley fills, which possess their own unique complexities (*cf.* Reinson *et al.*, 1988; Boreen and Walker, 1991; Pattison, 1991a; 1992; Dalrymple *et al.*, 1992; MacEachern and Pemberton, in press; Zaitlin *et al.*, in press), can be grouped into three main subdivisions.

The most directly related facies are produced by the process of transgressive erosion (ravinement) itself, and include the transgressive lags (Facies A), and the erosionally-based gritty and pebbly muddy sandstones and sandy shales, interpreted as distal ravinement deposits (Facies B), both typically overlying discontinuities demarcated by the *Glossifungites* ichnofacies.

The second group of facies correspond to those sediments deposited while relative sea level is rising, but were too distal to display evidence of transgressive erosion and were not associated with progradational systems.

These transgressive deposits include shelfal shales (Facies E), low energy (non erosive) marine flooding surfaces and their deposits, and shelf tidal sand ridges (Facies F).

The last group of facies reflect interstratified progradational deposits, contained within, and dominated by, the transgressive deposits discussed above. Such units mainly correspond to the distal equivalents of short-lived stillstand shorefaces (Facies C) (Pattison, 1991a). Facies D corresponds to the continued or resumed transgression of the stillstand deposits, and reflects an intergradational relationship between Facies C and Facies E.

The observed stacking patterns of facies and facies associations are highly variable, even within a given field area; this has been commented on by several workers (*e.g.* Pattison, 1991a; Posamentier and Chamberlain, 1991a, b; 1993; MacEachern *et al.*, 1992a). The highest degree of variability occurs in the northeast and southeast portions of the study area, where the cored intervals encompass the myriad of VE3-related transgressive erosion surfaces. In general, most areas consist of a complex stacking of Facies A, B, and C, with multiple internal ravinement surfaces (Figures X-16 and X-17). Above VE4, these areas record a dominance of Facies D and E, with minimal coarse clastic intervals or HE FS. Presumably following VE4 transgression, the deeper basinal setting of this area was not affected by later stepwise transgressions in the southwest (*cf.* Figure X-18). These areas also appear to have been too distal from the sediment source to receive significant coarse detritus. This is consistent with observations of the low relief on, and the presumably rapid transgression across, the VE4 surface(s) to the east of Willesden Green (Walker and Boreen, 1991).

The facies associations in the Willesden Green-Caroline-Garrington-Harmattan East area (Figure X-18), show Facies A veneering the VE4 surface(s), and pass into alternations of Facies E and F; Facies D is locally present, though rare. The Facies E in this area also contains coarse sand and thin pebble stringers; Hein *et al.* (1986) interpreted these stringers to be derived from submarine debris flows, which were possibly storm-forced. The juxtaposition of coarse clastics and black shales is in marked contrast to the facies associations above the VE3 surface(s) to the east. VE4 remains problematic. Despite the progressive, stratigraphically climbing steps cut southwestward along the surface, interpreted to reflect stillstand-induced notches (Boreen, 1989; Davies, 1990; Walker and Davies, 1991), stillstand deposits of the kind present above VE3 are absent. The prevailing interpretation of the VE4 surface is that a pronounced lowstand preceded the VE4 transgression, cutting a regionally extensive unconformity which shifted the shoreline well to the east, possibly as far as Joffre (*cf.* Walker and Davies, 1991). This lowstand surface of erosion was profoundly modified during the ensuing transgression; ravinement produced a relatively flat FS/SB as far west as Willesden Green, after which, modification took the form of stillstand notches which rise stratigraphically to the southwest, with a total relief of 16 m (Walker and Davies, 1991). Davies and Walker (1993) attributed the coarse clastics to forced regression-induced progradational bodies which onlap the VE4 wave ravinement-cut steps. Mapping demonstrates that these tongues may be 3 m thick near the point of onlap, but thin basinward and disappear within 15 km. The absence of these coarse units in Facies E units above VE4 in the northeast and southeast portions of the study area is consistent with this, attributable to their greater distance from the sediment source, even if associated with minor falls in sea level. It is tentatively interpreted that these onlap markers consist of coarse detritus, moved basinward by storms and/or tides as basinal extensions of forced regression shorefaces, cannibalised during resumed transgression by tides to form tidal sand ridges. The character of the VE4 transgression is clearly more complex than previously suspected. The insights on the range of complexities possible, afforded by Pattison (1991a) from his study of the "VE3" transgression may serve to herald similar refinements in a "second generation" sequence stratigraphy of the VE4 transgression.

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CHAPTER XI

SUMMARY AND CONCLUSIONS

This thesis has sought to go beyond the simple identification of trace fossils within the Viking Formation and the Peace River Formation. Instead, it has demonstrated the broad range of applications that detailed ichnology has to the sedimentologic and stratigraphic interpretation of the rock record. The contributions of this research can be broadly grouped into two main areas. One concerns the ichnological applications to sequence stratigraphic analysis. The other is associated with ichnological applications to paleoenvironmental interpretations. To a large degree, these two applications cannot be clearly separated from one another, and most case studies presented in the thesis demonstrate both applications.

SEQUENCE STRATIGRAPHIC APPLICATIONS

Chapters II and III introduced the reader to the applications of ichnology to the developing paradigm of sequence stratigraphy. The general concepts of sequence stratigraphy are not dealt with in the thesis itself; excellent reviews are available in Posamentier and Vail (1988) and Van Wagoner *et al.* (1990; 1992). The identification and interpretation of bounding discontinuities is of fundamental importance to sequence stratigraphy. Within the thesis area, substrate-controlled ichnofacies demarcating sequence stratigraphically significant surfaces are widespread, providing unique criteria for the recognition of these surfaces, and imparting data regarding their origin. To date, ichnology has been a largely unexploited tool in this regard.

The *Glossifungites* ichnofacies is a relatively easily recognised assemblage of trace fossils which commonly demarcate stratigraphic breaks in the rock record. The existence of this suite indicates that the substrate has been erosionally exhumed and/or subaerially exposed. The assemblage also indicates that infaunal colonisation occurred after exhumation but prior to significant deposition of the overlying strata, highlighting a hiatus or pause in sedimentation. The eroding event could not have been directly responsible for the final deposition of the overlying strata. Finally, the overwhelming majority of *Glossifungites* assemblages are marine or marginal marine in origin, particularly in pre-Tertiary intervals, indicating that marine conditions existed prior to deposition of the overlying interval. Analysis of a large number of examples in the rock record show that virtually all sequence stratigraphically important surfaces may become colonised by this substrate-controlled suite, including sequence boundaries (estuarine arms of incised valleys; forced regression shorefaces, submarine canyon margins), transgressive surfaces of erosion (wave ravinement surfaces, tidal scour ravinement surfaces, high energy maximum flooding surfaces) and amalgamated sequence boundaries and flooding surfaces (FS/SB)(flooding surfaces over subaerial exposure surfaces, incised valley surfaces, high energy parasequence boundaries). Careful observation and interpretation of the ichnological suites of over- and underlying deposits provides much information regarding the probable origin of the surface and the character of the succeeding depositional event. Where sequence stratigraphic surfaces are not erosional, juxtaposition of ichnofacies inconsistent with a progressive or orderly change in the depositional setting may be employed to highlight the existence of a break. Such ichnological successions are analogous to lithofacies successions and like them, must adhere to Walther's Law. When ichnological data is integrated with physical sedimentological data, a powerful approach to the sequence stratigraphic analysis of the rock record is established. Chapters II and III highlight several examples of where this has been accomplished, and the case studies of Chapters VII, VIII, IX and X show specific cases where this technique has been effectively applied to the thesis interval.

INTEGRATED ICHNOLOGICAL-SEDIMENTOLOGICAL MODELS: APPLICATIONS TO THE INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS

The second major contribution of this thesis is in the establishment of a number of integrated ichnological-sedimentological models which provide criteria for the recognition and interpretation of selected depositional environments in the rock record. The main depositional settings in the thesis interval are shorefaces, estuarine incised valley fills and transgressive settings.

Chapters IV and V are conceptual papers, which deal with tempestites and shorefaces, respectively. Tempestites are the primary building blocks of many shoreface successions and display a number of features by which they can be recognised, namely: a) a sharp erosional base, with or without a basal lag; b) a main sandstone interval characterised by low angle laminations, parallel to subparallel to lower set boundaries (HCS, SCS or QPL); c) escape traces (fugichnia) recording the attempt of buried or entrained organisms to reach the sediment-water interface; d) rare waning flow deposits, consisting of oscillation ripple, combined flow ripple, climbing ripple and lesser current ripple lamination; e) dwelling structures of opportunistic organisms near the tops of beds, recording initial tempestite colonisation; f) gradational burrowed tops of the tempestite, showing biogenic structures of the resident, fairweather trace fossil suite cross-cutting the opportunistic suite; passing into g) thoroughly burrowed fairweather deposits containing an equilibrium trace fossil suite. Many such tempestites contain a relatively distinctive mixed *Skolithos-Cruziana* ichnofacies (Pemberton and Frey, 1984), reflecting *in loco* fluctuations in energy. The preservation potential of tempestites involves highly complex inter-relations between a number of physical and biological factors, and tends to be greater in distal settings and proximal settings, but reduced in settings intermediate along the depositional profile.

Within the Cretaceous of the Western Interior Seaway of North America, the shoreface succession can be subdivided into lower offshore, upper offshore, lower shoreface, middle shoreface, upper shoreface and foreshore. These subdivisions are based partially on ethological interpretations of the trace fossil assemblages, and partially on the character of the preserved physical structures. The proposed model shows the ichnological assemblage progressively changing from predominantly grazing and foraging structures in the shelf and lower offshore, to predominantly deposit feeding structures in the upper offshore and lower shoreface, and to mainly suspension feeding structures in the middle shoreface, upper shoreface and foreshore. Under high energy conditions, suspension feeding behaviours may be replaced by the grain-selective deposit feeding structures of *Macaronichnus segregatis*. Observation of a number of shoreface successions shows that the main zone of variability in the preserved record appears to lie in the lower and middle shoreface. This variability revolves around the relative dominance of tempestite accumulation, leading to the establishment of three depositional "types", namely: a) a strongly storm-dominated succession, characterised by abundant erosionally amalgamated tempestites, with minimal preservation of post-storm fairweather deposits; b) an intermediate or moderately storm-dominated succession, characterised by preservation of both tempestite and fairweather deposits which impart a laminated-to-burrowed appearance; and c) a low energy or weakly storm-affected shoreface succession, where storm events are infrequent and/or of low intensity, permitting thorough biogenic reworking of the sediment.

Chapters VI, VII and VIII serve as case studies of each shoreface "type". Chapter VI deals with the strongly storm-dominated shoreface succession within the Harmon-Cadotte members of the Peace River Formation. In addition, analysis of the entire offshore to backshore succession allowed the interpretation of the interval as an intermediate barred shoreline system, subjected to a seasonal storm cycle (winter-summer cycles). Some data suggest that at least locally, the Harmon-Cadotte shoreface was part of a storm-dominated delta system. Chapter VII deals with a moderately storm-dominated shoreface succession in the Viking Formation of the Kaybob field area. The distinctive characteristics of this shoreface are "laminated-to-burrowed" bedding, and the presence of a well-developed, high diversity, mixed *Skolithos-Cruziana* ichnofacies. From a sequence stratigraphic perspective, the succession also highlights a number of criteria useful for the recognition of a forced regression shoreface, indicating the presence of a sequence boundary separating the main sandstone at Kaybob from the underlying marine deposits of the regionally extensive Viking Formation parasequences. Chapter VIII deals with the Viking Formation of the Giroux Lake field area, and demonstrates the characteristics of a low energy, weakly storm-affected shoreface. The succession is typified by thoroughly bioturbated deposits displaying a wide diversity and high abundance of ichnogenera. The progressive change in the trace fossil suites conforms well with that proposed for shoreface successions in Chapter V. This applicability strengthens the credibility of the model, since it is based on a wide range of Cretaceous intervals in the Western Interior Seaway of North America, and not simply the Viking Formation. From a sequence stratigraphic perspective, the Giroux

Lake succession also permits the establishment of a distinctive parasequence type, herein referred to as a "high energy" parasequence. The succession possesses all the characteristics of a typical parasequence; that is, a shallowing upward succession of genetically related strata, bounded above and below by marine flooding surfaces. These "high energy" parasequences, however, unlike most other parasequences, are areally restricted, overlying an erosional or high energy flooding surface typically amalgamated with a sequence boundary. Such parasequences correspond to stillstand conditions during an overall transgression. A number of criteria are discussed in Chapter VII and VIII by which forced regression shorefaces, part of the lowstand systems tract, may be differentiated in the rock record from "high energy" parasequences, which are elements of the highstand or transgressive systems tract, depending upon whether the stacking pattern is progradational or retrogradational, respectively. The most useful criterion appears to be the character of the facies overlying the erosional discontinuity. The stratigraphic break may be regarded to have been generated no deeper than fairweather wave base, whether lowstand- or transgressively-induced. Consequently, under forced regression settings, facies overlying the break must reflect conditions at or shallower than fairweather wave base, since sea level is falling. In contrast, under transgressive settings, facies overlying the erosional break may reflect depositional conditions much deeper than fairweather wave base, since sea level is rising.

Chapter IX deals with the nature of estuarine incised valley fills in the Viking Formation. The intervals studied are from the Crystal, Cyn-Pem, Sundance, Edson and Willesden Green fields. The general wave-dominated estuarine model of Roy *et al.* (1980) and Dalrymple *et al.* (1992) has been previously applied to these successions (Pattison, 1991a,b; 1992), and is endorsed by this thesis. In addition, however, the integration of ichnology and sedimentology provides far greater insights into the depositional character of such estuarine systems, than has previously been described. The wave-dominated estuary displays a tripartite zonation of facies, namely: a) a landward sand-dominated bay head delta complex, b) a middle, muddy lagoonal or central basin complex, and c) a seaward, sandy estuary mouth complex. Channel systems, corresponding to a variety of possible depositional environments, are also preserved within these deposits.

The bay head delta sandstones display delta front storm beds with rare delta slope sediment gravity flow deposits and rare remnants of distributary channels. The sandstones are weakly burrowed with a low diversity, sporadically distributed suite of trace fossils, attributed to high aggradation rates, episodic deposition and possibly large fluctuations in salinity. The central basin complex consists of thinly interbedded, storm-generated sandstones and silty to sandy estuarine mudstones. Burrowing intensities are highly variable both laterally and vertically, and are dominated by the structures of trophic generalists with moderate proportions of specialised biogenic structures. The trace fossil suite indicates that brackish water conditions with regular fluctuations in salinity characterised the central basin, though periods of nearly fully marine salinity also occurred. The estuary mouth complex can be separated into successions associated with the landward side of the barrier complex and successions seaward of the barrier complex. The landward successions are dominated by storm beds and washover sandstones, interstratified with fairweather muddy sandstones. Burrowing tends to be of higher intensity and of more uniform distribution than in other parts of the valley. The main stresses are interpreted to be episodic deposition and possible variations in salinity. The succession on the seaward side of the barrier consists of thoroughly burrowed, pebbly sandy shales and muddy sandstones, reflecting the erosional remnant of the barrier bar itself, largely removed by transgressively-induced erosive shoreface retreat. The trace fossil suites on the seaward side show little evidence of brackish water conditions. The channel sandstones range from completely unburrowed to weakly burrowed, and are interpreted to locally represent fluvial channels (unburrowed), distributary channels (unburrowed or burrowed), tidal inlets (burrowed), tidal channels (burrowed) or re-incised channels (burrowed or unburrowed).

In contrast to these estuarine incised valley deposits, the underlying and laterally adjacent deposits into which the valley is excavated contains trace fossil assemblages interpreted as fully marine in character. These trace fossil suites are markedly different from the stressed, brackish-water assemblages characteristic of the valley fills. Careful observation of the preserved ichnological successions helps to differentiate valley and non-valley successions, particularly where central basin mudstones directly overlie offshore marine mudstones. Additionally, the successions in the Viking

Formation also contain well-developed *Glossifungites* assemblages, helping to delineate the sequence stratigraphically important surfaces within the incised valley deposits.

Chapter X deals with the upper portion of the Viking Formation (*i.e.* the "Viking grit"), across much of central Alberta. The aim of the paper is the characterisation of the deposits associated with incremental transgression of the Colorado Sea, which ultimately terminated Viking deposition. These deposits are bounded by high energy (erosive) marine flooding surfaces, some of which may be amalgamated with sequence boundaries, rather than by low energy (non-erosive) marine flooding surfaces. These high energy flooding surfaces are typically demarcated by the *Glossifungites* ichnofacies, highlighting their sequence stratigraphic significance. The chapter ultimately separates the observed facies into those that are directly related to ongoing (active) transgressive erosion (transgressive deposits), those that are associated with stillstand periods of progradation during the overall transgression (transgressively-related deposits) and those that are deposited while sea level is continuing to rise, but too distal to display evidence of ravinement. The latter deposits include marine shelfal shales and possible tidal sand ridges. The transgressive deposits overlie high energy marine flooding surfaces demarcated by the substrate-controlled trace fossil suites, and typically contain pebbles and granules dispersed within muddy sandstones and sandy shales. Trace fossils are locally abundant and demonstrate the existence of marine conditions during deposition, typically near fairweather wave base. The transgressively-related deposits are characterised by interbedded tempestites and burrowed sandy or silty shales, reflecting conditions consistent with upper offshore to lower offshore conditions. The distribution of these facies types shows that the history of transgression during late Viking time was complex, with high frequency fluctuations in relative sea level. As well, there are considerable differences between the VE3 transgression and the VE4 transgression (*cf.* Boreen and Walker, 1990; Pattison, 1991a; Davies and Walker, 1993).

APPLICABILITY

This thesis has attempted to generate integrated ichnological-sedimentological models for a variety of depositional settings, as well as demonstrate the utility of ichnology to developing sequence stratigraphic analyses. Most of the proposed models, as well as the ichnological applications to stratigraphy, have not been based solely upon the thesis interval nor restricted to the thesis study area. The conceptual models, where possible, have been established using data from a variety of stratigraphic intervals of different ages and in a variety of locations, in order to optimise their range of applicability to the rock record. In general, the proposed models are *most* applicable to the Viking Formation and Peace River Formation and, to a lesser degree, to the Cretaceous of the Western Interior Seaway of North America. Additionally, however, the models and stratigraphic applications elucidated in thesis may also be appropriate, in varying degrees, to rock intervals of a variety of ages and tectonic settings. In a broader perspective, the approach used in this thesis - the integration of ichnology with sedimentology and stratigraphy - is seen to be fundamentally important in deriving viable paleoenvironmental interpretations and in resolving genetic stratigraphic histories. This is an under-utilised but powerful approach to the interpretation of the ancient record.

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