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ASPECTS OF MARGINAL MARINE SEDIMENTOLOGY, STRATIGRAPHY AND ICHNOLOGY OF THE UPPER CRETACEOUS HORSESHOE CANYON FORMATION, DRUMHELLER, ALBERTA.

BY
JASON MICHAEL LAVIGNE ©

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

DEPARTMENT OF EARTH AND ATMOSPHERIC SCIENCES

EDMONTON, ALBERTA

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Dr. S.G. Pemberton - Supervisor

Dr. C.R. Stelck

Dr. J.R. Spence

Date: oct 1/99

Human beings are perhaps never more frightening than when they are convinced beyond doubt that they are right.

Laurens Van der Post

DEDICATION

This thesis is dedicated to my father, William James Lavigne. Although not always understanding what I did or why I did it, he unconditionally supported my pursuits wholeheartedly, no matter how frivolous or whimsical they appeared. Thanks.

Jason

ABSTRACT

The lower portion of the Horseshoe Canyon Formation (Campanian-Maastrichtian) has been well documented to contain many characteristics of marginal marine depositional systems. Estuarine channels in the Horseshoe Canyon Formation are representative of deposition in distributary channels within a prograding deltaic complex. There is no evidence of a regional unconformity at the base of the channels. Erosive internal surfaces reflect allocyclic processes common in deltaic settings. The stratigraphic section at the Hoodoos Recreation Area identically conforms to the idealized sequence in a fluvial distributary system.

The borings of bivalves in wood (*Teredolites*) are common constituents of many marginal marine settings. Their stratigraphic utility depends on placing them within a detailed sedimentological and stratigraphic framework. Woodgrounds provide reliable, mappable surfaces significant in genetic stratigraphic studies. Log-grounds represent transported clasts that have little stratigraphic data associated with their occurrence.

ACKNOWLEDGEMENTS

It has been said that no work is truly the sole work of its author. This thesis is no exception. I have had the distinct privilege to work with and discuss all aspects with of this thesis with many highly talented individuals and have, although inadvertently, molded their ideas to the reality that lies beyond my rose-colored glasses. For this many apologies for warping such good ideas to suit my own needs.

George Pemberton is more than anyone has a right to ask of a supervisor. He believed in me when no one else did and he gave me a chance when no one else would. He always made sure I had food on the table, especially during tough times with the departmental Gestapo. He enthusiastically encouraged all of the hair-brained ideas that went through my head and let me learn from my own mistakes. He generously sent me to conferences and field trips and supported any other learning opportunity that arose.

Dave Eberth (Royal Tyrrell Museum) first introduced me to the study area and taught me everything I know about working in the field. Dave also offered his field data (much of it unpublished) to help me along. Special thanks also goes to all of the staff at the Tyrrell Museum for all of the support and assistance over the years, especially Dr. Dennis Brahman, Dr. Paul Johnson, Dr. Phil Currie, Kevin Aulenback, Tim Schowalter, and Deb Lister.

Carmen Pears was a more than capable field assistant from the fall of '95 until the summer of '98 most of which was unpaid and done out of the goodness of her heart. Thanks a million, you'll always have a special place in my heart.

Fellow students Mike Lawford, Brett Wrathal, Kevin Brett and Jeff Reinprecht were all excellent friends and colleagues and provided hours of fun and stimulating geological discussion (even if a lot of it was at the Power Plant).

Whether crashing mountain bikes in Moab or arguing about the marking of stratigraphy labs, Steve Hubbard was always a sheer joy to work with. He always had a keen eye for *Teredolities* and collected data from his own work simply to watch me get my jollies.

Eric Hanson was always there to help, whether running a field trip in Drumheller or taking me to "the John" to log core when I was broke. He has my deepest sympathies for logging 1000m of core that all looks the same.

I also have been very fortunate have been mentored by some of the most talented Doctoral students in existence. Tom Saunders knows the outcrops in the Drumheller area better than anyone. He ran a field trip at the beginning of my degree that will always be as memorable to me as it will be to the citizens of Rosedale. His immense knowledge and love of stratigraphy, sedimentology and ichnology is staggering. All of this Tom willingly and freely shared. Going to Toms' office was always a trip to a wonderfully magical place.

Murray Gingras proved to a remarkable friend and colleague and was never afraid to put me in my place in discussions, geological or otherwise. Over the course of my stay in Edmonton, Murray and I solved virtually every modern problem plaguing both geologists and society at large. If only we could find all of those beer-stained cigarette packages……

John-Paul Zonneveld also was a vast resource of knowledge whether it be rocks, fossils or how to tell a good scotch. J.P. generously took me along to Fort St. John to show me why I would never want to work there and then he and Eric reminded me again the following year. Some day he and I will have to get serious about "Terrasequences". Until then it is a great story and we will try not to let too many facts get in the way of that story.

Brief, but immensely helpful discussions with James MacEachearn, Mike Ranger, Gerry Reinson, Richard Evoy and Dave Mundy have all helped me understand many things which I didn't and they all did so cheerfull. Mike generously allowed me to tag along to Fort McMurray to assist in his field work.

Thanks also go to Rick Richardson (Alberta Research Council) who generously allowed me access to the vast database of geophysical logs in his care. The Dau and Dooley families in Drumheller are also thanked for permission to examine outcrops on their property. David Kistenfager and Geraldine Tonak (Talisman Energy) are thank for their tireless efforts in helping to collate the final document all though all errors are solely my own.

Words cannot express my eternal gratitude to Ron and Laura Pears of Carbon, Alberta for putting a roof over my head for much of the field work in Drumheller. They gave freely of their home, refrigerator, vehicles and wallets and most of the data presented in this thesis could have not have been collected without their support which was beyond generous.

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CHAPTER I

INTRODUCTION

Along the Red Deer River Valley near Drumheller, Alberta (Figure I-1A), outcrop of the Horseshoe Canyon Formation preserves transitional environments from fully marine, through marginal marine and into terrestrial strata. This outcrop is both continuous and easily accessible for about 100 km along the valley allowing direct observations to be made as to the nature and stratigraphic relationships of the strata in three dimensions. Regionally, the formation occurs in an arcuate band along the eastern edge of the Alberta central plains (Figure I-1B).

The present thesis deals with aspects of the marginal marine sedimentology, ichnology and stratigraphy as they apply to interpreting the ancient succession east of Drumheller. Chapter II deals with the deltaic Lower Horseshoe Canyon Formation and examines how autocyclic processes dominated during Cretaceous deposition. Chapter III deals with the trace fossil *Teredolites* and how its occurrences can be used in genetic stratigraphy and in palaeoenvironmental reconstruction.

STRATIGRAPHIC FRAMEWORK OF THE HORSESHOE CANYON FORMATION

The sediments of the Horseshoe Canyon Formation represent an overall regressive succession deposited during the final retreat of the Bearpaw Sea from the North American continent (Shepheard and Hills, 1970). This regressive event initiated just prior to the

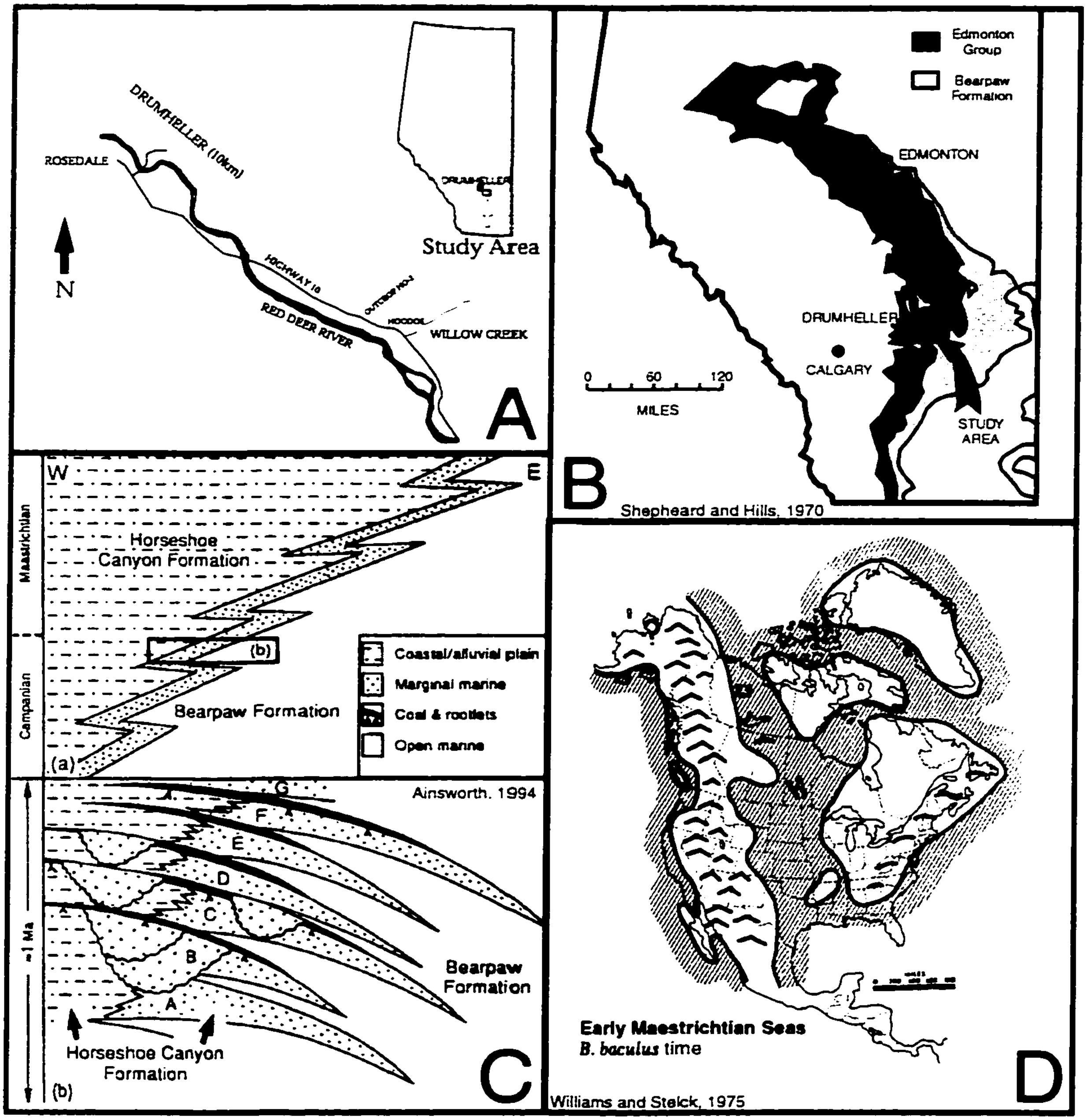
FIGURE I-1 **Location and Setting of the Horseshoe Canyon Formation in this Study.**

A) Location Map of the study area in southern Alberta.

B) Distribution of outcrop of the Bearpaw Formation and Edmonton Group in southern Alberta (from Shepheard and Hills, 1970).

C) Progradational nature of the Bearpaw-Horseshoe Canyon transition in Drumheller. Figure (b) shows several regressive wedges capped by coals (from Ainsworth, 1994).

D) Palaeogeographic reconstruction of North America during Horseshoe Canyon Formation time (from Williams and Stelck, 1975).


ROSEDALE
DRUMHELLER (10km)
Study Area
DRUMHELLER
N
HIGHWAY 10
OUTCROP HOLE
HOODOO
WILLOW CREEK
RED DEER RIVER
A
Edmonton Group
Bearpaw Formation
EDMONTON
DRUMHELLER
CALGARY
0 60 120
MILES
STUDY AREA
B
Shepheard and Hills, 1970
W
E
Maastrichtian
Campanian
Horseshoe Canyon Formation
(b)
Bearpaw Formation
(a)
Coastal/alluvial plain
Marginal marine
Coal & rootlets
Open marine
Ainsworth, 1994
G
F
E
D
C
B
A
≈1 Ma
Bearpaw Formation
Horseshoe Canyon Formation
(b)
C
Early Maestrichtian Seas
B. baculus time
D
Williams and Stelck, 1975

Campanian/ Maastrichtian boundary.

The Horseshoe Canyon Formation (Irish, 1970) lies conformably on top of the Bearpaw Formation and represents an eastward thinning clastic wedge deposited along the western margin of the Cretaceous Inland Seaway (Figure I-1D). In the Drumheller area, the transition consists of a series of paralic, sandy tongues locally capped by coals that interfinger with the marine mudstones of the Bearpaw Formation (Ainsworth, 1994, see Figure I-1C, this paper).

Due to the regressive nature of the contact, it is highly diachronous and youngs to the east. In the southern Alberta Plains, the Kneehills tuff of Allan and Sanderson (1945) lies near the base of the Battle Formation (*sensu* Irish, 1970). In east-central Alberta near Sheerness, the tuff lies conformably on marine mudstones of the Bearpaw Formation, clearly demonstrating the wedge-shaped geometry of the sedimentary package consisting of the Horseshoe Canyon and Whitemud Formations (Campbell, 1962).

In the Drumheller area, the Horseshoe Canyon Formation changes from marine deltaic shoreface sandstones at the lower contact, and passes up through estuarine and into fluvially-dominated systems higher in section. The upper, non-marine portion of the Formation consists predominantly of channels and their associated overbank deposits as well as numerous coals, carbonaceous mudstones, and ironstones. On average, the Formation is on the order of 750 feet (230m) thick (Irish 1970).

PREVIOUS WORK

The Horseshoe Canyon Formation was named by Irish (1970) to identify the deltaic and non-marine beds that separate the Bearpaw and Whitemud Formations. Since that time, much work has been done in examining the transition from the marine to the non-marine in the Drumheller area. This work was conducted in two phases. The first phase involved the work of Shepheard and Hills (1970), Gibson (1977), Waheed (1983) and Rahmani (1988). These works consisted primarily of sedimentological examinations, focusing on sedimentary structures and palaeoenvironmental reconstructions.

Shepheard and Hills (1970) interpreted the depositional environment as an ancient deltaic complex and mapped a sequence from the prodelta and delta front back to the lower floodplain environments and divided the package into six units as well. Rahmani (1988) noted facies relationships in channel deposits were reworked to reflect estuarine processes.

The second phase of exploration saw the incorporation of stratigraphic principles in examining the succession. The work of Saunders (1989) represented the first attempt to place the succession into a stratigraphic framework. Saunders incorporated ichnology and sedimentology and employed a transgressive-regressive stratigraphic approach in order to divide the package into three distinct stratigraphic zones.

Ainsworth (1994) applied an allostratigraphic approach to examining the Bearpaw-Horseshoe Canyon transition and divided the succession into seven informal allomembers. The area examined by Ainsworth represents a landward extension of the area studied by Saunders (1989). Chapter II examines the landward edge of the area studied by Ainsworth (1994).

NATURE AND AGE OF THE LOWER HORSESHOE CANYON FORMATION CONTACT

The contact between the Bearpaw and Horseshoe Canyon Formations is characterized by the interfingering of the marine mudstones of the Bearpaw and the marginal marine sandstones and mudstones of the Horseshoe Canyon Formation. The precise contact can be difficult to observe in outcrop and is almost impossible to discern from geophysical logs.

In the present study area, what is generally considered the contact is sharp and well exposed at the Hoodoos Recreational area where delta front sands of the Horseshoe Canyon Formation conformably overlie what are conventionally interpreted to be marine mudstones of the Bearpaw Formation (*sensu* Shepheard and Hills, 1970). Chapter II examines this convention and reinterprets this surface in a broader sedimentological and stratigraphical context.

In other areas, as well as many subsurface wells, the contact is not as easily discernable. This is often due to the fact that the uppermost Bearpaw Formation often contains a series of upwards coarsening mudstone to siltstone and sandstone cycles. In these situations, the contact is frequently placed at the base of the first major sandstone unit greater than 3m thick that caps a coarsening upwards cycle. (Dawson *et al.*, 1994)

The lack of a datable, regionally extensive stratigraphic marker at or near the Bearpaw-Horseshoe Canyon transition makes assigning an absolute date to this event extremely difficult. Lerbekmo and Coulter (1985) using magnetostratigraphic data placed the base of the Maastrichtian Stage at coal 5, which is coincident with the base of the *Baculites baculus* zone. This biostratigraphic horizon has an absolute date of 71 Ma (Lerbekmo and Coulter, 1985). The time transgressive nature of the Bearpaw- Horseshoe Canyon Formation contact further complicates absolute correlation. Its' diachronous nature implies that in the west, the contact is upper Campanian in age but in the east, the contact is almost Paleocene in age (based on the position of the Kneehills tuff dated at 66 Ma. by Folinsbee *et al.*, 1961). Bearpaw Formation sediments pinch out in the subsurface some 350km northwest of the study area (in the vicinity of 2-16-57-11W5, Dawson *et al.*, 1994). This indicates that the contact has significant areal extent and likely formed over an appreciable duration of time. It is therefore undesirable to infer that this surface represents a horizontal, time equivalent veneer that can be dated at one end and have that date correlated along its entire extent.

LITHOSTRATIGRAPHIC CORRELATION WITHIN THE HORSESHOE CANYON FORMATION

Thirteen coal seams locally numbered from 0 to 12 occur throughout the Horseshoe Canyon Formation (Gibson, 1977). In Drumheller, regionally traceable Coal 0 occurs approximately 25m above the commonly accepted Bearpaw- Horseshoe Canyon Formation contact (Ainsworth, 1994). The lateral continuity of these marginal marine coals is quite good as they are interpreted to have formed in widespread lower coastal plain environments.

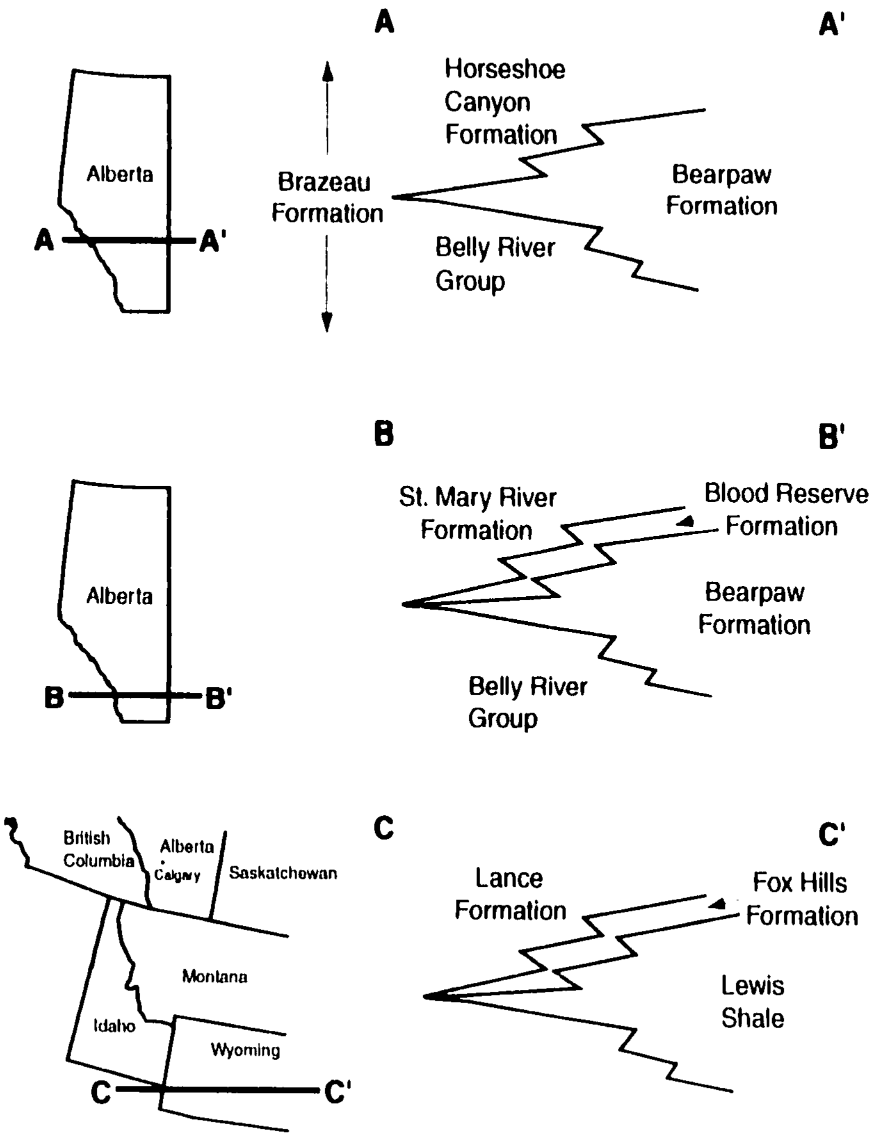
Coal seams higher in the Formation tend to be less distinct and often split into coal zones and carbonaceous mudstones. Coal zones typically comprise units on the order of several meters thick and are often very difficult to correlate locally. Some seams, such as seam #10 can be, however, used for regional lithostratigraphic correlation. Historically, this has led to much frustration over regional correlation of the non-marine portion of the Horseshoe Canyon Formation. Elliot (1960) voiced the common opinion of the time that the upper non-marine section of the Formation was universally regarded as "just so much 'crud' which must be drilled through before a more interesting section is encountered" (Elliot, 1960, p. 324; Elliot's quotation marks). The lack of a distinctive, regional marker between the Bearpaw Formation and Kneehills tuff leaves the stratigrapher working on the non-marine portion of the Horseshoe Canyon Formation in a veritable "no man's land".

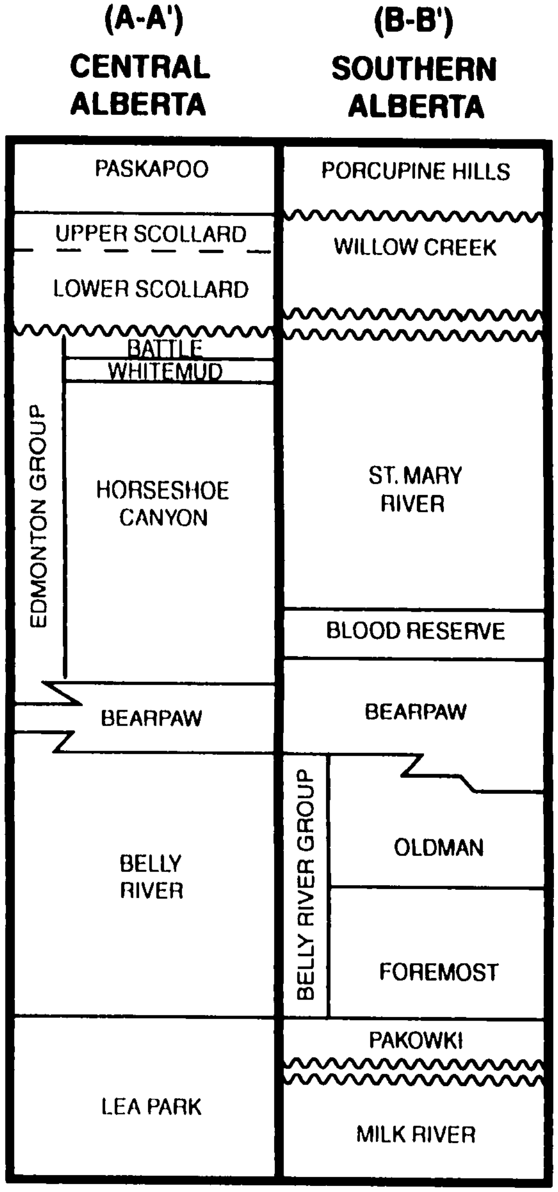
STRATIGRAPHIC NOMENCLATURE OF THE UPPERMOST CRETACEOUS OF MIDDLE NORTH AMERICA

In the central Alberta Plains, the various environments from marine through to non-marine have eluded an easily recognizable and widespread subdivision. This contrasts with Southern Alberta where the marine Blood Reserve Formation is the equivalent of the lower, marine Horseshoe Canyon Formation and the St. Mary's River Formation is equivalent to the upper, non-marine Horseshoe Canyon Formation

FIGURE I-2 **Stratigraphic Nomenclature in the Campanian-Maastrichtian section in Middle North America.**

Schematics on the left show the nomenclature used in describing formations at various geographic positions along the western margin of the Cretaceous Interior Seaway. Note the Stratigraphically equivalent units including 1) Lewis and Bearpaw Formations; 2) Fox Hills, Blood Reserve and Lower Horseshoe Canyon Formations; and 3) Lance, St. Mary River and Upper Horseshoe Canyon Formations. Stratigraphic charts for southern Alberta are included on the right (from Dawson *et al.*, 1994).





DAWSON *et al*, 1994

(Figure I-2).

In Wyoming, the Fox Hills Formation occupies the position equivalent to the lower, marine portion of the Horseshoe Canyon and Blood Reserve Formations. It contains virtually identical facies, as well as similar vertebrate and invertebrate body fossils and trace fossils as the Horseshoe Canyon Formation in Drumheller (Waage, 1968 and Land, 1972). In fact, Yarwood (1931) identified marine sandstones beneath the St. Mary's River Formation as "Fox Hills" in an exploration well in southern Alberta. This emphasizes the continuity of environments within the palaeogeographic setting shown by Williams and Stelck (1975, Figure I-1D, this paper) and demonstrates the persistence of facies throughout the basin at that time.

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CHAPTER II

ESTUARINE CHANNELS IN THE LOWER HORSESHOE CANYON FORMATION; DELTAIC DISTRIBUTARIES OR INCISED VALLEYS?

INTRODUCTION

Channel fills in the Horseshoe Canyon Formation near Drumheller, Alberta, demonstrate many of the sedimentological aspects considered to be characteristic of marginal marine depositional systems. Previous researchers have interpreted the deposits as being indicative of both multiple incised valley complexes and alternatively, as tidally-influenced estuaries (Rahmani, 1988 and Ainsworth, 1994).

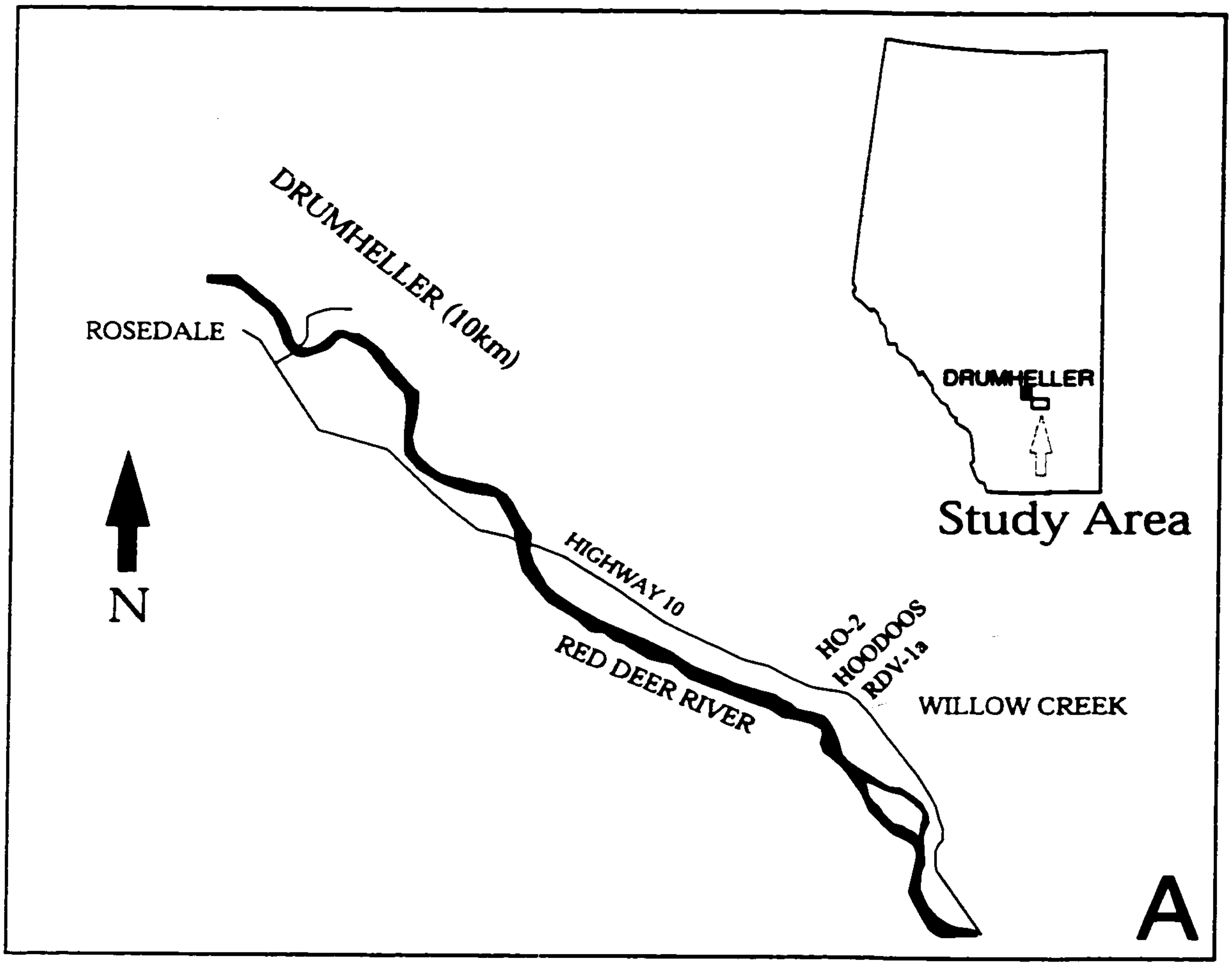
Since the 1970's, a large volume of research regarding estuarine systems has been produced. This is partially due to the general recognition that estuarine depositional systems typically reflect a complex array of sedimentological processes producing marked differences in facies distribution within estuarine deposits. Active research has also been spurred by the recognition that many ancient estuarine deposits contain economically significant volumes of hydrocarbons. This database affords reliable interpretations of depositional processes reflected in the Drumheller outcrops.

Much research has also been conducted in tidal sedimentology in the last decade. Many deposits in the Cretaceous of middle North America have been identified to contain evidence for ancient tidal activity. Excellent synopses of the criteria for tidal influence are provided in de Raaf and Boersma (1971), DeBoer *et al.* (1989), Nio and Yang (1991) and Shanley *et al.* (1992). Summarized briefly, some diagnostic criteria for the recognition of tidal influence in ancient stratigraphic sections include: tidal bundles (Visser, 1980; Allen, 1981; Smith, 1988; Middleton, 1991); flaser, wavy and lenticular bedding (Reineck and Wunderlich, 1968); cross bedding with evidence for current reversals (Kreisa and Moiola, 1986 and Middleton, 1991;); reactivation surfaces (de Mowbray and Visser, 1984) and sigmoidal bedding (Kreisa and Moiola, 1986; Shanley *et al.*, 1992).

The Horseshoe Canyon Formation (Campanian/Maastrichtian) in southern Alberta displays excellent outcrop examples of estuarine channels. The channel deposits are exposed along Willow Creek, a tributary of the Red Deer River just east of Drumheller, Alberta (Figure II-1). Basal portions of the Formation represent a complex interfingering of marine and marginal marine deposition. Land (1972) documented a similar relationship in the contemporaneous deposits of the Fox Hills Sandstone in Wyoming.

The outcrop section present is approximately parallel to the inferred depositional strike of the study area. These outcrop examples of estuarine channels have been well documented by previous researchers (Nio and Yang, 1991; Ainsworth, 1994; Ainsworth and Walker, 1994 and Eberth, 1996). The abundance of tidal sedimentary structures has led previous workers to interpret the succession as a series of tidally-dominated estuarine channels. Ainsworth (1994) attempted to resolve whether the channel complex represented multiple incised valley fills that had been cut into each other or alternatively, "by the persistent shifting of one channel within the large incision" (Ainsworth, 1994, pg. 60). The purpose of this study is to evaluate the allostratigraphic framework proposed by Ainsworth, (1994) by examining the depositional setting of the units.

FIGURE II-1 **Location map of the study area.**


DRUMHELLER (10km)
ROSEDALE
N
HIGHWAY 10
RED DEER RIVER
HO-2
HOODOOS
RDV-1a
WILLOW CREEK
DRUMHELLER
Study Area
A

ESTUARINE FACIES MODELS

Estuaries are defined as a "semi enclosed coastal body of water which has free access to the ocean and which seawater is measurably diluted by freshwater from land drainage." (Pritchard, 1967). This definition is of little use to the geologist due to the fact that the physical processes responsible for the resultant sedimentary facies are not directly controlled by the salinity of the water (Dalrymple and Zaitlin, 1989). In addition, a variety of environments such as deltaic distributary channels, lagoons and portions of back barrier bays also are constrained by the similar physical conditions. Estuarine deposits must be classified on the basis of the geometric distribution of the sediments as well as the relationships to laterally adjacent sedimentary facies.

The interpretation of salinity is not based on the sediments themselves, so much as the response of organisms living within the depositional system. Despite the inability to quantitatively determine the salinity of an ancient succession, its effect on organisms and their resultant biogenic structures in estuarine environments has been used to assign ancient stratigraphic successions to a specific position within an estuarine system (Howard *et al.*, 1975, Howard and Frey, 1975, Pemberton *et al.*, 1982). To this end, a growing body of literature exists dealing with brackish water trace fossil assemblages (Wightman *et al.*, 1987; Pemberton and Wightman, 1992; and Gingras *et al.*, 1999).

In general, trace fossil assemblages in brackish water settings are typified by diminutive size, simple morphologies, low diversity, high abundance and traces from both the *Skolithos* and *Cruziana* ichnofacies (Wightman *et al.*,1987; Benyon *et al.*, 1988; Bechtel *et al.*, 1994; and Pemberton and Wightman, 1997). The application of ichnological analysis in conjunction with detailed sedimentological and stratigraphic frameworks enables an even more accurate interpretation of depositional environments.

Modern estuaries show distinct zonations of organisms from fluvial to marine-dominated portions (Howard *et al.*, 1975; Gingras *et al.*, 1998). While salinity exhibits a major control on the distribution of organisms in estuarine settings, other factors such as substrate texture, sedimentation rates, oxygen and turbidity also are critical and may preclude colonization of certain portions of estuarine systems. To this end Dalrymple *et al.* (1992) summarized the key processes involved in estuarine settings and noted a complex interplay of wave, tidal and fluvial processes (Figure II-2a). They also described a typical tripartite subdivision of modern estuaries consisting of marine sand, estuarine mud and fluvial sand.

Of particular interest to this paper are the estuarine muds, interpreted to represent the ancient turbidity maximum. This feature results from the interaction of suspended clay with landward directed saline bottom water which is forced up-estuary during tidal cycles. At the landward edge of the saline intrusion, density currents arising from contact with seaward-directed fluvial discharge creating the null zone (Allen, 1991). Here, suspended clays lump together in a process known as flocculation and may be deposited from suspension as sand-sized clusters.

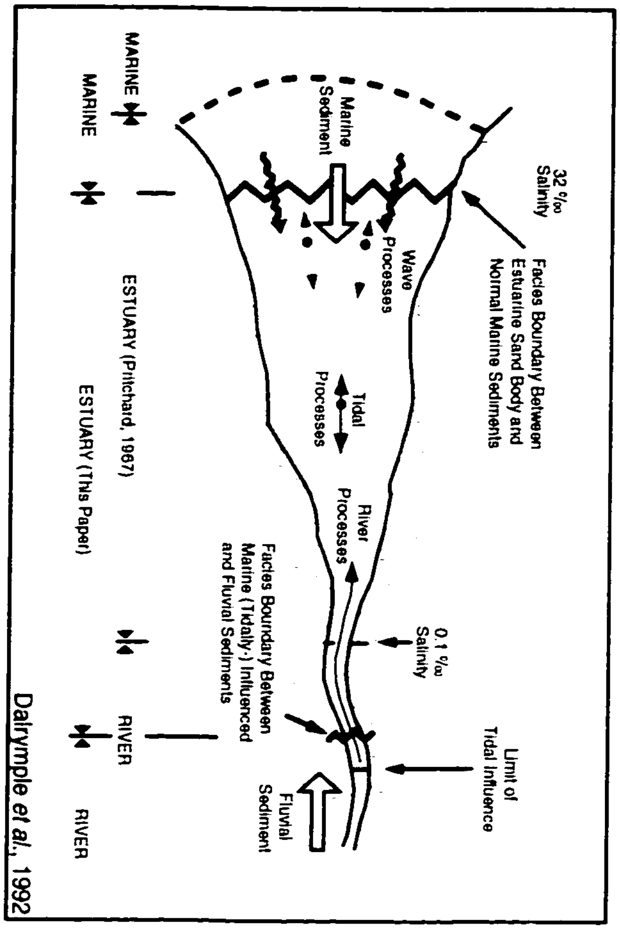
The position of the turbidity maximum is dependent on the tidal range, wave energy, fluvial discharge (Dalrymple *et al.*,1992) as well as the nature of the suspension load. Each of these parameters is variable (and often seasonal) and therefore the turbidity maximum moves within the estuarine system. Allen (1991), for instance, noted variations within the position of the turbidity maximum in the Gironde Estuary (France) as a

FIGURE II-2 **Major processes affecting estuarine sedimentation.**

A) Schematic representation of the complex interplay of wave, tidal and riverine processes on estuarine deposits. Note how the current definition of the estuary is modified from a geologically indiscernible parameter (absolute salinity) to the geologically perceivable facies contact (Dalrymple *et al.*, 1992).

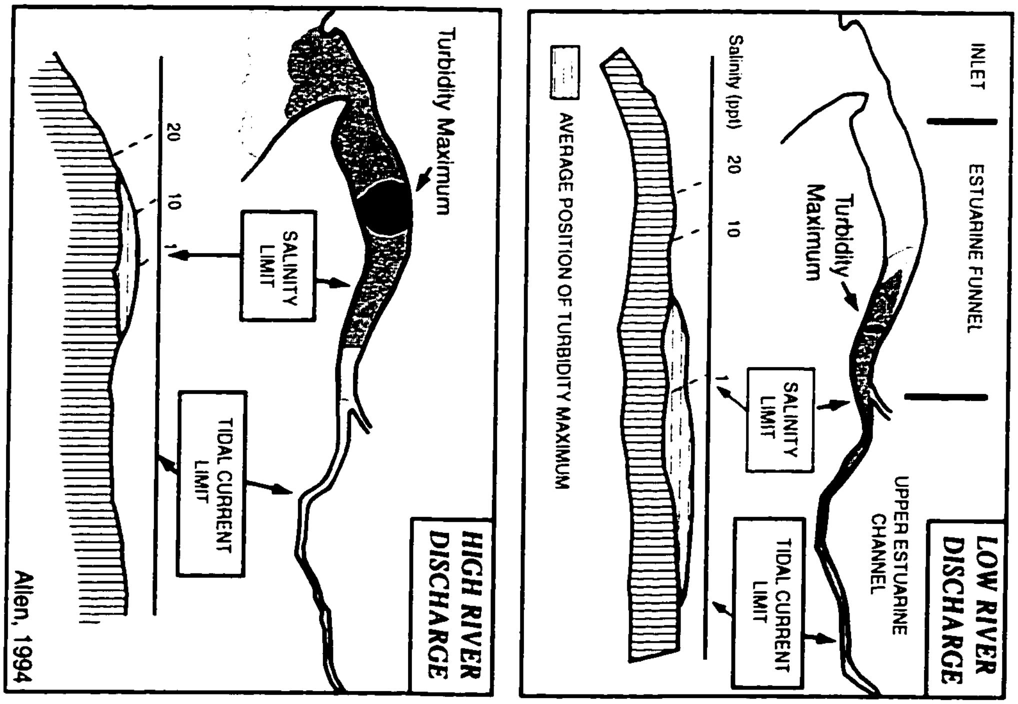
B) Hydraulic setting in the Gironde estuary, France (Allen, 1994). The turbidity maximum can be seen to migrate due to seasonal fluctuations in fluvial discharge. Note also that the tidal current limit occurs some 40 km landward of the salt intrusion.

A



Dalrymple *et al.*, 1992

B



Allen, 1994

function of fluctuation in fluvial discharge (Figure II-2b). Periods of high fluvial discharge resulted in the seaward migration of the turbidity maximum on the order of 20km. Complexities such as this dictate that care should be taken to identify the expression of this autocyclic process in the rock record.

ESTUARINE DEPOSITS IN THE HORSESHOE CANYON FORMATION

The contact between the Bearpaw and Horseshoe Canyon Formations is difficult to consistently place. The transition zone consists of a series of transgressive marine tongues in a marginal marine setting, the uppermost portions of which consist of a series of coarsening upward cycles. The upper contact is generally placed at the base of the first major sand unit greater than 3m thick that caps a coarsening upwards cycle (Dawson *et al.*, 1994). Correlations utilizing this convention may be inaccurate due to the fact that a regionally extensive stratigraphic marker is lacking at this horizon, rendering the correlation of these thin sands tenuous. As the contact reflects the retreat of the epeiric sea from the continent, it is strongly diachronous; the contact is oldest in the west and youngs to the east.

Despite problems with the placement of the boundary it is desirable to use a stratigraphic horizon if one is available, especially in outcrop studies. At the Hoodoos Recreation Area (Figure II-3a), a sharp contact near the base of the section is generally regarded as the Bearpaw/Horseshoe Canyon Formation contact (i.e. Shepheard and Hills, 1970, Plate 2, fig. 4). It corresponds to the contact between allomembers A and B of Ainsworth (1994). Here, the transition consists of horizontally laminated shale with cm-scale interbedded siltstones and sandstones that are sharply overlain by a thick, relatively massive sandstone. Ainsworth (1994) placed a sequence boundary at this level due to the perceived regional incision of channels at this horizon. The present disputes the interpretation of this surface as a sequence boundary.

Additionally, it is suggested that this is not the best horizon to place the Bearpaw/ Horseshoe Canyon contact. It is not favored as a sequence boundary because of the fact that while it is sharp locally, other areas show a gradational transition into the overlying coarse-grained sandstones (Figure II-3b).

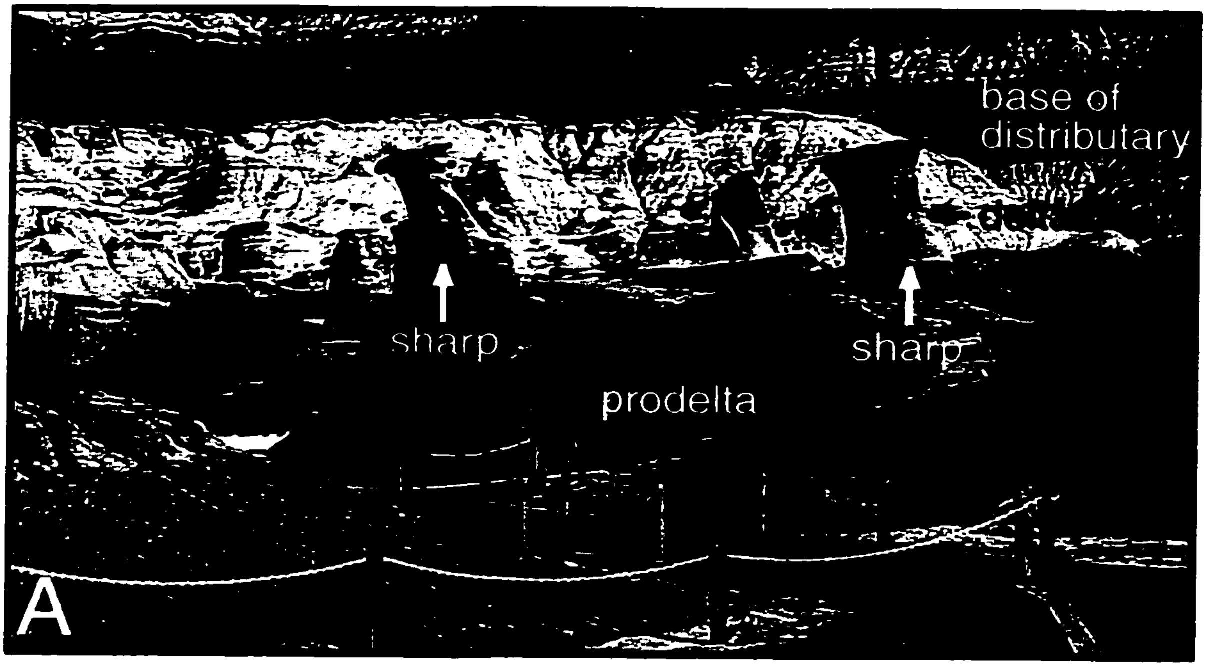
The underlying Bearpaw Formation contains open marine fossils of the *Baculites baculus* zone. The mudstones at the Hoodoos are generally barren of body fossils and contain only rare diminutive *Planolites*. This suggests a stressed environmental setting. Marginal marine environments are generally characterized by stressed to absent trace fossil assemblages due to stresses imposed by episodic sedimentation, overall high rates of sedimentation and frequent salinity fluctuations. Due to differences in fossil content, it is suggested that the basal portion of the section at the Hoodoos Recreation Area is not the Bearpaw Formation. The true contact would exist where these mudstones and siltstones rest conformably on more open marine mudstones of the Bearpaw Formation.

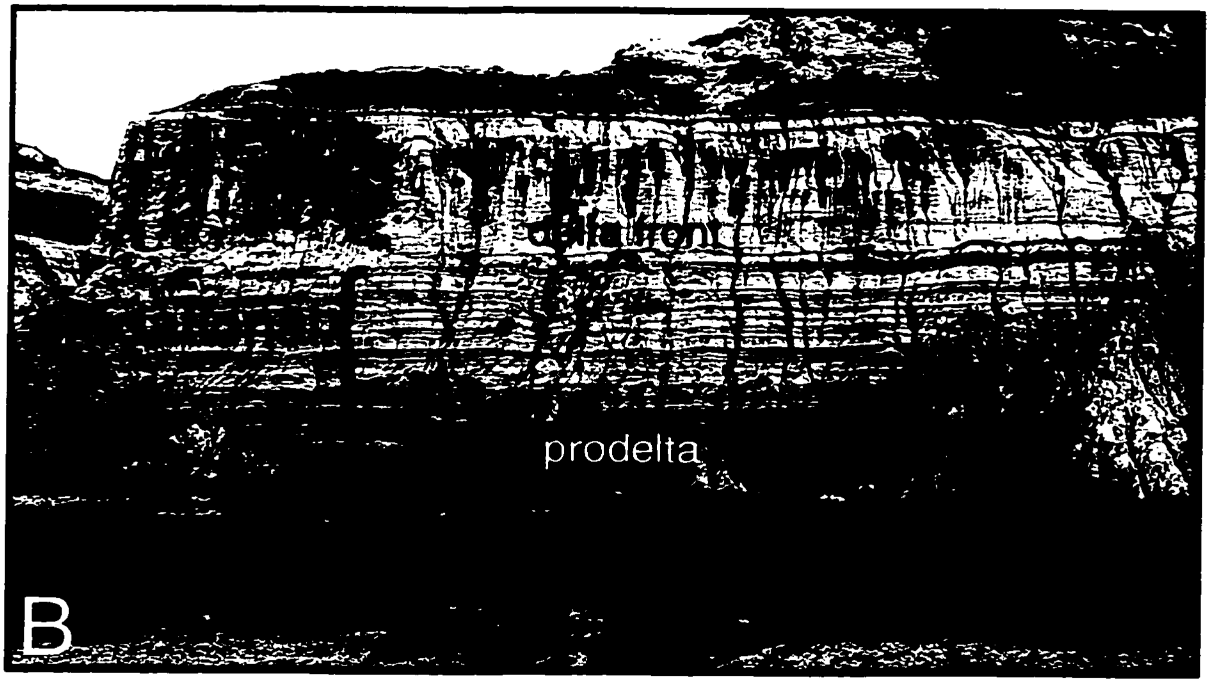
Stratigraphic cross-sections through the area are generally constructed utilizing coal seams as datums (as in Rahmani, 1988). From a genetic standpoint, coals are the only regionally mappable and easily identifiable units in the stratal package. Due to a complex interfingering of dynamic depositional systems, the exact contact between the Formations may be of a lesser importance than identifying the interval as a transition zone.

FIGURE II-3 **Nature of the Bearpaw-Horseshoe Canyon Formation Transition.**

A) Sharp, erosive contact between prodelta interbedded mudstone and sandstone and overlying delta front sandstone at the Hoodoos Recreation Area.

B) The same contact, seen 10 km basinward. Here the contact has lost its erosive character and is much more gradational suggesting a conformable transition.


base of
distributary
sharp
sharp
prodelta
A


delta front
prodelta
B

STRATIGRAPHIC POSITION OF THE WILLOW CREEK CHANNEL UNITS

Ainsworth and Walker (1994) gave a detailed discussion of the stratigraphic position of the Willow Creek estuarine valley system. The channel system lies directly on top of the prodeltaic mudstones of allomember A of Ainsworth (1994). This contact has been considered a potential sequence boundary by the aforementioned authors although neither lateral margin of the channel system was observed. The lack of lateral bounding surfaces makes interpretations of an incised valley system difficult to substantiate.

Reinson (1992) stressed the importance of basal unconformities in placing estuarine deposits in a sequence stratigraphic framework. Estuaries are generally regarded as transgressive features and should therefore lie directly above regional unconformities.

In Willow Creek, the basal unconformity is poorly documented. Locally, there is a sharp contact between the prograding deltaic deposits and the overlying channel units. In other areas of the Red Deer River Valley, the gradational nature of the contact makes the interpretation of the surface as representative of an unconformity problematic.

The outcrop belt in the Drumheller Valley is often praised for its excellent three-dimensional exposure of a regressive shoreline succession. While this is certainly true for much of the outcrop, in the case of the channels in Willow Creek, present outcrop geometry is somewhat frustrating as the northern lateral margin of the channel system is not exposed in outcrop. This hinders the identification of the unit into which the channel systems are cut. Previous workers have failed to recognize the southern margin as being exposed at the newly measured section at the Hoodoos Recreation Area (for description, see Figure II-12).

SEDIMENTOLOGICAL AND PALAEOECOLOGICAL EVIDENCE OF A MECHANISM TO GENERATE VARIABLE INTERNAL ARCHITECTURE OF THE CHANNEL FILLS

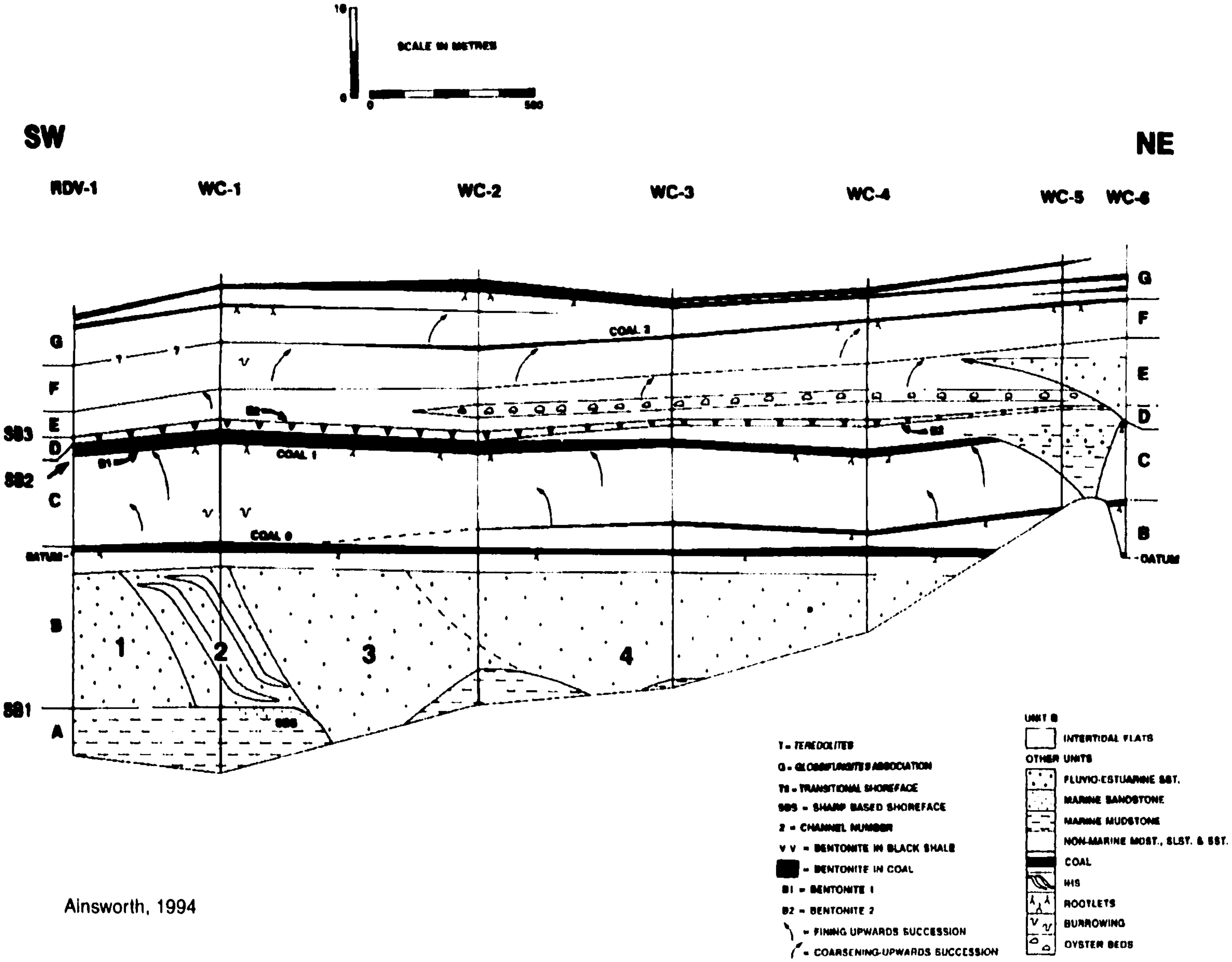
Of the four channel systems described by Ainsworth (1994)(Figure II-4), three are sand- dominated with only the second unit containing a significant mud component. This does not necessarily imply a genetic difference in the channel formation, but may rather represent a shift of the relative position of the turbidity maximum through time during the successive infilling of the individual channel units.

The mud content of the second channel unit is present in the form of inclined heterolithic stratification (IHS) (Thomas *et al.*, 1987) which were deposited on lateral accretion surfaces of point bars. In this channel unit, this type of deposition is a result of proximity of the turbidity maximum. While typically IHS are thought of as being deposited as mud during slack water and sand during flow conditions as a result of diurnal tidal reversals, Clifton and Phillips (1973) documented IHS being deposited over a longer temporal scale as a result of seasonal fluctuations in the turbidity maximum. This suggests that not all IHS deposits are created equal and while being indicative of tidal influence, they cannot absolutely be taken as an expression of diurnal cycles.

The predominantly sand-filled units of channels 1, 3 and 4 also contain prominent lateral accretion bedding. Lacking the heterolithic character, these accretion beds would be referred to as epsilon cross-bedding, the bedding surfaces of which are commonly demarcated by siderite pebbles. This underscores the fact that when considering epsilon cross-bedding versus IHS, the depositional processes may be identical, but the position

FIGURE II-4 **Relationship of channel units at the basal portion of the Willow Creek section.**

This work examines the channel fills and interprets them as deltaic distributaries. They erosively overlay the mudstones and siltstones of the prodelta (Allomember A of Ainsworth, 1994).



Ainsworth, 1994

within a marginal marine depositional system can dictate the resultant sedimentary expression.

Ichnological Evidence for Variability in the Position of the Turbidity Maximum

Modern point bars in brackish water settings contain an abundance of traces characteristic of the *Skolithos* and *Cruziana* ichnofacies (Wightman *et al.*, 1987). Figure II-5a shows the tubes of maldainid polychaetes preserved on a muddy point bar of a modern tidal creek in Willapa Bay, Washington. This ichnocenose also contains traces created by bivalves, crustaceans and polycheates.

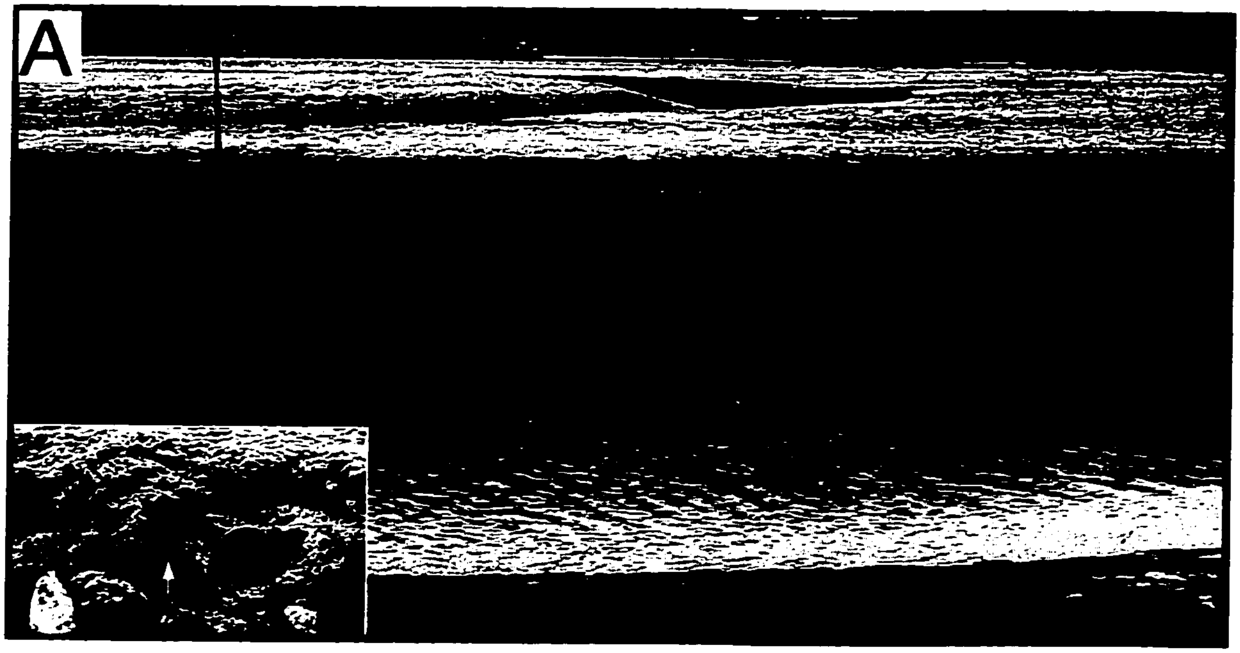
Ancient examples of brackish water trace fossil assemblages have also been well documented. Bechtel *et al.* (1994) and Wightman and Pemberton (1997) described IHS dominated estuarine channel fills in the Lower Cretaceous McMurray Formation to be dominated by *Gyrolithus*, *Cylindrichnus* and *Teichichnus* (Figure II-5b). These assemblages were interpreted to represent opportunistic colonization of newly deposited substrates during slack water periods.

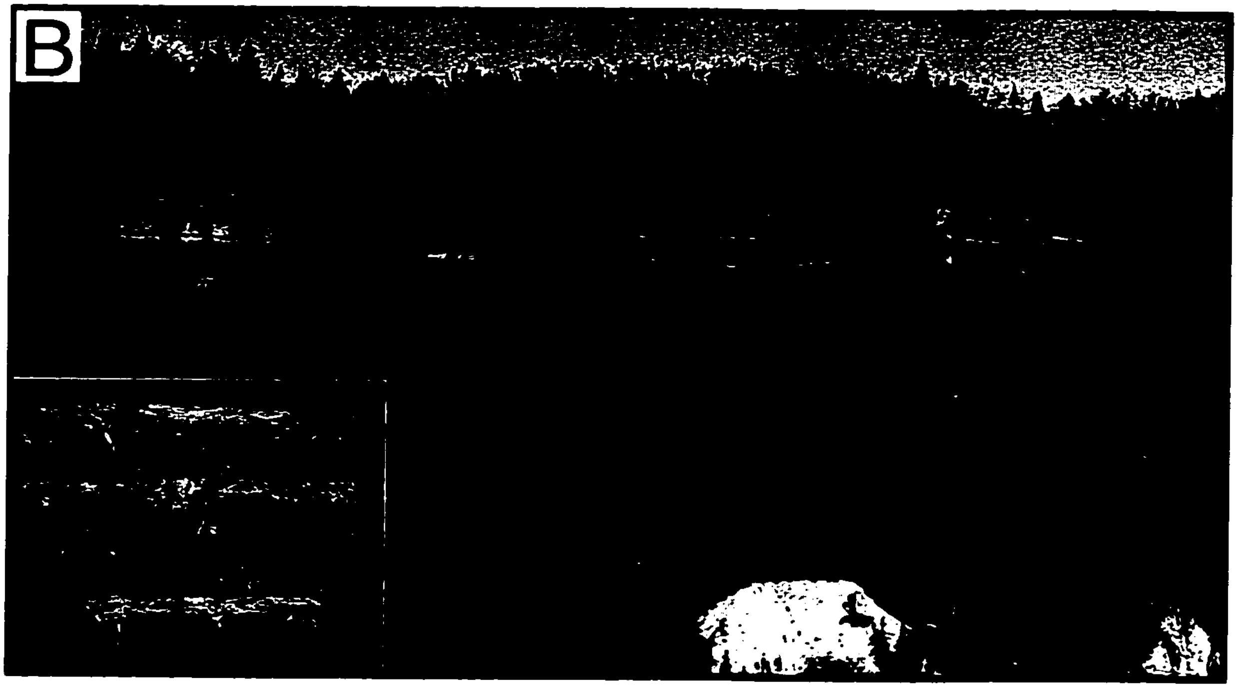
The muddy component of IHS successions are often deposited on estuarine point bars at slack water periods resulting from low current energy during tidal reversals. This provides burrowing organisms a short time to colonize the newly deposited muddy substrate deposited on the point bar. The hiatus at these horizons was termed the colonization window by Pollard *et al.*, 1993 (see Figure II-6). This concept is of fundamental importance in the interpretation of ancient tidally-influenced successions. Even in higher energy, sand-dominated IHS successions, the presence of finer-grained

FIGURE II-5 **Comparison of modern and ancient point bar settings.**

A) Modern intertidal point bar in Willapa Bay, Washington showing inclined lateral accretion within reexhumed point bar deposits on the cutbank of a modern tidal channel. Inset at bottom left shows the tubes of Maldainid polycheates (arrowed) within these deposits.

B) Large-scale lateral accretion beds (IHS) in the Lower Cretaceous McMurray Formation on the Steepbank River near Fort McMurray, Alberta. The estuarine deposits unconformably overly the Devonian Waterways Formation (the white unit at the base of the outcrop section). The inset at the lower left shows a series of muddy accretion beds densely burrowed with *Cylindrichnus*.


A


B

accretion surfaces implies a significant decrease in current energy that should allow for colonization by infaunal organisms. In some examples within the McMurray Formation, the slack water period is interpreted to be a seasonal phenomenon due to the thickness of the slack water deposits and allowing for the time

required to develop certain trace fossils (i.e. *Cylindrichnus*). This corresponds to the more densely colonized bottom sets of Pollard *et al.* (1993) while simpler traces occupy a narrower colonization window on the foresets of laterally migrating point bars on a semi-diurnal to seasonal scale (Figure II-6).

Ichnology of Willow Creek Channels

Inthe Horseshoe Canyon Formation, the second channel unit in Willow Creek (Ainsworth ,1994) is comprised of distinct, muddy IHS. Several of the more pronounced accretion surfaces contain tidal rhythmites (Figure II-7a). Nio and Yang (1991) described a neap/spring cyclicity to these units which contain various proportions of sand, mud and carbonaceous material described as 'triplets' by Ainsworth and Walker (1994).

The tidal rhythmites are distinctive in that they lack biogenic structures. Thin section analysis of the sandy units reveals that paired carbonaceous drapes are composed of micro scale back-flow ripples (Figure II-7b) representing periodic expression of the subordinate flow direction (i.e. flood stage).

Estuarine environments contain two major stresses that could preclude trace-making organisms; high rates of sedimentation and fluctuating salinity. The preservation of tidal rhythmites without internal erosion surfaces suggests reasonably high rates of

FIGURE II-6 **The "colonization window" in point bar successions.**

Estuarine environments are subject to sedimentation and salinity stresses that may preclude trace-making organisms except during periods of relative quiescence. During these periods, a continuous treadmill of colonization occurs on the trough and foresets of bedforms. This colonization may occur on a seasonal basis (possibly indicative of neap tidal cycles). Photo "A" shows such a surface in estuarine point bar deposits within the Lower Cretaceous McMurray Formation. The lower set of foresets has its upper surface colonized predominantly by *Cylindrichnus*. The overlying bedform consists of another set of unburrowed foresets (lens cap for scale). Bottom set beds and reactivation surfaces may be exposed longer and exhibit more extensive bioturbation. This is more similar to trace fossils from less stressed environments where colonization has a greater temporal duration and results in multi-tiered ichnofabrics. There is a much higher diversity as a result of less physical stress constraining the activities of infaunal organisms. Photo B shows such an assemblage of traces in open marine deposits of the Lower Cretaceous Wabiscaw Formation. *Rosselia*, *Asterosoma* and *Chondrites* (arrowed Ro, As and Ch respectively) are shown. Note how the *Asterosoma* crosscut both *Rosselia* and *Chondrites*. (Schematic portion of the diagram after Pollard *et al.*, 1993).

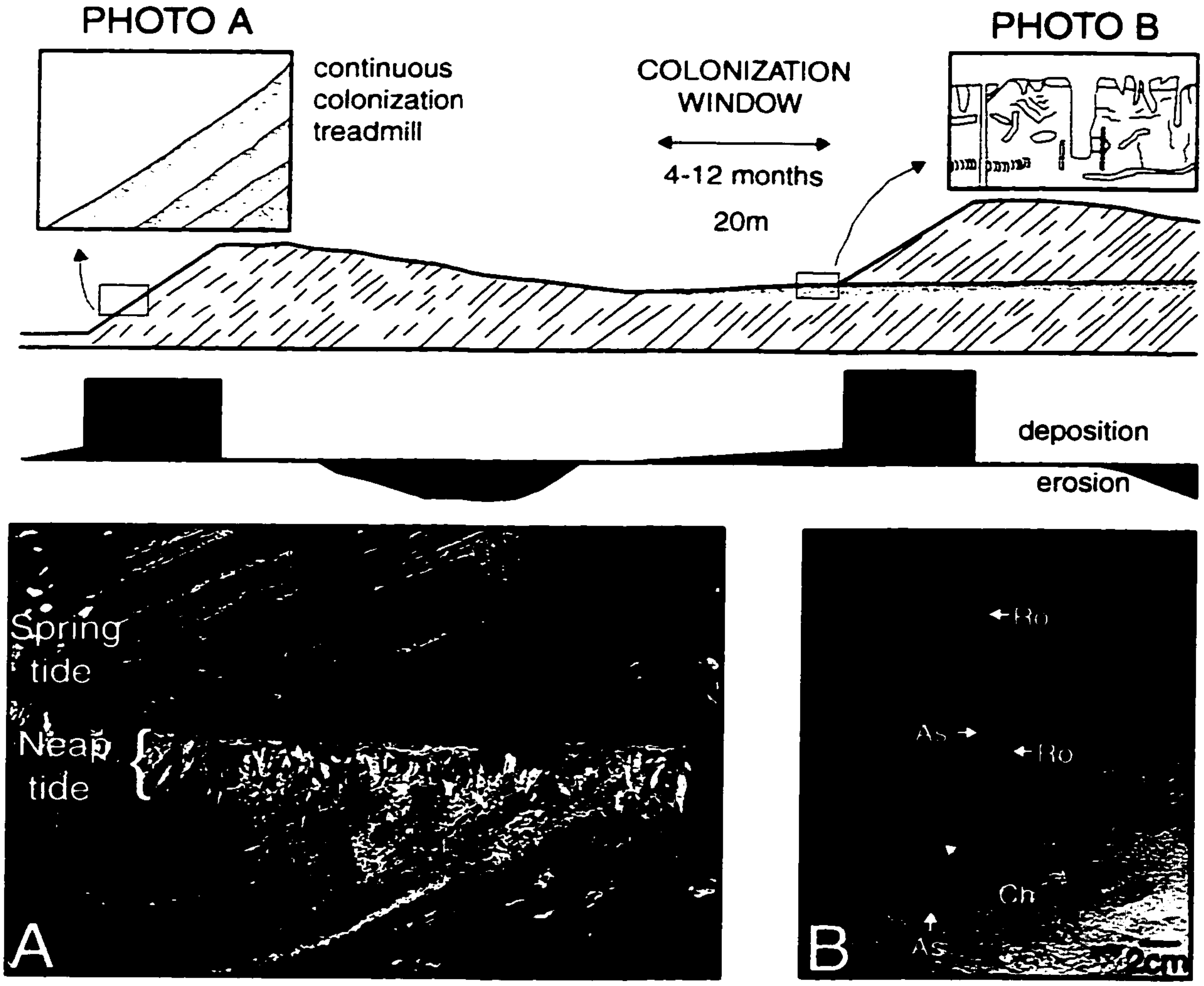
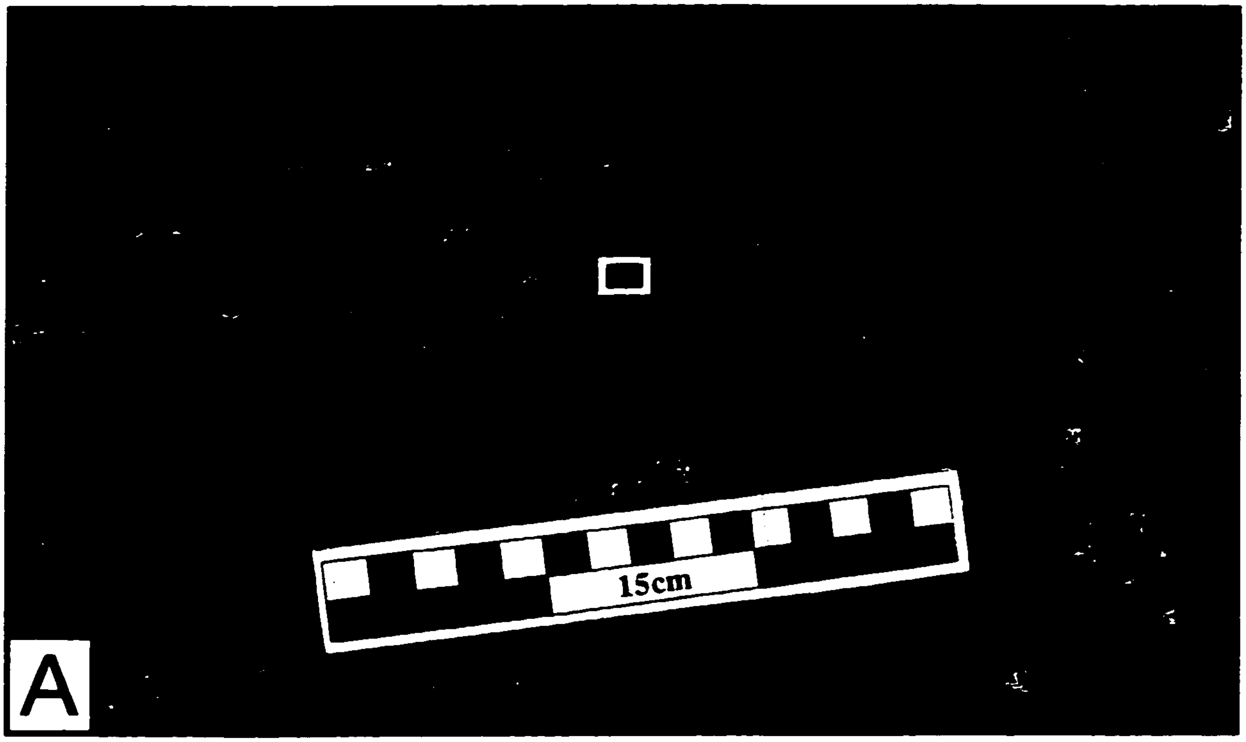


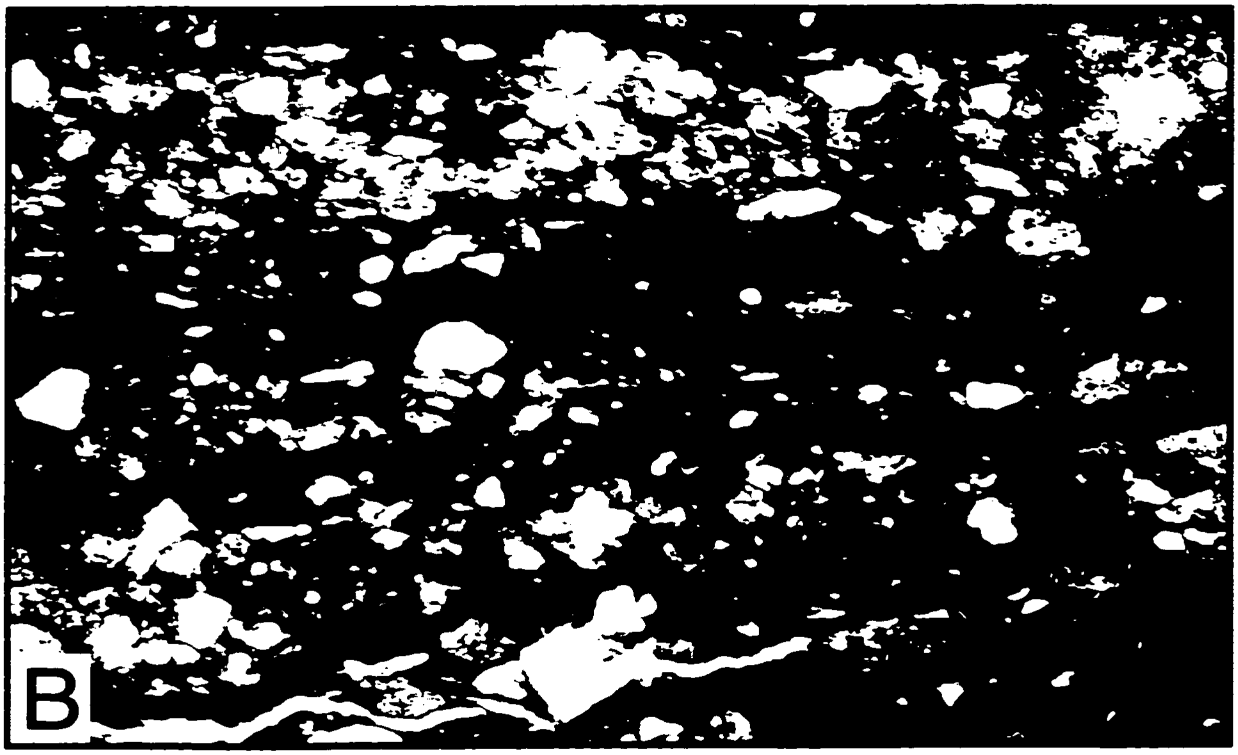
PHOTO A
continuous
colonization
treadmill
COLONIZATION
WINDOW
4-12 months
20m
PHOTO B
deposition
erosion
Spring
tide
Neap
tide
A
Ro
As
Ro
Ch
As
B
2cm

FIGURE II-7 **Tidal bundles in Willow creek.**

A) Detail of sandstone, mudstone and carbonaceous triplets in point bar deposits of Channel Unit 2.

B) Thin section photomicrograph of tidal bundles showing small-scale ripples defined by carbonaceous detritus between sandstone layers (dense bands of quartz grains). PPLx90.


15cm
A


B

sedimentation. The thickness of the sand units containing paired carbonaceous drapes (daily deposition?) are generally on the order of 3mm thick. This, coupled with the cm thick muddy heteroliths implies that sedimentation rates were not rapid enough to exclude burrowing organisms but may be rapid enough to mask traces of bioturbation.

As freshwater settings generally contain a paucity of trace fossils, the complete absence of trace fossils seems to be suggestive of extreme brackish or fresh water, fluvial deposition. Conversely, the presence of tidally generated sedimentary structures implies a tidal influence. Despite this apparent paradox, the association of tidal sedimentary structures in a fluvial setting can be explained based on the physiographic configuration of the hinterland. Depositional slopes in the central plains during the Cretaceous are generally regarded as being extremely flat. In this setting, even in microtidal systems, the tidal prism translates up estuaries for large distances. Tidal backwater effects can therefore extend well beyond the extension of the salt wedge (Allen, 1991, see Figure II-2b, this paper). These freshwater tides are capable of producing sedimentary structures generally regarded as tidal despite being deposited in freshwater. In essence, they reflect tidal energies without expressing marine chemistries. Ultimately, it is almost impossible to separate the effects of salinity and sedimentation rates.

Both sedimentation and salinity stresses likely worked in tandem to varying degrees and result in the absence of traces. The interpretation of salinity and sedimentation rates place channel unit 2 in Willow Creek at the landward edge of the turbidity maximum.

Based on sedimentological and ichnological evidence each of the channel units in Willow Creek has been placed at an interpreted palaeogeographic position relative to the turbidity maximum (Figure II-8). Channel 1 has been assigned to a position seaward of the turbidity maximum due to the presence of large, broad *Diplocraterion*.

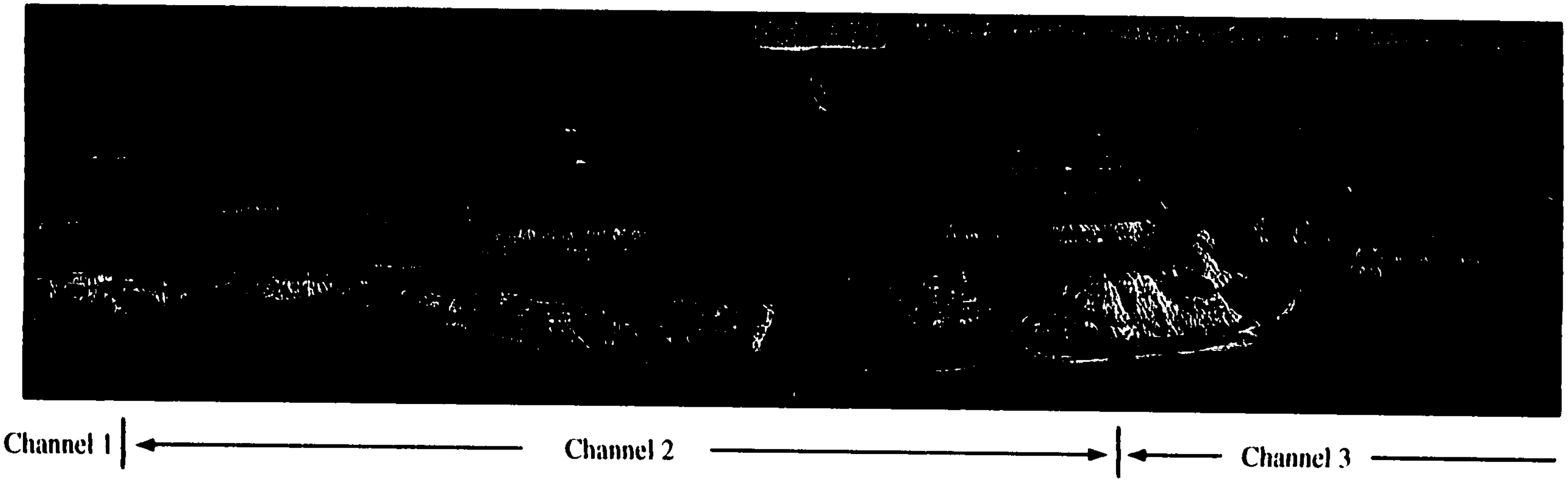
Channel 2 is assigned to the marine end of the turbidity maximum due to the predominance of muddy IHS, occurrence of tidally derived sedimentary structures and lack of trace fossils. The turbidity maximum within this channel unit can also be observed in outcrop approximately 500m landward of locality RDV-1a. (Figure II-9). Channels 3 and 4 are assigned to positions well landward of the turbidity maximum in that they both contain less distinctive tidal influence (occasional paired carbonaceous drapes on foresets of trough cross-beds) and are devoid of biogenic structures. On the whole, the channels show less marine influence to the northeast, which suggests that the Willow Creek outcrops were being deposited further from the palaeoshoreline through time.

DELTAIC DISTRIBUTARIES OR INCISED VALLEYS?

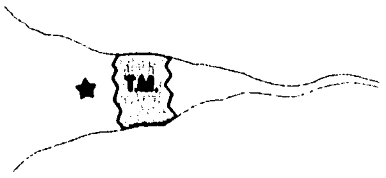
The interpretation of the estuarine channel system being floored by an unconformity is highly dependent on the nature of the relationship between sediments above and below the stratigraphic discontinuity in question. In the Willow Creek area, the underlying allomember A consists of a heterolithic, muddy prodeltaic sequence. If the overlying channel system can be shown to represent distributary channels in a delta front succession, the resulting stratigraphic section is conformable and represents the natural vertical transition of environments in a prograding deltaic system. It cannot, therefore, be considered a sequence boundary.

FIGURE II-8 **Interpretation of channel units as a function of relative position to the turbidity maximum.**

Based on sedimentological and ichnological criterion, each of the channel units of Ainsworth (1994) can be placed along an estuarine profile relative to the position of the turbidity maximum. The channels young to the right of the photo and show a progressive decrease in marine influence as they represent positions further from the shoreline at their respective times of deposition.

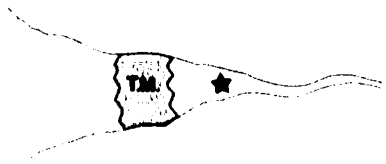


CHANNEL 1



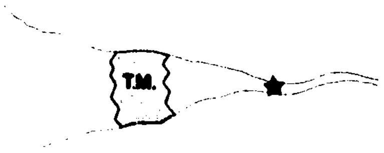
Erosive intraformational siltstone cobble conglomeratic base. Large *Diplocraterion*.

CHANNEL 2



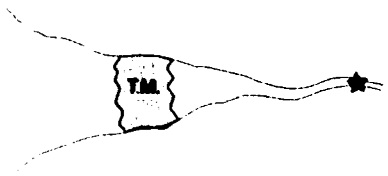
Muddy IHS beds. Tidal bundles consisting of mud, sand and carbonaceous triplets. Microscopic backflow ripples on accretion surfaces. No bioturbation.

CHANNEL 3



Tough cross bedded sandstone with carbonaceous debris in troughs. No bioturation.

CHANNEL 4

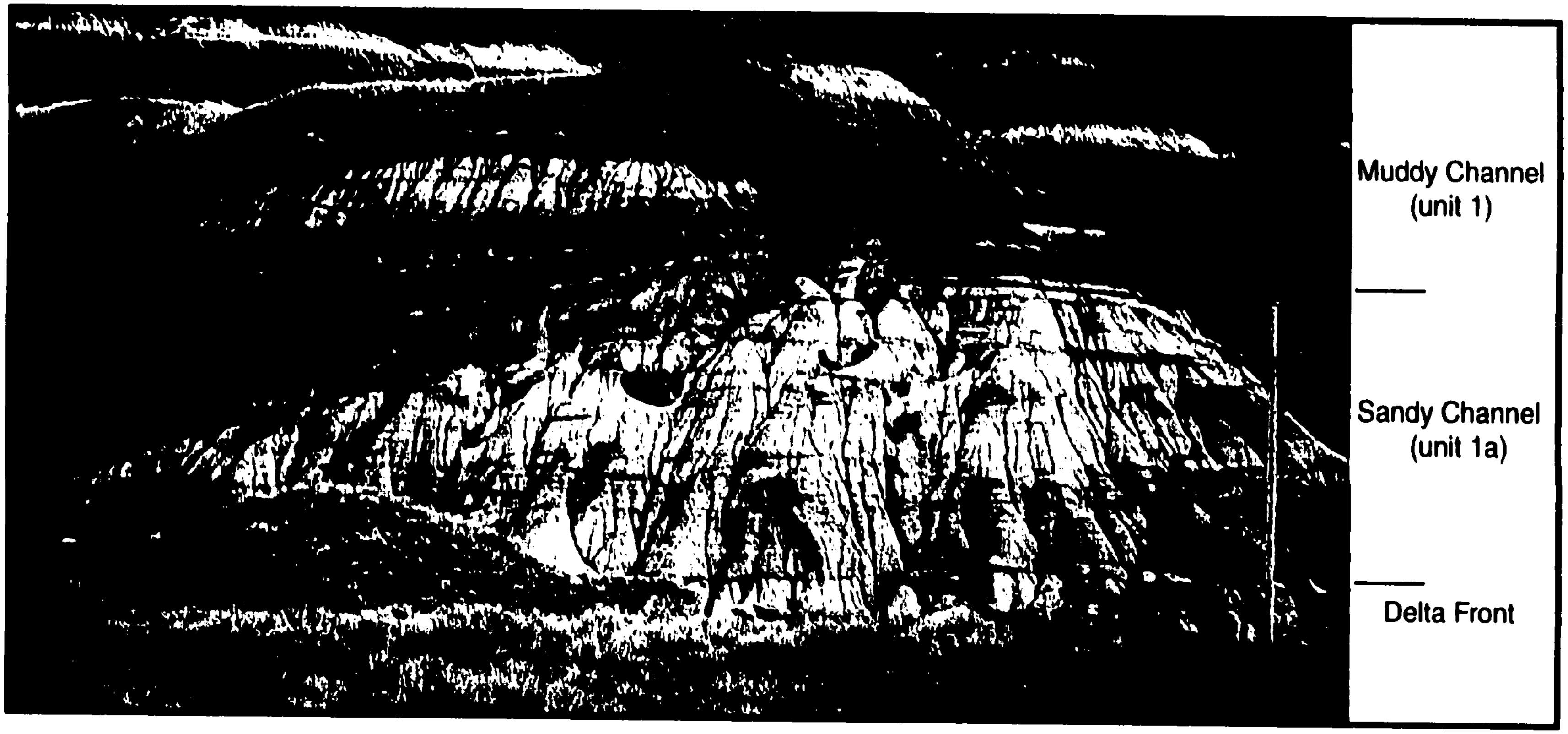


Similar to channel unit 3.

★ -Relative Position of Channel Units Relative to Turbidity Maximum (T.M.)

FIGURE II-9 **Position of the turbidity maximum in channel unit 1.**

Outcrop HO-2 of Rahmani (1988). The muddy channel unit corresponds to the turbidity maximum of channel unit 1. It also shows that a previously unmapped channel unit (here termed unit 1a) exists beneath unit 1 of Ainsworth (1994) and above the delta front sandstone. (see text and Figure II-16).


Muddy Channel
(unit 1)
Sandy Channel
(unit 1a)
Delta Front

WILLOW CREEK CHANNELS AS INCISED VALLEYS

Ainsworth (1994), based on criteria suggested by Van Wagoner *et al.* (1990), used several lines of reasoning to discount the possibility of the channel complex observed at Willow Creek being the result of deltaic distributaries. These include the occurrence of the channels at a single stratigraphic horizon; a basinward shift in facies above the incision; and the size of the channels. Ultimately, he decided that either lowstand incision or the avulsion of a large deltaic distributary could be responsible for the channel complex (Ainsworth and Walker, 1994).

Van Wagoner *et al.* (1990) proposed that deltaic distributaries do not occur at single stratigraphic horizons but rather stack vertically in multiple horizons. Despite contentions to the contrary, the channels in Willow Creek do, in fact, stack obliquely. This is evidenced by the fact that the incision of channel systems show variable relief along the top of the prodeltaic sequence and that several channel sequences can be observed in vertical succession along a dip profile as demonstrated at outcrop RDV-1a. Both suggest aggradation of the channel systems through time.

Ainsworth (1994) stated that at RDV-1 the erosion surfaces are "cut into offshore marine mudstones, and therefore show a distinct basinward shift in facies" (Ainsworth , 1994a, page 48). This observation does not preclude the channels as being distributaries. Progradational depostional settings are *by definition* representative of basinward shifts in facies. In addition, if the mudstones are not offshore, but viewed as prodeltaic in nature (see below) they would therefore represent conformable vertical succession of facies.

Ainsworth (1994) also considered the size of the channel system to be problematic as modern distributaries in the Mississippi are on the order of 1.7km wide (Van Wagoner *et al.*, 1990). Rahmani (1988) mapped the Drumheller valley system to be on the order of 5 to 12km in width (Figure II-10a). This neglects the fact that the valley system was not formed from a simple cut and fill episode, but rather represents a series of channels separated in time and space. In fact, as pointed out by Ainsworth (1994) the valley system at Willow Creek represents four sedimentologically distinct channel fill units.

As the Willow Creek section represents the lateral migration of channels, the dimensions of the outcrop belt are not directly related to the size of the channels that formed it. When considering the size of an individual channel, Leeder (1973) proposed a relationship between the channel width, the bankfull height and the dip of accretion beds with the channel (Figure II-11). Applying Leeder's formula and using a maximum channel height of 12m and an average dip of 10° (Ainsworth and Walker, 1994), the bankfull width of the channel systems is on the order of 102m. This is reasonable for an individual distributary channel.

It is therefore concluded that there is no evidence for the channel complex to be representative of an incised valley system. The subsurface mapping of Rahmani (1988) is problematic in that it groups different facies and channel units into a single large channel-like body. This gives the illusion of a single broad incision rather than what it really represents; a complex series of small, migrating channels that each exhibits a distinct sedimentological character.

FIGURE II-10 **Comparison of Drumheller estuarine complex to other, subsurface valley complexes.**

A) Map of Rahmani (1988) showing the distribution of estuarine deposits in the Drumheller area.

B) Map of valley complexes in the Lower Cretaceous Glauconitic Member of the Mannville Group showing similar scale as the Drumheller examples (from Wood and Hopkins, 1992).

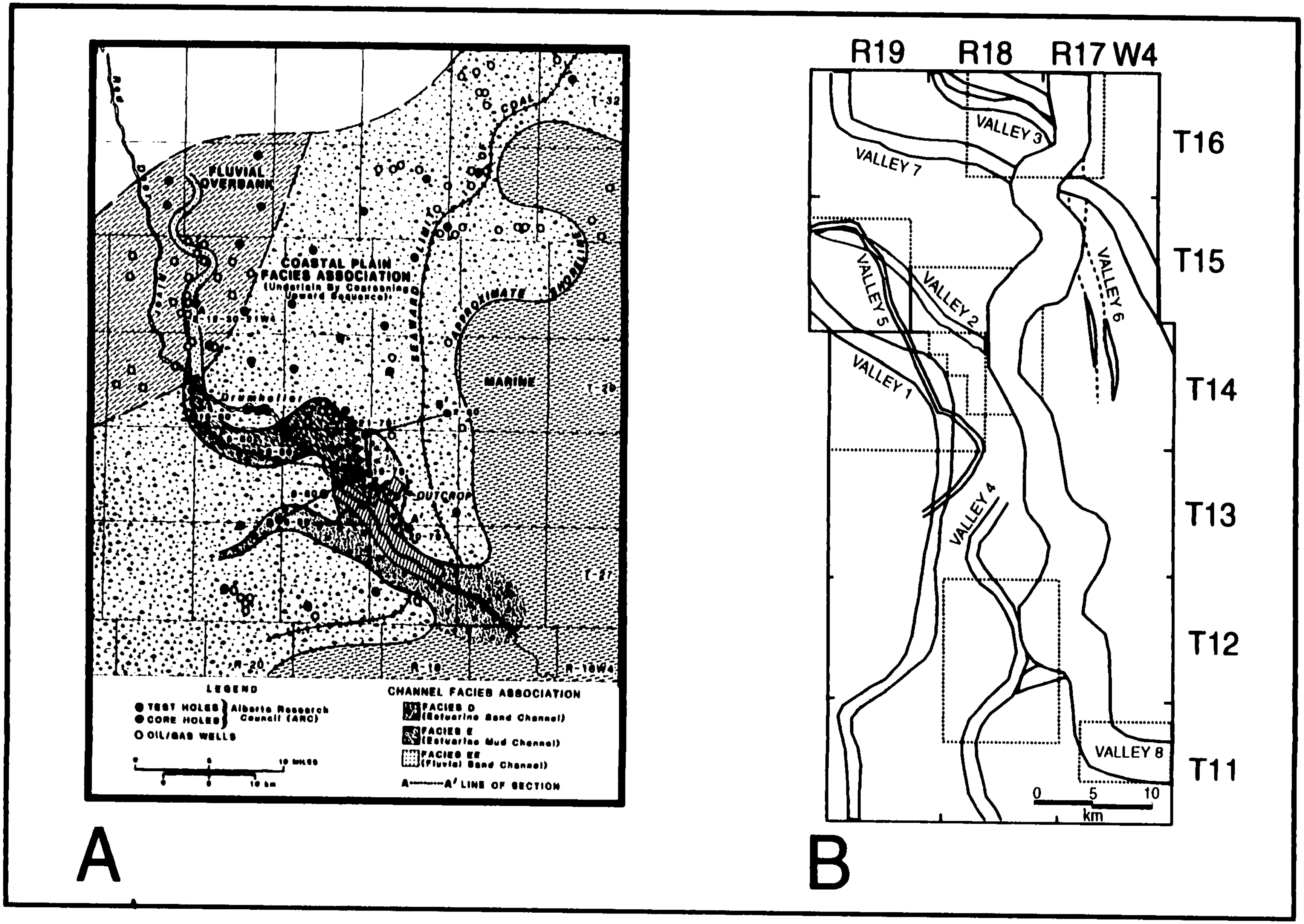
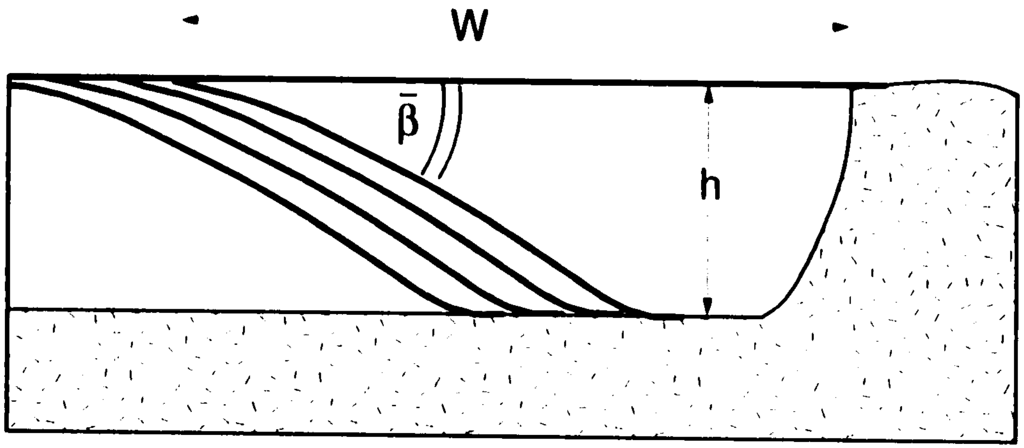

A
FLUVIAL OVERBANK
COASTAL PLAIN FACIES ASSOCIATION
(Underlain by Coarsening Upward Sequence)
SEAWARD LIMIT OF COAL
APPROXIMATE SHORELINE
MARINE
Drumheller
OUTCROP
T-32
T-29
T-27
R-20
R-19
R-18W4
LEGEND
TEST HOLES
CORE HOLES
Alberta Research Council (ARC)
OIL/GAS WELLS
0
5
10 MILES
CHANNEL FACIES ASSOCIATION
FACIES D (Estuarine Sand Channel)
FACIES E (Estuarine Mud Channel)
FACIES EE (Fluvial Sand Channel)
A——A' LINE OF SECTION
B
R19
R18
R17 W4
T16
T15
T14
T13
T12
T11
VALLEY 1
VALLEY 2
VALLEY 3
VALLEY 4
VALLEY 5
VALLEY 6
VALLEY 7
VALLEY 8
0
5
10
km

FIGURE II-11 **Scale of individual channel units in Willow Creek.**

A) Method for calculating the width of a paleochannel based on the bankfull height and the dip of the accretion beds (Leeder, 1973).

B) Application of Leeders' formula to the deposits of channel unit 2, yielding a paleochannel bankfull width of approximately 102m.

A



$W = 1.5h/\tan\bar{\beta}$

B

Bankfull Height (h) @ 12m
Dip of Accretion Surfaces ($\bar{\beta}$) @ 10^{0}
Calculated Paleochannel Width = 102m

WILLOW CREEK CHANNELS AS DELTAIC DISTRIBUTARIES

Dalrymple (1992, fig. 29A) summarized the typical sedimentary succession of a fluvial distributary in a tide-dominated deltaic system (Figure II-12a, this paper). They are comprised of a coarsening upwards basal section consisting of prodeltaic fines overlain by coarse delta front sediments. These units are sharply and erosively overlain by fluvial/distributary channel deposits that exhibit a fining upward character that are overlain by accretionary bank deposits and, in humid climates, delta plain coals. The section at RDV-1a (Figure II-12b), at the mouth of Willow Creek represents an almost identical succession as the idealized section mentioned above.

DESCRIPTION OF MEASURED SECTION RDV-1A

The base of the section is composed of heterolithic, coarsening upwards, prodeltaic fines (Allomember A of Ainsworth, 1994). These sediments are sharply overlain by what are interpreted to be delta front sands as exposed at the Hoodoos Recreation Area. The upper portions of the prodelta are characterized by large-scale ball and pillow structures (Figure II-13a). Kuenen (1965) experimentally demonstrated that this type of feature is consistent with rapid loading of sand onto a muddy, unconsolidated substrate (Figure II-13b).

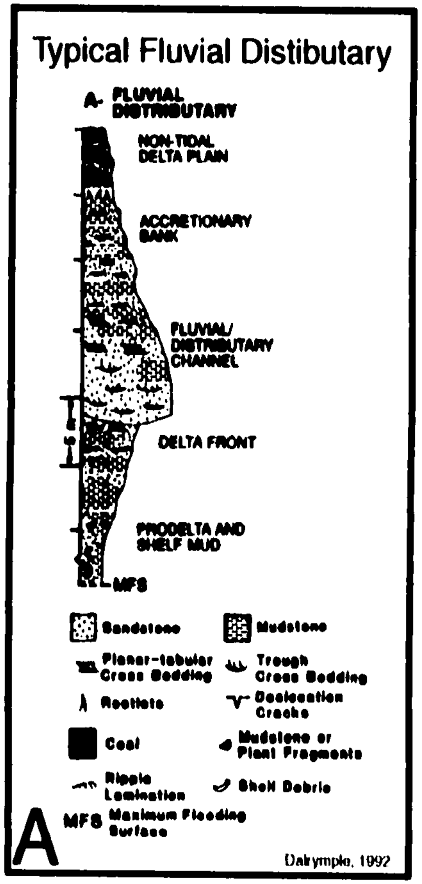
The contact is traceable basinward at East Coulee where the overlying sands contain abundant swaley and hummocky cross stratification and trace fossil suites consisting of *Cylindrichnus*, *Ophiomorpha*, *Rosselia* and *Macaronichnus*. This storm-

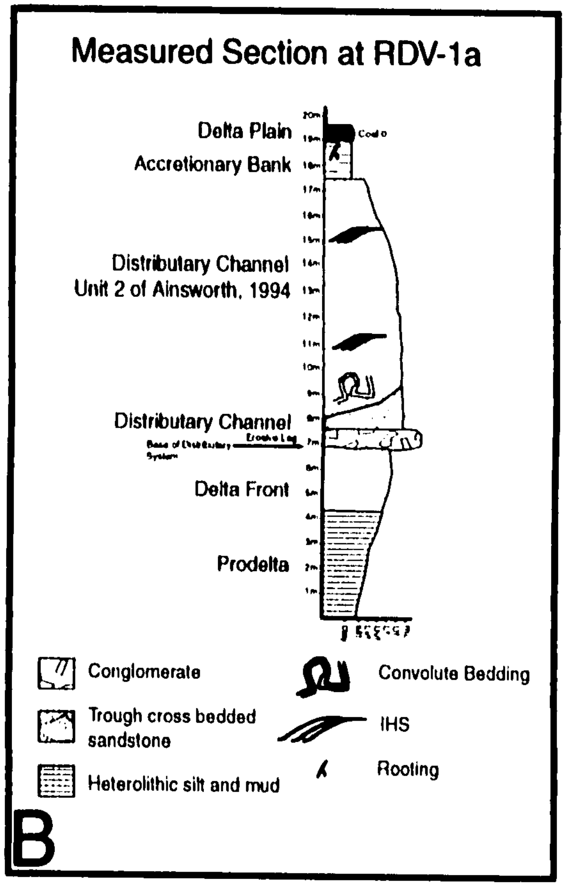
FIGURE II-12 **Vertical sequence generated in a fluvial distributary as compared to the outcrop exposure at the Hoodoos Recreation area.**

A) Typical fluvial distributary of Dalrymple (1992).

(B) Vertical sequence of a measured section at the Hoodoos Recreation Area (location nomenclature after Ainsworth, 1994).

(C) Outcrop photo showing uppermost portion of channel system at the Hoodoos Recreation Area.


Typical Fluvial Distibutary
A- FLUVIAL DISTRIBUTARY
NON-TIDAL DELTA PLAIN
ACCRETIONARY BANK
FLUVIAL/ DISTRIBUTARY CHANNEL
DELTA FRONT
PRODELTA AND SHELF MUD
MFS
Sandstone
Mudstone
Planar-tabular Cross Bedding
Trough Cross Bedding
Rootlets
Desiccation Cracks
Coal
Mudstone or Plant Fragments
Ripple Lamination
Shell Debris
MFS Maximum Flooding Surface
Dalrymple, 1992
A


Measured Section at RDV-1a
Delta Plain
Coal 0
Accretionary Bank
Distributary Channel
Unit 2 of Ainsworth, 1994
Distributary Channel
Base of Distributary System
Erosive Lag
Delta Front
Prodelta
Conglomerate
Convolute Bedding
Trough cross bedded sandstone
IHS
Heterolithic silt and mud
Rooting
B

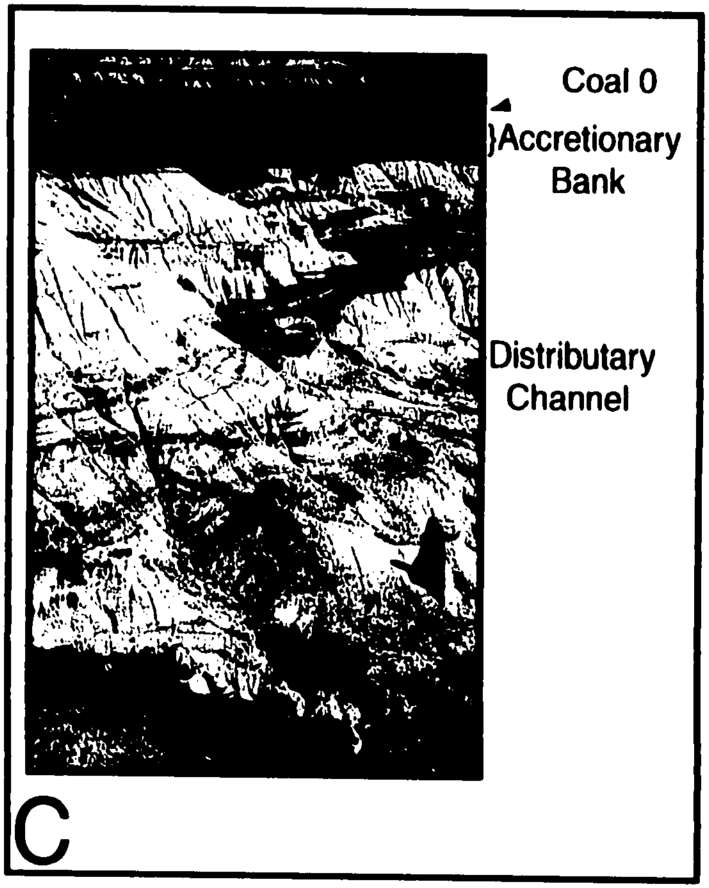
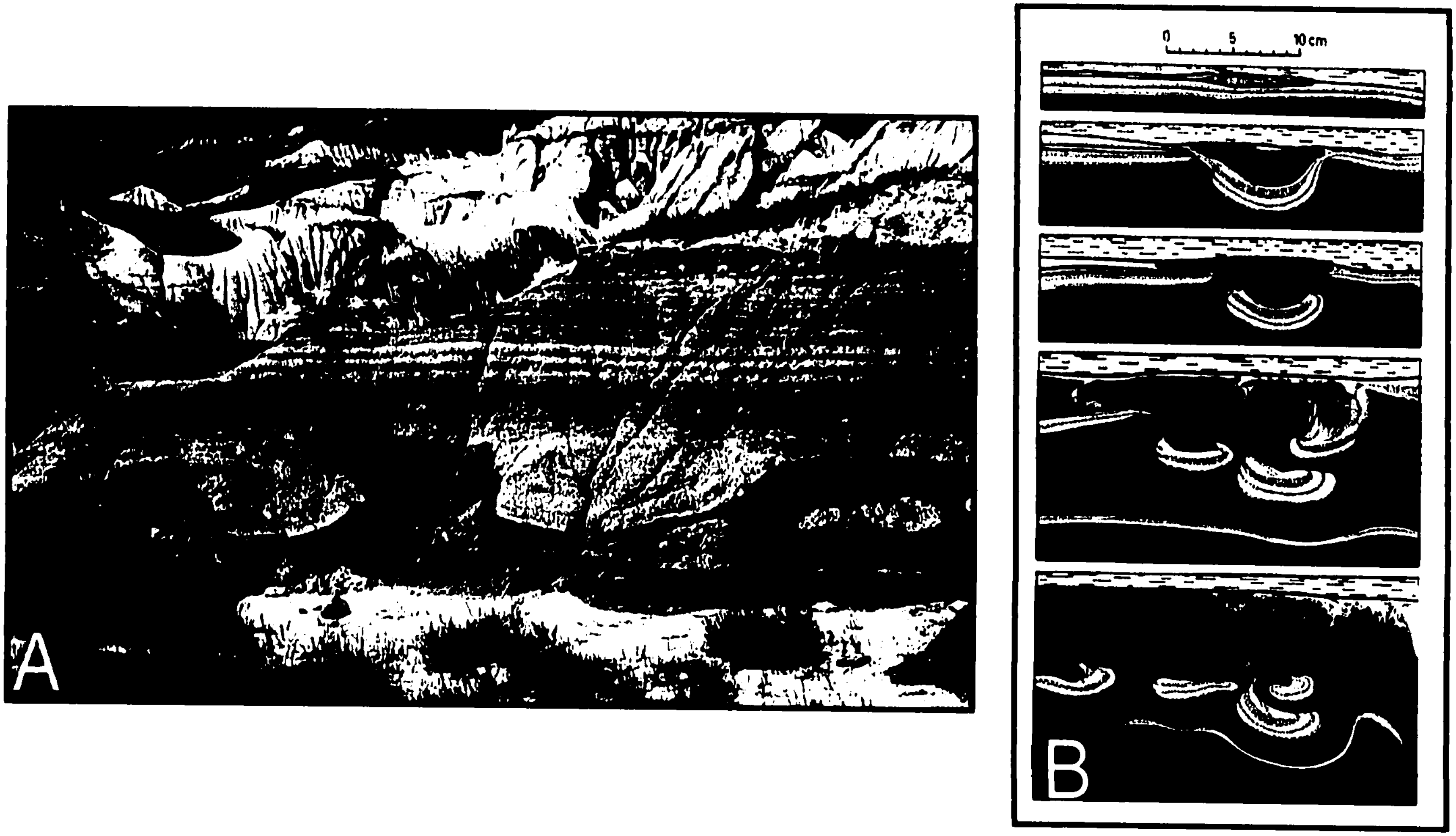

Coal 0
}Accretionary Bank
Distributary Channel
C

FIGURE II-13 **Soft sediment deformation structures in delta front sediments at the Hoodoos Recreation area.**

A) Ball and pillow structures comprised of sandstones that have sunk into underlying finer-grained sediments. (85cm ice axe for scale at base of leftmost structure).

B) Succesive stages of formation of ball and pillows in unstable sediment from a laboratory experiment (from Kuenen, 1965).


A
B
0
5
10cm

dominated environment is the result of wave reworking of the delta front. This highlights the lateral facies variability in deltaic settings. At the Hoodoos Recreation Area deposition is in a fluvially-dominated, tidally-influenced setting. The same depositional environment is wave-dominated 10km basinward at East Coulee. Deltaic systems can show facies complexity due to localized variations in sedimentary processes as suggested by Bhattacharya and Walker (1991).

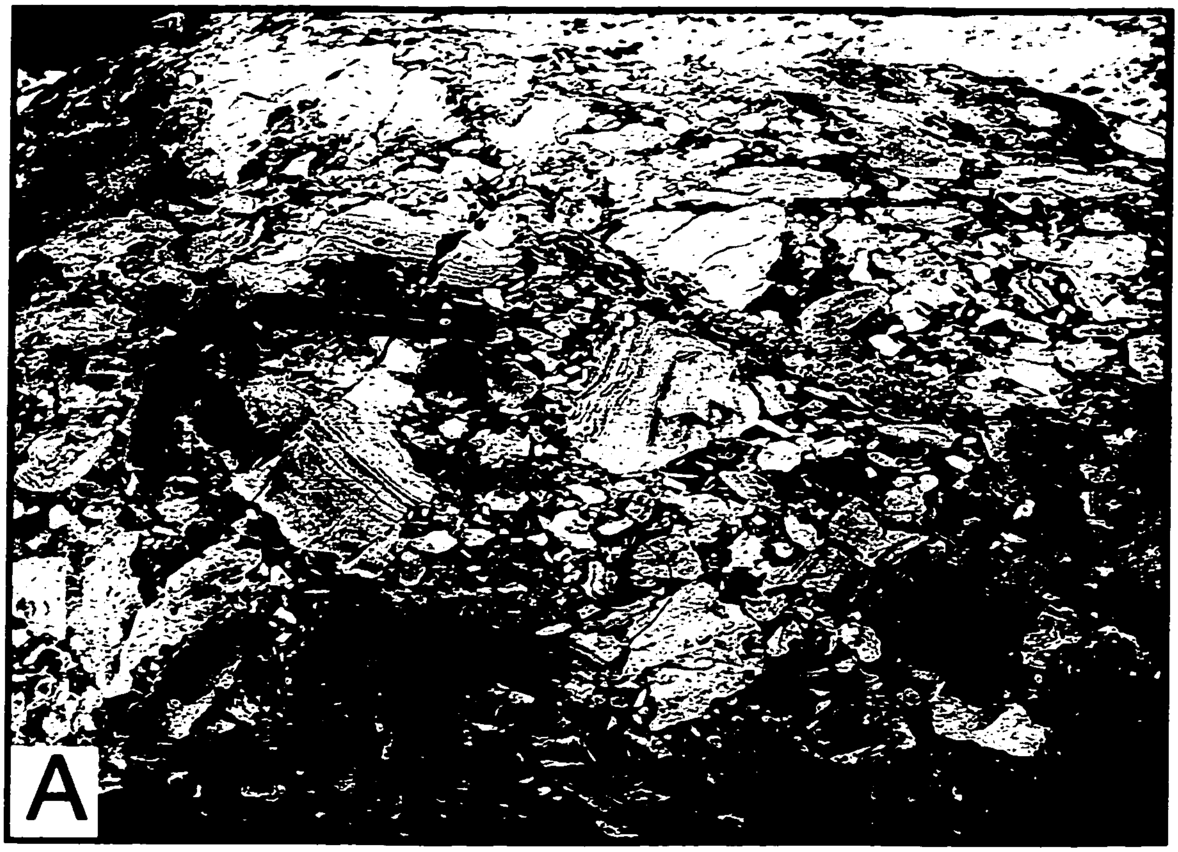
At the Hoodoos Recreation Area, The large hoodoo is capped by an incision lag generated by distributary channels cutting into the delta front. Locally this is demarcated by an 80cm thick, well-cemented siltstone pebble conglomerate. This surface is mappable for over 1 km landward where it changes character into a thin (dm scale) sideritized pebble horizon (see Figure II-14).

Overlying this surface are two, stacked distributary channel facies associations consisting of fining upwards, trough cross-bedded sandstones. The two units are distinguishable on the basis of a discordant inclined bounding discontinuity separating the units and a pink diagenetic staining in the lower unit (channel 1 of Ainsworth, 1994). In contrast, the upper unit (channel 2 of Ainsworth, 1994) is characteristically comprised of bright, white sandstone. Broad *Diplocraterion* have been collected from unit 1 while no trace fossils were observed in unit 2. While both units contain trough cross bedding, unit 2 is distinctive due to the muddy, heterolithic bedding with tidal rythmites, IHS bedding and soft sediment deformation structures (*cf.* Figure II-15). Unit 1 exhibits an upward shallowing in the dip of the IHS suggesting channel abandonment (Figure II-16). Separating the two units is a sharp, inclined surface interpreted to represent the reactivation of a distributary subsequent to the abandonment of the unit 1. The angular

FIGURE II-14 **Variability along the basal surface of the distributary channel system.**

A) Laminated, siltstone pebble conglomerate at the base of fluvial distributary system at the Hoodoos Recreation area. The clasts are derived from the underlying laminated siltstone-mudstone prodelta sediments.

B) Base of the distributary system 1.5 km landward of the Hoodoos Recreation Area at locality HO-2 of Rahmani (1988). Here the surface is comprised of a heavily siderite-cemented ironstone pebble horizon (15cm scale).


A

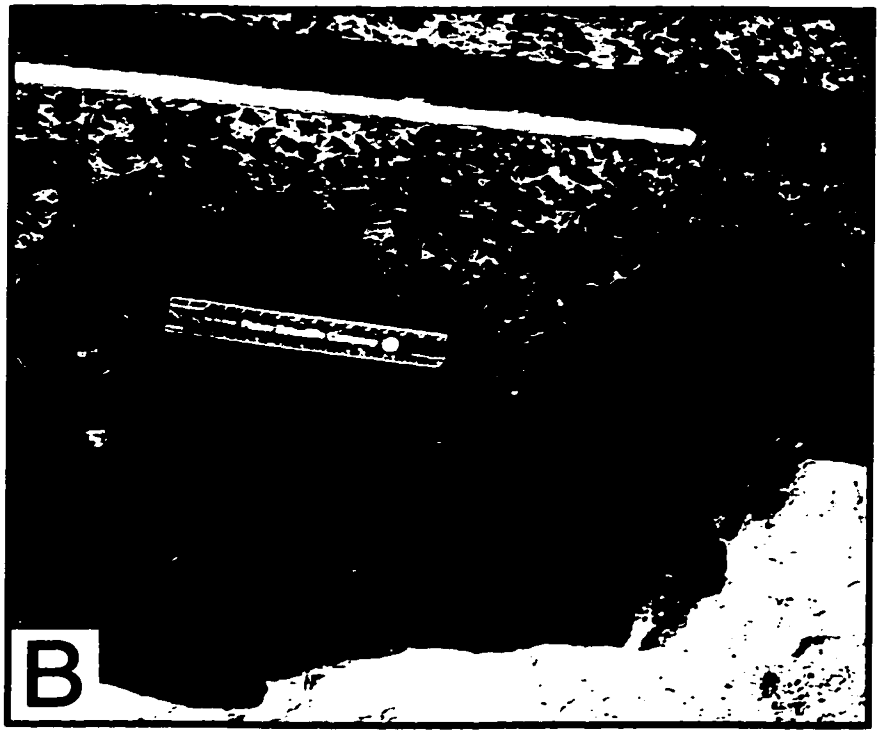

B

FIGURE II-15 **Characteristics of Willow Creek distributary channel deposits.**

A) Bank collapse blocks comprised of laminated sandstone and mudstones incorporated into coarser-grained channel sandstones.

B) Convolute bedding interpreted as downslope slumping on a pointbar. Note how the deformation is confined to a discrete interval within the overall pointbar succession. Solid portion of staff is 50cm.

C) Wedge sets within pointbar deposits caused by frequent readjustment of point bar surfaces.

D) Concentration of imbricated, rounded siderite pebbles deposited on a lateral accretion surface in a heavily cemented sandstone concretion.

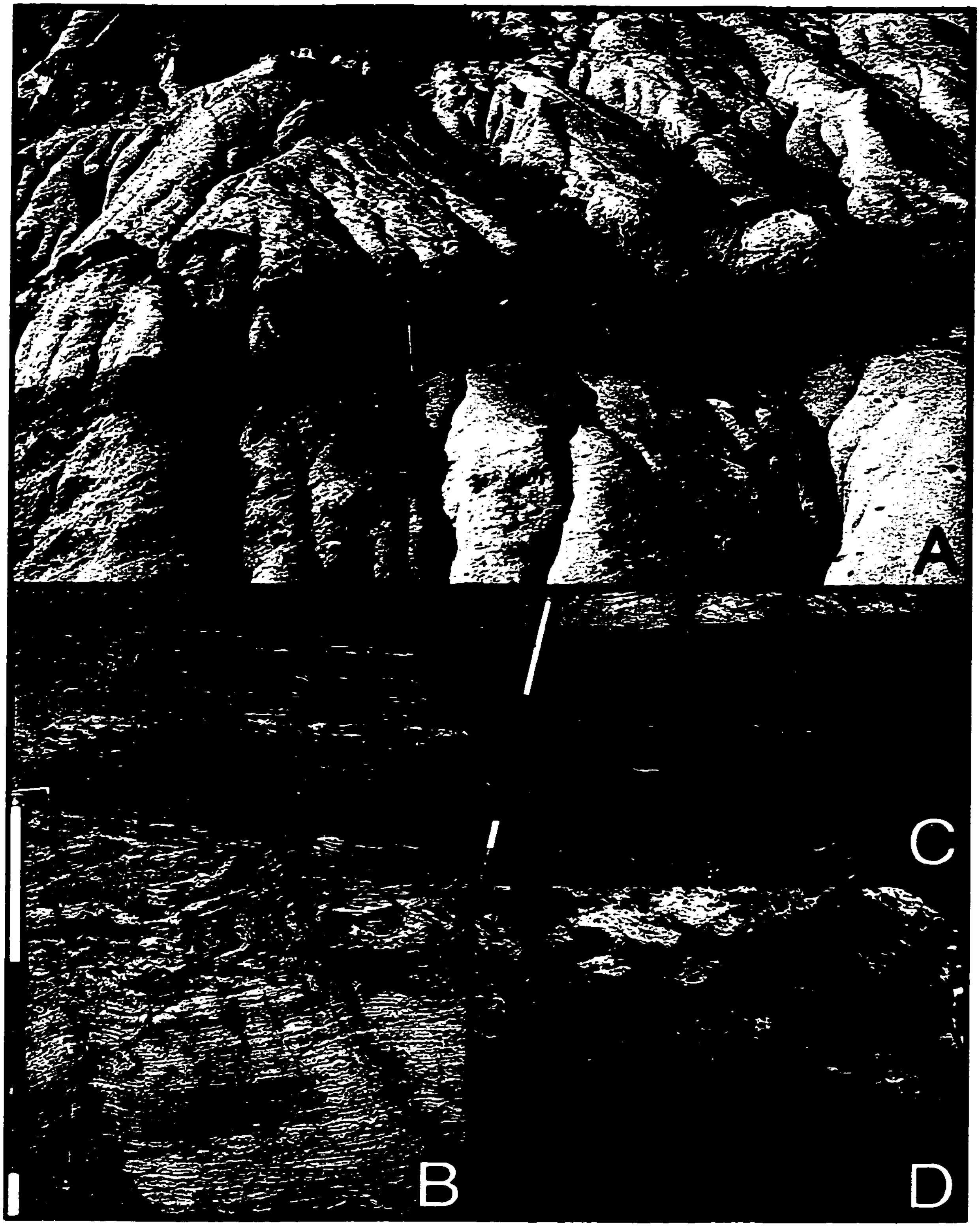

A
C
B
D

FIGURE II-16 **Complex channel architecture at Hoodoos Recreation Area.**

This photo shows a marked discontinuity between two discrete channel units. Previous workers did not observe the lower unit, channel 1a. It shows evidence of channel abandonment near the top in the form of vertically aggradational muddy fill. The photo also shows sedimentation on the delta plain and is capped by regionally extensive coal 0.


Coal 0
Accretionary Bank
Channel Unit 1
Channel Unit 1a
Contact between channel units 1a and 1
Abandonment phase in channel unit 1a

discordance is a result of the two dimensional representation of a point bars in the second unit migrating at an oblique angle to those in the first.

The channel units pass vertically into a 1.5m thick dark grey carbonaceous rich shale containing small coalified roots (Figure II-17). The shale is overlain by coal 0 which has a sharp, irregular base comprised of 1 cm thick carbonaceous rich sandstone that passes vertically into the coal. The basal carbonaceous rich sandstone is representative of abundant clastic input prohibiting coal development in an environment otherwise conducive to coal formation in a delta plain setting.

The placement of the boundary of Allomenbers A and B in the area around the Hoodoos Recreation Area leads to the confusion of the continuity of the vertical succession of facies. Ainsworth (1994) placed the A/B boundary at the top of the prodeltaic fines and made it coincident with a sequence boundary. Although the contact is sharp locally, it is gradational in other localities. It is based on the assumption that the sand on mud contact represents the floor of an incised valley complex (see above). In his framework, all of the sand beneath coal 0 was grouped into a single unit despite the presence of the intraformational conglomerate several meters above the allomember boundary and the variable nature of the individual fills.

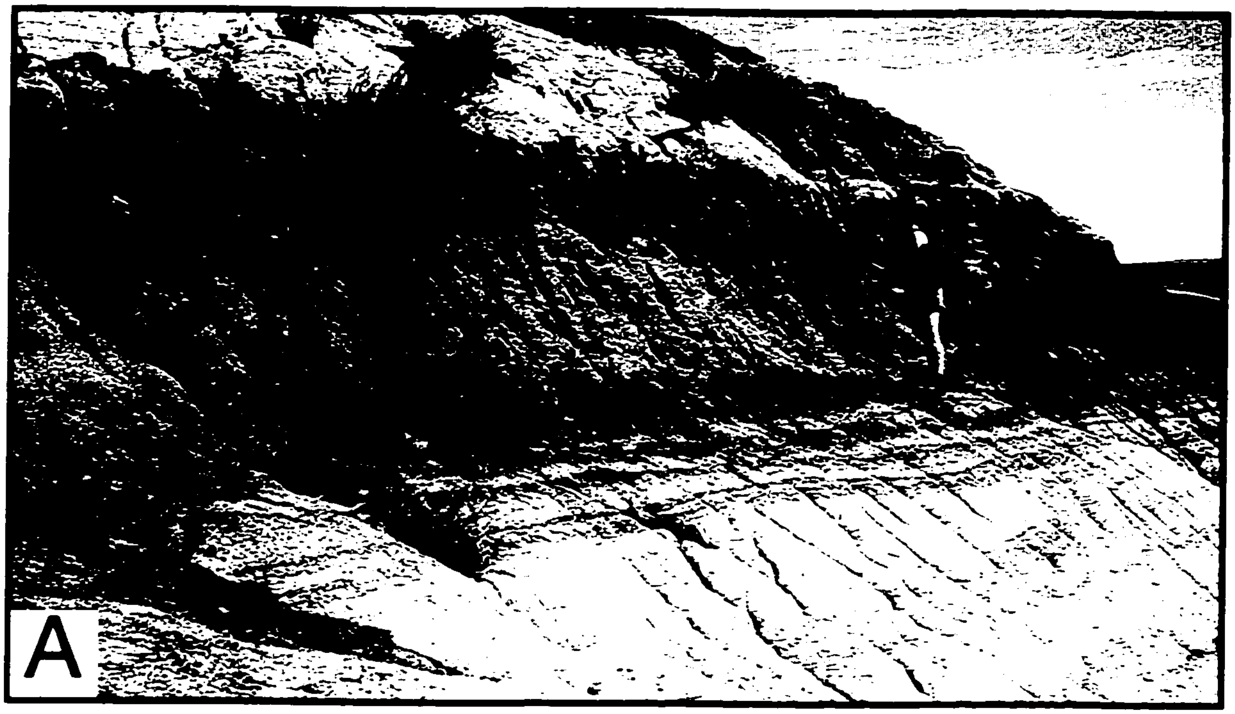
SUMMARY

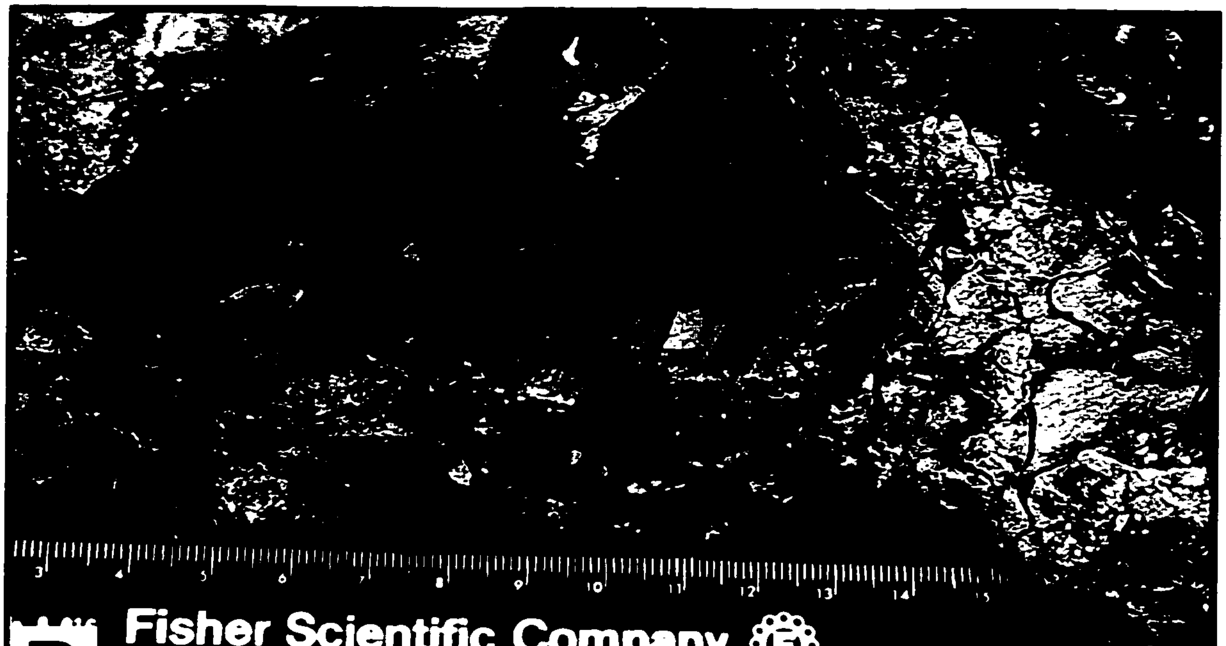
In surface orientated stratigraphic frameworks, caution must be taken not to artificially subdivide genetically related sequences. It is the contention of this work that allomember B of Ainsworth is not a valid subdivision and that the strata between and

FIGURE II-17 **Delta plain deposits capping distributary channel system at the Hoodoos Recreation Area.**

A) Flat- lying delta plain shales capping the distributary channel sequence.

B) Coalified root (arrowed) in delta plain shales.


A


B
Fisher Scientific Company
PRINTED IN U.S.A.

including the prodeltaic muds and coal 0 is a single genetically related succession. The incision demarcated by the intraformational conglomerate resulted from the autocyclic incision of deltaic distributaries into a delta front. The measured section at RDV-1a exemplifies the predictable vertical progression of facies reflected in a prograding tidally-influenced deltaic setting. This is consistent with the sedimentological and ichnological analysis that shows the channel systems are prograding further past the shoreline through time (see above) which is explained by the continued progradation of the overall deltaic package.

APPLICATION TO SUBSURFACE EXPLORATION AND PRODUCTION OF ESTUARINE RESERVOIRS

In general, estuarine depositional systems are composed of a complex array of facies that could potentially pose difficulties in subsurface reservoir evaluation. This work will briefly touch on the implications these complexities present when assessing in place reserves. Of considerable importance to this are subsurface mapping and correlation practices in estuarine reservoirs that prohibit a clear understanding of facies variability.

Rahmani (1988) traced the Horseshoe Canyon Formation valley system into the subsurface approximately 40km up dip. The major channel was mapped at widths between 5 and 12km. He also showed a tripartite subdivision of facies along the channel axis (See Figure II-10a).

The subsurface component of this data is questionable. Most of the inferred system is unconstrained by data points. The estuarine trunk is also shown to contain a large distributary (on the order of 3 km wide) that drains into the major channel. This would potentially add complexities within the system and disrupt the idealized tripartite subdivision. These factors plus the fact that the outcrop component of this system shows internal complexity suggest that the facies map presented by Rahmani (1988) is highly schematic in that it artificially groups facies associations.

From a reservoir production standpoint, the internal heterogeneities within Willow Creek channel 2 effectively compartmentalize this unit. Perhaps deviated drilling could maximize penetration of the more permeable sands but water floods would likely bypass a significant volume of pay. These problems do not exist in channel units 1,3 and 4. It is therefore unwise to map all of these units as a homogeneous rock body in the subsurface.

Wood and Hopkins (1992) mapped a complex association of incised valleys in the Glauconite Formation in southeastern Alberta (Figure II-10b). One of the valley systems is mapped to a maximum width of approximately 10km and extended in a north-south direction for 70 km. The potential of a valley system of this size containing homogeneous strata is almost non-existent. It more likely composed of a complex array of facies and facies associations; only some of these will constitute reservoir units. This is likely responsible for the complex water flood response observed by Hopkins *et al.* (1991). The lateral extent of the valley complex is not necessarily related to the amount or distribution of reservoir facies. More detailed mapping is needed to delineate the reservoir units within the valley system.

Both cases emphasize that detailed sedimentological examinations are required to elucidate the internal complexities within estuarine reservoirs. This requires close well spacings and tying in existing core to geophysical log signatures to increase the accuracy in mapping and reserve calculation.

CONCLUSIONS

Evidence for a regionally extensive unconformity in the marginal marine basal Horseshoe Canyon Formation is lacking. The sedimentary succession is conformable and more representative of laterally and vertically stacked, tidally-influenced, fluvial distributaries in a progradational deltaic setting. A measured section at the Hoodoos Recreation Area shows prodeltaic fines sharply overlain by delta front sands. The sharp, erosive nature of the contact appears to be localized, as the facies change is gradational basinward. This precludes any interpretation suggesting the contact is unconformable. Furthermore, the stratigraphic section exactly corresponds to the vertical facies succession expected in a progradational deltaic setting.

Delta front sands are sharply and erosively truncated by a series of distributary channel deposits. The contact between these facies is locally demarcated by a 20-80cm thick siltstone pebble conglomerate that thins in a palaeolandward direction. Distributary channel deposits pass vertically into rooted, grey carbonaceous shale which is overlain by a regionally correlatable coal. This interval conforms to vertical successions in idealized fluvial-distributary facies models. The basal portion of the succession at the Hoodoos Recreation Area is therefore regarded as conformable and represents autocyclic processes operating within a prograding deltaic setting. This is contrary to the suggestions of Ainsworth (1994) that the system represents an incised valley complex.

This work finds that Rahmani (1988) was correct in suggesting that the system represented a tidally influenced distributary system. In fact, Shepheard and Hills (1970) first suggested that the basal Horseshoe Canyon Formation represented a deltaic system and identified environments from the prodelta to the delta plain.

The application of allostratigraphy to these strata hinders the clear recognition of the vertical facies successions by imposing artificial boundaries in conformable strata. Allostratigraphic correlation focuses on external mechanisms to generate stratigraphically significant bounding discontinuities. In modern deltaic settings complex internal processes generate abrupt facies changes across sharp boundaries. These autocyclic processes occur on a higher frequency than the allocyclic ones and thereby often overprint the longer duration cycles. Current stratigraphic methodology emphasizes bounding discontinuities. Care must be taken to account for variation *within* depositional systems and not relegate all sharp, erosive contacts as reflections of relative base level changes.

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CHAPTER III

PERSPECTIVES ON THE SIGNIFICANCE OF *TEREDOLITES* OCCURRENCES IN THE UPPER CRETACEOUS, MARGINAL MARINE DEPOSITS OF SOUTHERN ALBERTA

INTRODUCTION

By documenting climatic conditions such as seasonality and relative precipitation in a geographic area and by examining the corresponding floral and faunal assemblage, modern ecologists are able to establish ecological zonations. Applying uniformitarian theory, palaeoecologists may infer prevailing palaeoclimatic conditions in stratigraphic successions bearing fossil wood, as many types of wood present in modern communities have ancestors known from the fossil record. In this way fossil wood has long given geologists and palaeontologists insight into many aspects of palaeoecology and palaeoclimatology (Francis, 1986).

The same can be said for the trace fossils of organisms that bore into wood. Many of the wood-borers that leave characteristic trace fossils have distinct ecological controls that limit their distribution. By observing the borings of these creatures in *in situ* fossil wood, constraints are placed on possible depositional environments. In some cases, wood may provided a medium of preservation that allow trace fossils to pass into the rock record where evidence of the activity of the trace-makers would otherwise go undetected.

Two groups of creatures that produce characteristic wood borings are pholad and teredinid bivalves. In addition to being prevalent globally in modern settings, they also have widespread geographical distribution in the rock record. As a result, many reports of their trace fossils (*Teredolites*) exist from various formations worldwide (see Table III-1).

Despite the abundance of literature regarding these occurrences, many are only mentioned in passing, often as a component of facies descriptions. Works pertaining to the implications of these borings in terms of stratigraphic applications are relatively few (Bromley *et al.*, 1984 and Savrda, 1991 a&b, 1993).

While not presuming to be exhaustive, this work is meant to demonstrate the salient aspects of stratigraphic and palaeoenvironmental interpretations based on the occurrences of *Teredolites* in Campanian and Maastrichtian strata of southern Alberta and also on neoichnological investigations from the west coast of North America (see Figure III-1).

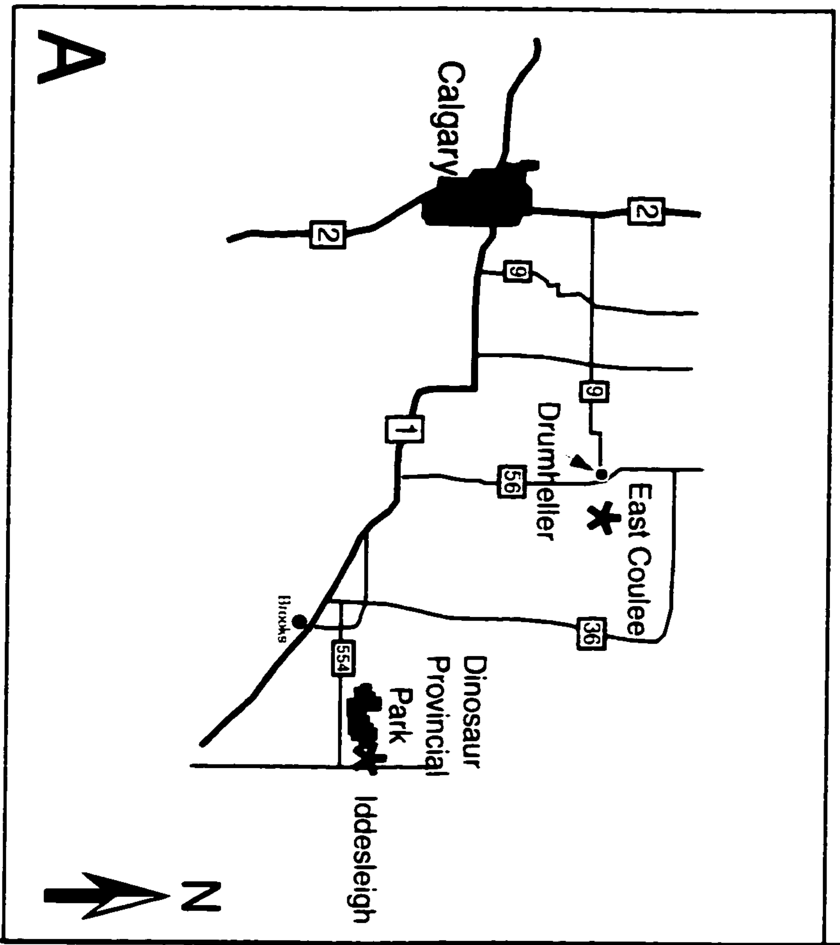
THE ICHNOFACIES CONCEPT

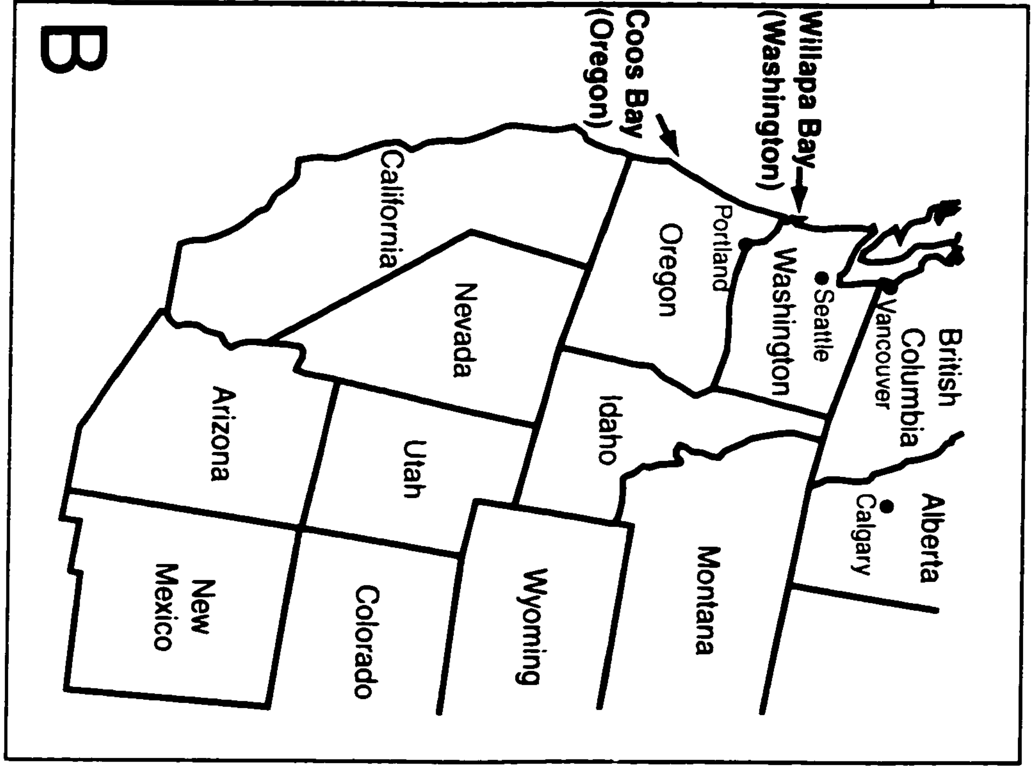
The concept of facies was first used in "comparative lithology" by Walther (1894) to "make genetic comparisons" of the qualities of a rock and to place the highest emphasis on those qualities which were imparted at the time when the rock was first formed. He recognized that the primary qualities of a rock were highly dependent on "the sum of the meteorological and oceanographical conditions for inorganic and organic processes" and therefore, the climate can be inferred from these primary qualities (Walther, 1894, p. 977; translation from Middleton, 1973). Facies are descriptive and

FIGURE III-1 **Location maps for the *Teredolites* occurrences considered in this study.**

A) Map of a portion of southern Alberta showing the locations of the East Coulee and Iddesleigh *Teredolites* sites (labeled with asterisks-*)

B) Map of the northwestern United States showing the location of Willapa Bay, Washington and Coos Bay, Oregon (arrowed).


A
Calgary
2
2
9
9
1
56
36
554
Drumheller
East Coulee
Brooks
Dinosaur
Provincial
Park
Iddesleigh
N


B
Willapa Bay
(Washington)
Coos Bay
(Oregon)
British
Columbia
Vancouver
Seattle
Washington
Portland
Oregon
California
Nevada
Idaho
Alberta
Calgary
Montana
Wyoming
Utah
Arizona
Colorado
New
Mexico

should not in themselves imply an environmental interpretation. In general, a facies should represent "lithologic, structural and organic aspects detectable in the field" (de Raaf *et al.*, 1965). Due to the fact that the deposition of a facies is intimately linked to its environment of deposition, facies have a mappable extent and a predictable relationship to laterally adjacent facies.

Similarly, trace fossil assemblages were recognized to consist of recurring suites of traces characterizing similar types of behavior indicative of specific environmental settings (Seilacher, 1967). Further, several suites of trace fossils were shown to be characteristic of a specific substrate condition. These are the *Trypanites* ichnofacies, characteristic of fully lithified substrates (Frey and Seilacher, 1980); the *Glossifungites* ichnofacies characteristic of firm, semilithified substrates (Frey and Seilacher, 1980 and Pemberton and Frey, 1985); and the *Teredolites* ichnofacies, characteristic of woody or xylic substrates (Bromley *et al.*, 1984).

These trace fossil suites are of particular use to the stratigrapher because they provide insight into substrate conditions, such as textural consistency, prevalent at the time of colonization. As substrate condition can often be demonstrated to be a function of allocyclic changes through burial and exhumation, many of these trace fossil occurrences demarcate stratigraphically significant surfaces (*i.e.* Bromley, 1975; Bromley *et al.*, 1984 and Pemberton and MacEachern, 1995).

The *Teredolites* ichnofacies (Bromley *et al.*,1984) is substrate-controlled in that it only pertains to assemblages of traces that occur in wood substrates. If a thorough examination can place the occurrence into a tightly constrained sedimentological and stratigraphic framework, the geologist receives a rare glimpse into aspects of physical and ecological parameters at the time of deposition. While ichnofacies names are often based on predominant traces within a given assemblage, the *Teredolites* ichnofacies is not exclusively represented by the ichnogenus *Teredolites*; *Thalassinoides*, *Diplocraterion* and *Psilonichnus* are also occasional constituents (*i.e.* Dam, 1990).

While the occurrence of isolated pieces of bored wood within a stratal package has potential implications for palaeoenvironmental reconstruction, their stratigraphic value may be questionable. In order to be effective as stratigraphic indicators, occurrences of *Teredolites* must be shown to be representative of *in situ* woodgrounds and not isolated occurrences of the ichnogenera in allochthonous clasts. This is a not a trivial distinction, especially in genetic stratigraphic studies.

TRACES OF ORGANISMS THAT BORE INTO WOOD

Trace fossil names should not ascribe to an identity of the trace maker, inferred or otherwise (Pemberton and Frey, 1982). Accordingly, they should be erected solely on the basis of morphological characters. Similarly, the subdivision of an ichnogenus into ichnospecies is also accomplished solely on the basis of morphologic variation of the trace fossils in question. One can encounter problems if undue presumptions are made regarding the identity of the trace maker. Strictly speaking, ichnologically-supported environmental interpretations are not based on trace fossils themselves but, rather, the ichnologists' perception of what actually made the trace.

Many modern organisms bore into wood and it is reasonable to assume they did so in the geologic past. Crebar and Ash (1990) illustrated pocket rot in extant

Metasequoia glyptostroboides and documented similar attack in Upper Triassic trees in Arizona. The traces of many "modern" organisms have been documented in the rock record. The work of mites has been reported in the Pennsylvanian (Cichan and Taylor, 1982 and Labandeira *et al.*, 1997) and Lower Permian (Goth and Wilde, 1992); termites in the Upper Cretaceous (Rohr, 1984); beetle larvae in the Tertiary (Brues, 1936); and beetles and wasps in the Pleistocene (Klinger et al., 1984). These trace fossils excavated in wood indeed span a vast amount of geological time.

Taxonomically, Genise (1995) erected four new ichnogenera based on insect borings in permineralized plant material from the Upper Cretaceous of Argentina. Current research trends in non-marine ichnology make it likely that future studies will document many more traces in wood created by a host of organisms.

This work will focus on the borings of pholad and teredinid bivalves. They presently are the most numerous of reported trace fossils in wood. In general, they are distinctive and easily differentiable from the traces of other invertebrates. The activity of wood-boring bivalves has been noted from xylic substrates as old as the Jurassic (Moore, 1870 and Kelly, 1988b) and continue to be common in Recent marine to marginal marine settings.

SYSTEMATIC ICHNOLOGY

The taxonomy of trace fossils attributed to wood-boring bivalves was reviewed by Kelly and Bromley (1984) who recognized a single valid ichnogenus, *Teredolities* Leymerie. They also recognized two ichnospecies: *T. clavatus* Leymerie and *Teredolites longissimus* Kelly and Bromley. A brief summary of these ichnospecies is given below.

Teredolites clavatus Leymerie 1842

Diagnosis: Clavate borings predominantly perpendicular to the grain in woody substrates having length/width ratio usually less than 5. (Kelly and Bromley,1984)

Remarks: Such borings are produced today by species of *Martesia*. Fossil occupants of these traces include *Martesia* and *Opertochasma*.

Teredolites longissimus Kelly and Bromley 1984

Diagnosis: Clavate borings predominantly parallel to the grain in lignitic substrate having length/width ratio usually greater than 5. Commonly sinuous to contorted (Kelly and Bromley,1984).

Remarks: Commonly lined with calcite, the thickness of which increases towards the aperture. Borings of the teredine ship-worms which include those of *Teredo* itself, fall within this ichnospecies. Juvenile forms pass through a phase having the morphology of *T. clavatus*.

EVALUATION OF *TEREDOLITES* ICHNOSPECIES DIFFERENTIATION BASED ON THE ECOLOGY OF MODERN WOOD-BORING BIVALVES

Imperative in the study of trace fossils is the realization that any two similar trace fossils could have been created by entirely different organisms that exhibited similar behavior patterns. Also of paramount importance is recognizing that any given creature may create numerous different traces as a function of varying behavior. Complicating matters further, the same creature, exhibiting the same behavioral patterns, can create different traces based on differences in substrate consistency (Bromley and Fürsich, 1980). As a result, an understanding of neoichnology is vital to meaningful interpretations of trace fossils in the rock record. This study is intentionally limited to ecological parameters as they affect modern wood-boring bivalves because they are generally regarded as the creatures responsible for producing the most abundant and easily recognizable trace fossils in wood.

Due to the economic impact wood-borers have on modern sea-based transportation systems, a large body of research exists that attempts to identify controls on the pests' distribution (*i.e.* Quayle, 1992). Wood-borers have also been documented to pose a threat to mangrove swamps (Barkati and Tirmizi, 1991) and as such can locally have a potentially large environmental impact.

There are several environmental controls on the distribution of modern wood-boring bivalves. Salinity, temperature, and a supply of wood appear to be the most significant. Both pholads and teredinids are exclusively marine. They can tolerate brackish conditions but salinities less than 9 or 10 ppt are lethal and uniform, normal marine salinities were found to be most conducive to rapid growth (Greenfield, 1952). In San Francisco Bay, teredinids were almost wiped out during a period high rainfall and spring runoff, but came back in full force once salinities returned to normal (Ricketts *et al.*, 1992).

Temperature may also be a limiting factor in teredinid and pholad bivalve distribution. Greenfield (1952) noted an increase in growth rate of teredinids in higher temperature waters. Hoagland and Turner (1980) showed a sub-tropical species of shipworm thriving near the warm water discharge of a nuclear power generating station in an otherwise temperate environment.

Based on examination of the borings of modern wood-boring bivalves, incipient *T. clavatus* can often be linked to the borings produced by pholad bivalves (Savrda and Smith, 1996). Some species are also rock-borers, and may create the hard ground equivalent ichnogenus *Gastrochaenolites* in the rock record. *Martesia* has even been observed boring into lead shielding on power cables in Florida (Springer and Beeman, 1960). As these organisms are essentially filter feeders, the maintenance of an open communication with the wood/water interface exhibits a major control on the geometry of borings. In general, they subtend into the substrate in a sub-vertical fashion perpendicular to the grain of the wood, are relatively shallow and may be intertwined around the borings of their neighbors.

In contrast, teredinids bore primarily parallel to the grain of the wood. In addition, a proportionately longer set of siphons than pholads allows teredinids to penetrate deeper into wood resulting in a more sinuous boring morphology. This allows teredinids to colonize wood nearer where the wood enters surrounding sediment (in the case of wharf pilings or tree stumps). Some forms gain an appreciable amount of sustenance from digesting wood with filter feeding playing a somewhat secondary role (Andersen, 1983). This type of behavior is more typical of incipient *T. longissimus*.

FACTORS INFLUENCING BORING MORPHOLOGY

Several factors serve to control the ultimate expression of associated borings in the rock record. The density of colonization, wood types (i.e. softwood verses hardwood), the degree of compaction (in the case of peat horizons) and diagenetic factors such as siderite cementation are all important.

As large numbers of bivalve larva typically colonize substrates, the competition for space is a major factor in the survival of wood-boring bivalves. This leads to crowding within the substrate, especially as the bivalves enlarge their domiciles. Since *Teredolites* seldom intersect, the overcrowding usually manifests itself as intertwining and contortion of the borings. In the modern, this overcrowding may result in decreased growth rates of individuals (Isham *et al.*, 1951).

As the number and size of individuals within a substrate increases, so does the degree to which the borings become crowded. Under these conditions the response of the bivalves changes from the passive response of random avoidance to active avoidance. In this case, the lack of substrate may cause branching of individual borings as the bivalve backs up and bores in a different direction in the search of unexploited substrate (Savrda and Smith, 1996). Calcite linings may also be secreted along the length of the boring in response to substrate overcrowding. This may be done in an attempt to stop the communication of fluids between adjacent tubes, as the interstitial substrate becomes increasingly thin (Turner, 1971 and Turner and Johnston, 1971). These linings are only associated with specimens of *T. longissimus*.

T. longissimus also appears to be more common in allochthonous deposits (*i.e.* Plint and Pickerill, 1985 and see Table III-1, this work) where relatively small xylic clasts are colonized and the amount of substrate available to each organism is diminished. In these situations overcrowding is common (often enhanced by the frequent diminutive size of the clasts being colonized) resulting in highly contorted borings. The degree to which any given trace is contorted is often enhanced by burial compaction.

Examples of *T. clavatus* commonly occur in substrates such as exhumed peats at marine flooding surfaces and sequence boundaries (FS/SB). Where they occur in dense numbers, the borings show contortion around one another, though to a lesser degree than do those specimens of *T. longissimus*. This may be due to the fact that the primary competition for space is limited to the vertical plane, as these borings remain essentially vertical. In the case of exhumed peats, the substrates commonly have undergone compression prior to exhumation thus post-colonization deformation of the borings is relatively minor upon reburial. Those specimens of *T. clavatus* occurring in isolated logs do, however, also show compactional deformation.

The common criterion to differentiate the two species of *Teredolites* is based on a ratio of the length of the boring to the diameter (Kelly and Bromley, 1984). Ratios less than 5:1 are considered to be representative of *T. clavatus*, while those above it are allied with *T. longissimus*. As the previously mentioned environmental factors impart controls on the resultant boring morphology, it is not desirable to attempt to link a certain boring morphology to a specific trace-making organism as pointed out by Pemberton and Frey (1982).

The clavate nature of both teredinid and pholad borings arises due to growth of the bivalve as it penetrates the woody substrate. As the animal grows larger, the diameter of the boring increases accordingly. The result is a boring that is larger in diameter at its termination than at the point of initiation. This characteristic morphology is the norm providing that rates of growth exceed those of penetration. In practice, many examples of *T. longissimus* fail to show the expected clavate morphology. In examples of modern wood from Willipa Bay, Washington, extremely long, narrow borings (length to diameter ratio 20:1) are quite common.

There are biological mechanisms that explain deviation from the predicted clavate morphology. In general, teredinids penetrate wood very rapidly; up to 2cm in a month (Isham *et al.*, 1951). If the creature penetrates the wood relatively quickly, the resultant boring may be excavated too quickly to reflect the growth of the borer. This may be the expected norm in softwoods. Similarly, if the organisms have very slow growth rates, a similar, non-clavate boring may be produced. The second alternative, though related to the first, seems less likely as most wood boring organisms are fairly short lived and have rapid growth rates, especially as juveniles (Ricketts *et al.*, 1994).

Substrate consistency also has a large effect on the resultant trace fossil morphology. The competency of the substrate is the major factor in differentiating the allied forms of *Thalassinoides* (soft), *Spongeliomorpha* (firm), and *Ophiomorpha* (shifting). Evans (1968) found variation in morphology of clavate borings as a function of substrate coherence in the modern.

These environmental and behavioral considerations have taxonomic implications. The manifestation of slightly different behavior may result in the ichnologist assigning the trace to one ichnospecies in favor of another. In light of this, perhaps an equally relevant method for differentiating between the two ichnospecies would be to consider the change in diameter of a boring along its length. In general, *T. clavatus* would show an overall greater change in diameter along its length than *T. longissimus*. This recognizes how the interplay between substrate condition and the behavior of the trace maker play crucial roles in the morphological expression of the resultant trace.

PRESERVATIONAL CONSIDERATIONS

Teredolites occurrences encompass a wide variety of settings and preservational styles (Figure III-2). Of the numerous occurrences from the Cretaceous Interior of North America, very few preserve any shell material or remnants of calcitic tube linings. This leaves much speculation as to a definitive identification of the trace maker. Even if valves were preserved, they are not particularly useful in species identification (Turner, 1969). Pallets are the most diagnostic structure in the identification of pholads and teredinids but rarely seem to survive the fossilization barrier.

The excellent preservation of *Teredolites* from the Eocene of the U.K. (*i.e.* Huggett and Gale, 1995 and Gale, 1995) is unlike that in the Cretaceous of North America. Despite the common occurrence of the trace fossil, with three notable exceptions, neither shell material nor calcitic tube linings from teredinid bivalves have been documented to be preserved in the Upper Cretaceous strata of North America (see Table III-1). Bromley *et al.* (1984) noted the presence of an imprint of one valve of the pholad *Martesia* at the end of one of the sideritized borings in the Maastrichtian

FIGURE III-2 **Various modes of preservation in *Teredolites* from the Horseshoe Canyon Formation.**

A) Diminutive *T. clavatus* in sideritized sand in a transgressive lag. The extremely small size (2-3mm in diameter) represents the initial development of these traces.

B) Relict *T. longissimus*. Individual borings retain a dusting of carbonaceous material on their exterior. There is no other evidence of the original wood in the sample. This corresponds to the ghost log-ground of Savrda (1993).

C) *T. longissimus* excavated into the top of a thin coaly layer. A similar *Teredolites* occurrence in the Blackhawk Formation of Utah was referred to *Thalassinoides* by Kamola (1985, Figure 13).

D) Photo of a thin-section through a series of *T. clavatus*. The borings are sand-filled and contain some larger pyrite and mudstone fragments visible in the borings at the bottom left. Primary lamination is still visible in the coal (black) at the right of the photo. Field of view is approximately 7cm. (Courtesy of D.A. Eberth)

E) Silicified log in estuarine channel deposits with sand-filled *T. clavatus*. The entire log is approximately 3m in length.

F) Cross-section view of log in figure (E) showing dense concentration of sand-filled borings.

G) Relict "log" containing sideritized *T. clavatus*. No original wood remains and the position of the "log" is inferred from the concentration of borings.

H) Close-up of a portion of the "log" in figure (G).

I) Detail of an individual *T. clavatus* in figures (G) and (H) showing the relict grain of the wood into which the boring was excavated (Zenoglyph of Bromley *et al.*, 1984).

J) Valve of *Martesia* preserved at the distal termination of a *T. clavatus*. (from Bromley *et al.*, 1984).


5 cm
C
8 mm
D
Fisher Scientific Company
H
G
I
1 cm
J
6 mm

Horseshoe Canyon Formation (Figure III-2J). The second occurrence is the only other known published example of this type of preservation in the Lower Cretaceous Bluesky Formation of North-central Alberta in the Peace River Oil Sands (Hubbard *et al.*, 1999; Figure 18c). In this deposit, shell material is present within the borings (Figure III-3a).

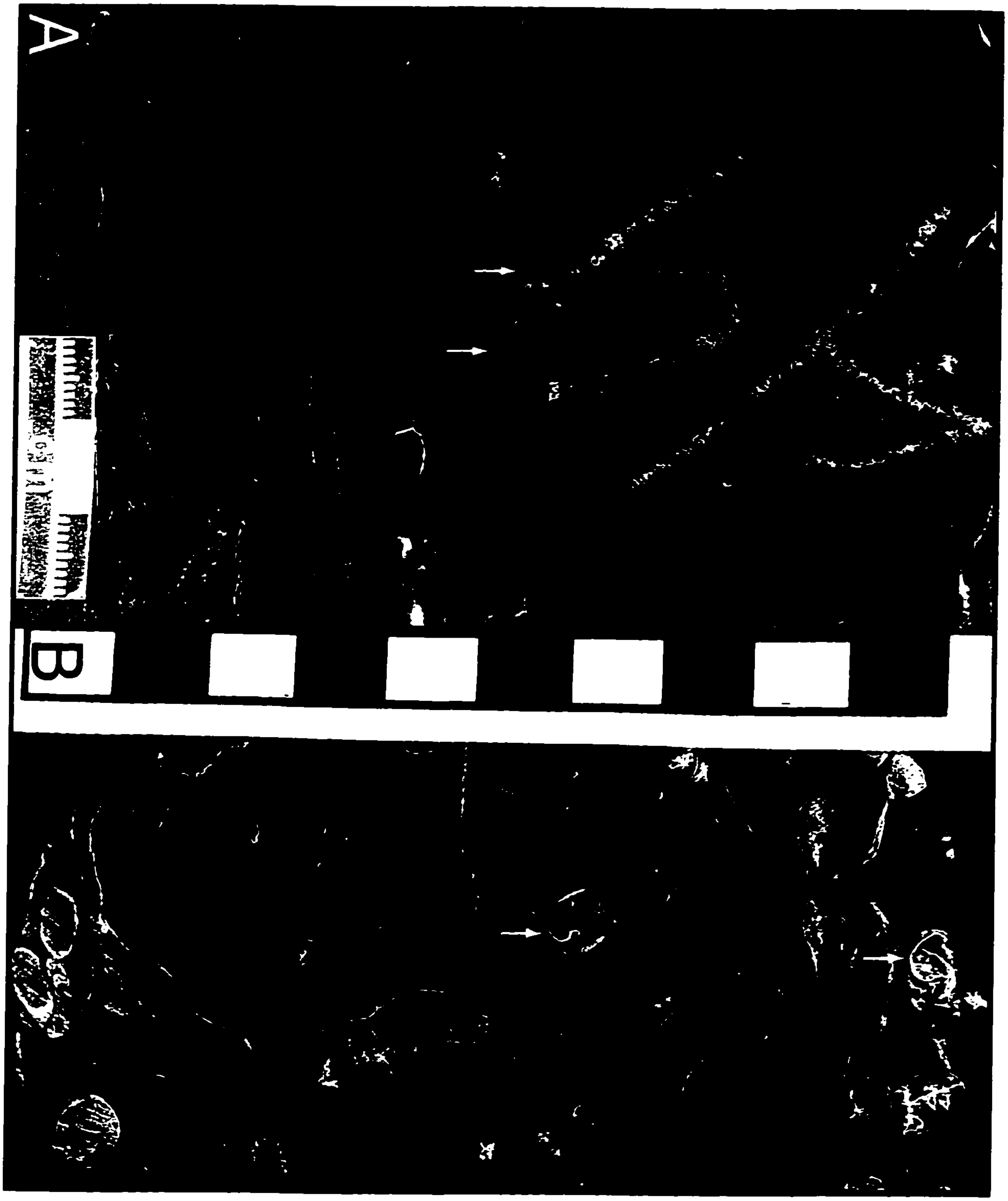
Another, unpublished occurrence has been brought to my attention by C.J. Collum in the Upper Cretaceous Badheart Formation. In these deposits, both shell material and calcitic tube-linings are present (Figure III-3b). Both of the latter two examples seem have extenuating diagenetic circumstances that may lead to this abnormally good preservation. The Peace River Oil Sands deposit preserves primary aragonite of bivalve shells throughout the Formation (Hubbard, 1999) while the Badheart Formation contains chamsosite ooids and has been interpreted as being deposited near cold water seeps (Collom, pers. comm.). By examining worldwide occurrences of *Teredolites*, Kelly, 1988b echoed the fact that the borings are far more numerous than the bivalves themselves.

There may be a valid diagenetic explanation for the notable absence of calcitic material associated with the trace makers. The vast majority of the North American occurrences of *Teredolites* occur in deltaic settings that contain abundant coals. Under these conditions, acidic groundwaters would be the norm and therefore preservation of the aragonitic shells would rarely be expected. This reasoning was used to explain the conspicuous absence of calcareous foraminifera in the Horseshoe Canyon Formation by Wall (1976).

FIGURE III-3 **Preservation of shell material in *Teredolites* from the Cretaceous of Alberta.**

A) Shell material (arrowed) from teredinid bivalves in *Teredolites longissimus* excavated into coaly laminae from the Bluesky Formation (Lower Cretaceous) in the Peace River oil sands deposit. Photo courtesy of S.M. Hubbard.

B) Pholad shells (arrowed) in *Teredolites clavatus* from the Badheart Formation (Coniacian). Most borings also have preserved calcareous tube linings (white rims around borings). Samples courtesy of C.J. Collum.


A
B

Siderite cementation is a common mode of preservation of *Teredolites* in the Horseshoe Canyon Formation. Specimens of *T. clavatus* are typically filled with a coarse sand fill. This sand contains abundant microvertebrate material such as shark teeth, and fish spines and scales. Cementation probably occurred as a result of organic-rich fluids moving through high porosity and permeability sand. This early cementation would serve to limit post depositional compaction of these traces.

Many other specimens are highly deformed. This is likely due to lithostatic compaction. It also appears to be more prevalent in smaller specimens and many of the specimens assigned to *T. longissimus*. A high degree of compactional deformation has not been observed in sideritized traces suggesting the cementation occurred very early diagenetically.

STRATIGRAPHIC APPLICATIONS

The presence of bored xylic substrates has commonly been used as a palaeoenvironmental indicator in post Jurassic rocks (*i.e.* Shanley and McCabe, 1990; Shanley *et al.*, 1992). In the case of woodgrounds, exhumed peat deposits formed in coastal swamps are often laterally continuous and colonization of these substrates typically is the result of lowstand erosion and subsequent marine flooding. These surfaces can be valuable stratigraphic indicators.

Bromley (1970) noted that modern rock boring bivalves are primarily restricted to shallow water. Turner (1973) reported wood-boring pholad bivalves at a depth of 1830m but these creatures are more abundant and proliferate in shallower waters if for no other reason than a better source of wood in nearshore environments. Lewy (1985) concurred and concluded that the development of extensive hardground bored surfaces would be limited to shallow water. This relationship also appears reasonable for wood-boring bivalves.

Two markedly different concepts have arisen aiding in the study of wood borings. Woodgrounds (*sensu* Bromley *et al.*, 1984) and log-grounds (*sensu* Savrda *et al.*, 1993) both attempt to place the borings in a useful context but usage of the terms in current literature shows poor understanding of the intended usage. A review of the concepts is therefore deemed necessary.

THE WOODGROUND CONCEPT

The term woodground was introduced by Bromley *et al.* (1984) in establishing the *Teredolites* ichnofacies from a locality in the Horseshoe Canyon Formation of southern Alberta. *Teredolites* occur at the base of a mud-filled channel where lowstand erosion locally exhumed a peat substrate (Figure III-4). The woodground represents a mappable surface demarcated by a dense concentration of pholad bivalve borings. Stratigraphically, the erosive base of the channel represents a sequence boundary/ flooding surface comprised of coeval lowstand and transgressive surfaces of erosion.

The unconformity is demarcated by sideritized *Teredolites clavatus* that penetrate as deep as 8cm into the underlying coal seam. Above this surface, the basal channel fill consists of a 1m thick upper medium-grained, trough cross-bedded sandstone that contains abundant coalified rip-up clasts originating from the upper surface of the

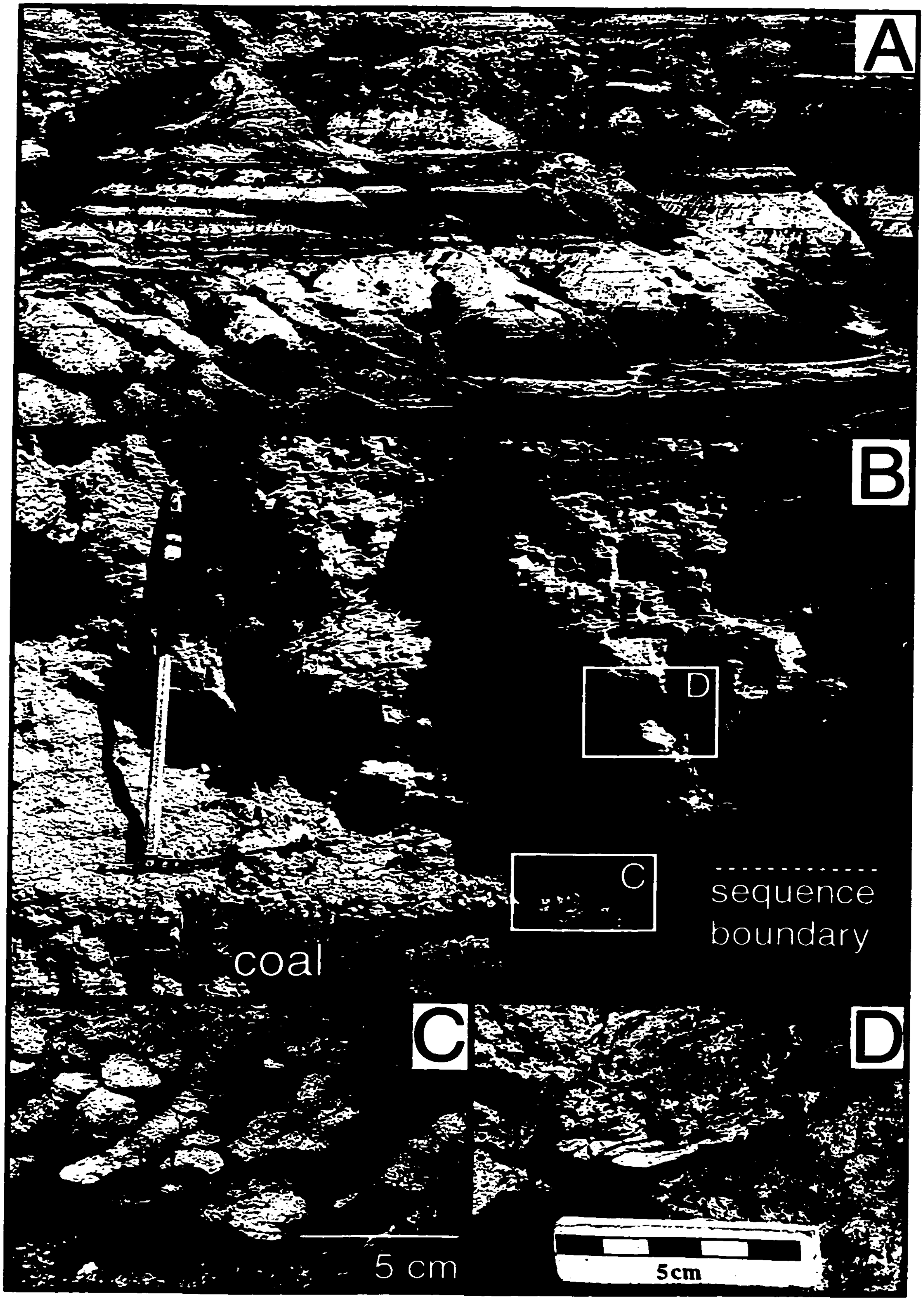
Figure III-4 **Development of a *Teredolites* association at a bounding surface in the Horseshoe Canyon Formation in southern Alberta.**

A) Mud-filled channel at East Coulee. Base of the channel rests erosively on the top of a coal seam.

B) Close up view of basal valley fill where a thin transgressive sandstone erosively overlies the coal. Sands are trough cross-bedded and contain abundant coalifed rip ups (axe is 85cm in length).

C) *Teredolites clavatus* excavated into the top of the coal. The trace-maker was the pholad bivalve *Martesia sp.* (see Figure III-2J).

D) *T. longissimus* excavated into wood rip-ups in the transgressive sandstone. These clasts were probably colonized in a more basinward locality and were washed shoreward and ultimately incorporated into the basal channel fill. The probable trace-maker was a teredinid bivalve.


A
B
D
C
sequence boundary
coal
C
D
5 cm
5cm

peat mat. Many of the wood clasts are orientated along trough cross beds and contain *T. longissimus*. These clasts in the basal channel fill are not *in situ* and only retain stratigraphic value due to their close proximity to the regional unconformity. They are not considered part of the woodground assemblage. Confusion has arisen over this distinction. Dewey and Keady (1987) described bored wood on lateral accretion surfaces in estuarine channels in the Eutaw Formation in Mississippi as woodgrounds. These occurrences are not *in situ* peat horizons, they are bored clasts. This is an improper application of the woodground concept. The occurrences are more akin to the log-ground of Savrda *et al.*(1993).

THE LOG-GROUND CONCEPT

Trace fossils are regarded as excellent environmental indicators because they are almost exclusively formed *in situ*. Savrda (1993) used the term "log-ground" when describing any piece of wood that exhibits borings. The concept of considering a piece of wood to represent a substrate condition is highly problematic. A log represents a unique "substrate" condition because the colonized media are fully transportable. An example from a cored interval through the Lower Cretaceous Grand Rapids Formation of Alberta demonstrates this as the well intersected a log that contains diminutive *Teredolities* (Figure III-5). This log is clearly not *in situ* and emphasizes the fact that as presently described, the term log-ground has little environmental or stratigraphic value.

The term log-ground (Savrda *et al.*, 1993) overemphasizes the significance of *Teredolites* associations. This is markedly different from, and against the intent of, the term

FIGURE III-5 ***Teredolites*** **-bored log from the Grand Rapids Formation, well 13-10-81-21W4 at a depth of 269m.**

A) Core photo of bored log. Growth rings in the tree are visible as are quartz-filled fractures. It is bored around its perimeter suggesting that it was colonized while floating. The borings are filled with sandstone from the surrounding unit.

B) Detail of photo (A).

(Well location courtesy of Indraneel Raychaudhuri)


cm
T.R.G.
cm
T.R.G.

wood-ground as introduced by Bromley *et al.* (1984). Wood-ground was introduced to represent a distinct substrate condition, differentiable from both soft-ground and hard-ground substrates whereas *Teredolites*-bored wood often merely represents bored xylic clasts within a given facies.

In this light, a newly proposed, descriptive and non-cumbersome definition of a log-ground would read as follows: " A facies characterized by an abundance of bored wood. Not limited to *Teredolites*, the boring activity of crustaceans, and attachment scars and borings of bryozoans and sponges is also significant. By the very nature of the deposit, the wood is recognized as being transported (allochthonous). It differs from a woodground (*sensu* Bromley *et al.*, 1984) in this respect.

Log-grounds can be a useful descriptor when describing facies characterized by abundant bored wood. It is suggested that this is a more useful definition of log- ground and usage in the context of isolated pieces of bored wood be abandoned and simply referred to as "bored wood".

Many of the cited "log-grounds" are acknowledged by the authors to be allochthonous (*i.e.* Savrda, 1991,1993; Plint and Pickerill, 1985; Mikulas, 1993). They are merely facies associations that contain abundant wood. While many of these logs are in fact bored, their stratigraphic significance is diminished due to the fact that they are commonly transported. This makes the environmental and stratigraphic significance of these clasts highly questionable. The presence of bored wood need not be indicative of the environmental conditions where the clast is incorporated into the stratal package, rather it depicts the conditions prevalent at the time and place where the clast was colonized.

Plint and Pickerill (1985) used the lack of tidal structures such as bimodal palaeocurrent indicators, paired mud drapes and bioturbation to discount a tidal origin for the Bracklesham Formation in southern England and cited the occurrence of *Teredolites* - bored wood as evidence for a non-marine *Teredolites*. Many of these so-called "diagnostic criteria" for tidal influence strata are conspicuously absent even in modern tidally influenced sediments.

In this case, negative evidence is not conclusive in supporting the interpretation of the Bracklesham Formation as representing a strictly fluvial system. In coeval deposits to the east of the study area of Plint and Pickerill (1985), the authors pointed out that "typical" estuarine structures are present in equivalent strata adjacent to the study area. It is perhaps more useful to think of the environmental setting of the *Teredolites* occurrences as the upper (freshwater-dominated) portions of an estuary rather than as a fluvial channel setting. From a biological perspective, it is more parsimonious to interpret that the wood was washed upstream from a marine or brackish source (possibly during transgression) than for teredinid bivalves to be flourishing in the non-marine. This also appears to be the case in the Six-Mile Canyon Formation in Utah where rafted logs occur at the base of a fluvially dominated channel incised into offshore mudstones (Schwans and Campion, 1997).

Plint and Pickerill (1985) also described a lignite from the same beds. Based on a lack of a rooted surface and associated palaeosol, the lignite was interpreted to be comprised of drifted plant debris. These xylic clasts were not colonized *in situ* and therefore any environmental interpretation based on their occurrence is not justified. This is not a woodground (*sensu* Bromley *et al.*, 1984) but more akin to a log-ground (this paper).

Like any trace fossil assemblage, it is imperative that the occurrences of bored wood be used in a tightly constrained context based on a detailed sedimentologic and stratigraphic framework. The presence of isolated bored wood fragments is not directly indicative of marine influence, especially in cases where the xylic material can be demonstrated to be of allochthonous origin. The only pieces of data that an occurrence of this nature directly implies is that either the depositional system in question contains a connection to a marine source such as in upper estuarine settings or that it was eroded out of older, adjacent settings.

Savrda (1991b) linked the occurrence of xylic substrates and/or *Teredolites* to transgressive systems tracts. Although most occurrences reported in the literature are found at or near transgressive surfaces (often as transgressive lags), the predominant occurrence of bored-wood in the transgressive systems tract may be more a matter of serendipity than a unique indicator. Savrda *et al.* (1993) attributed an abundance of bored-wood to increased influx of xylic material on transgression.

Estuarine sediments commonly contain bored wood but this is a function of proximity to a source of plant material and relatively high sedimentation rates enabling burial and preservation of the wood. These clasts have a higher preservational potential during transgression due to increasing accommodation.

In contrast, lowstands typically are characterized by subaerial erosion and non-deposition as a result of lower accommodation. Subsequently, thick and extensive lowstand systems tracts are statistically rare in the rock record. The low accommodation results in little preservation potential for bored wood and it may be nearly completely destroyed by boring organisms prior to burial.

While the position of bored wood in stratal packages may be intrinsic to sea level fluctuation, it is imperative to realize that there are taphonomic controls that make it difficult to separate preservational potential from a perceived allocyclic adjustment. Like many aspects of geology, it is not always about what happened, but more ones interpretation based on what is preserved.

A Fossil "Log-ground": The Empire Formation, Coos Bay, Oregon

The Eocene Empire Formation exposed at Fossil Point, Oregon provides an example of a mappable log-ground. A trace fossil assemblage that includes *Schaubcylindrichnus* sp., *Rosselia* sp. and *Ophiomorpha nodosa* provides evidence of shoreface deposition. The sediments also contain sparsely distributed yet abundant xylic clasts in the form of coalified wood. Much of the wood contains borings that would be assignable to both *T. clavatus* and *T. longissimus* (Figure III-6).

There are several lines of evidence that attest to the transported nature of the wood. Paleocurrent analysis based on the orientation of the long axis of the wood shows there is a bimodal distribution, consistent with a transported assemblage. Although several specimens reach several meters in length, the majority are on the order of 50cm long. The diminutive size coupled with the sparse distribution suggests that the wood was transported seaward and incorporated into the shoreface at the present outcrop locality.

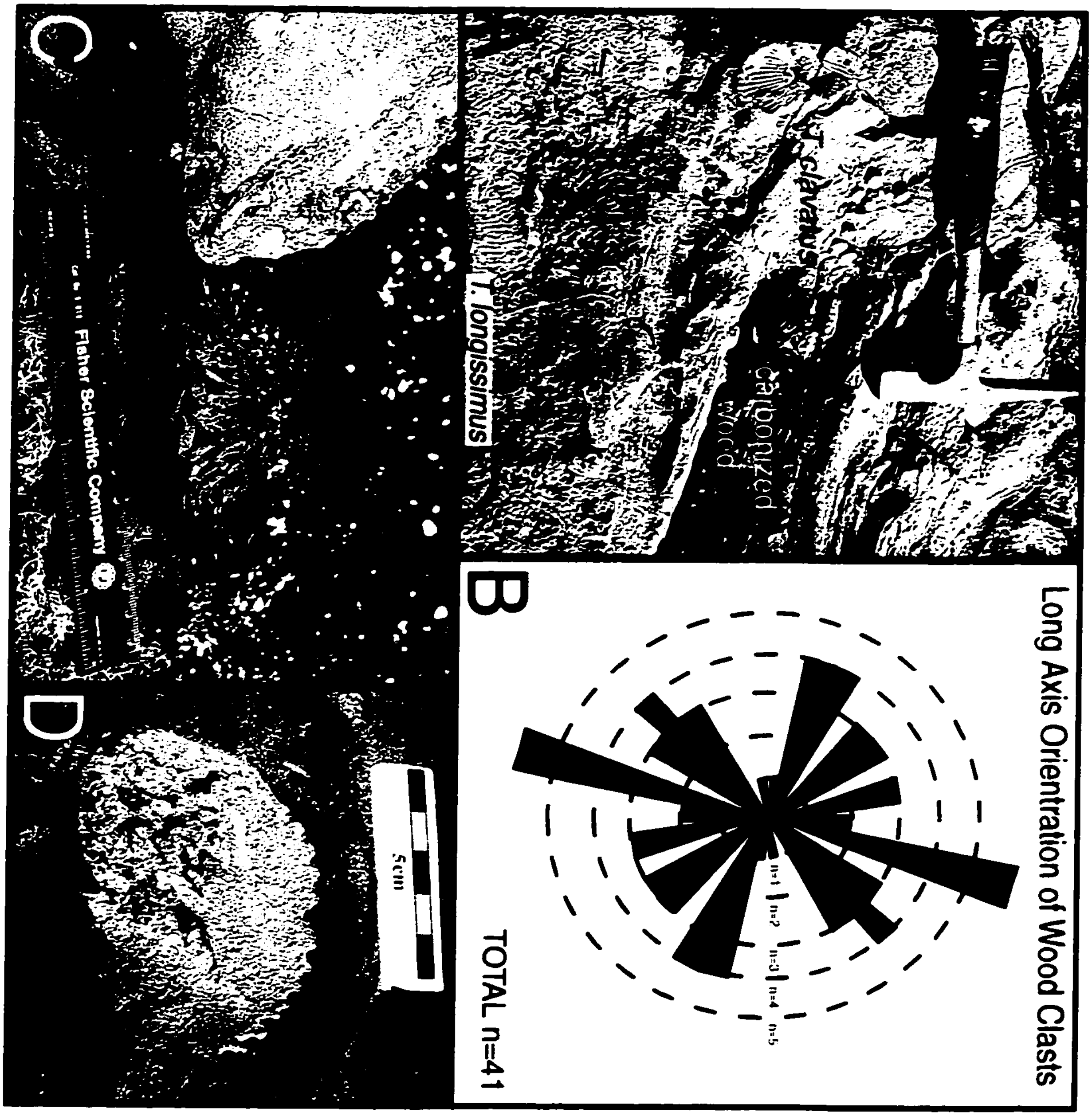
Figure III-6 ***Teredolites* occurrences in the Empire Formation, Fossil Point, Oregon.**

A) Two essentially parallel logs displaying different boring morphologies. A carbonized log containing *T. clavatus* (below hammer handle) lies next to a log that contains almost no original wood and is entirely bored with *T. longissimus* (bottom center).

B) Rose diagram showing the long axis orientation of 41 pieces of wood in the Empire Formation. Strong bimodal distribution provides evidence of the transported nature of the wood fragments.

C) *T. longissimus* in a segment of a carbonized log (Ruler is 15cm).

D) *T. longissimus* in a small wood fragment preserved in a scallop shell.


T. clavatus
carbonized wood
T. longissimus
Fisher Scientific Company
C
B
Long Axis Orientation of Wood Clasts
n=1
n=2
n=3
n=4
n=5
TOTAL n=41
D
5cm

Modern "Log-grounds": Willapa Bay Washington and Panama City, Florida

The log-ground concept can be useful if one can demonstrate that the wood in question is *in situ* or has undergone minimal transportation. This is the case in Willapa Bay, Washington where forested low-lying swamps are undergoing coastal ravinement (Figure III-7). The remnant root systems of large trees are ultimately being incorporated into the modern beach. Colonization of this wood by teredinid bivalves and isopods is prevalent.

This assemblage comprises a complex association of both transported wood fragments as well as trunks of trees that have undergone minimal transport. The occurrence of this wood as a function of wave ravinement at the beach horizon would represent a useful stratigraphic horizon (a transgressive surface of erosion) if it were to pass into the rock record.

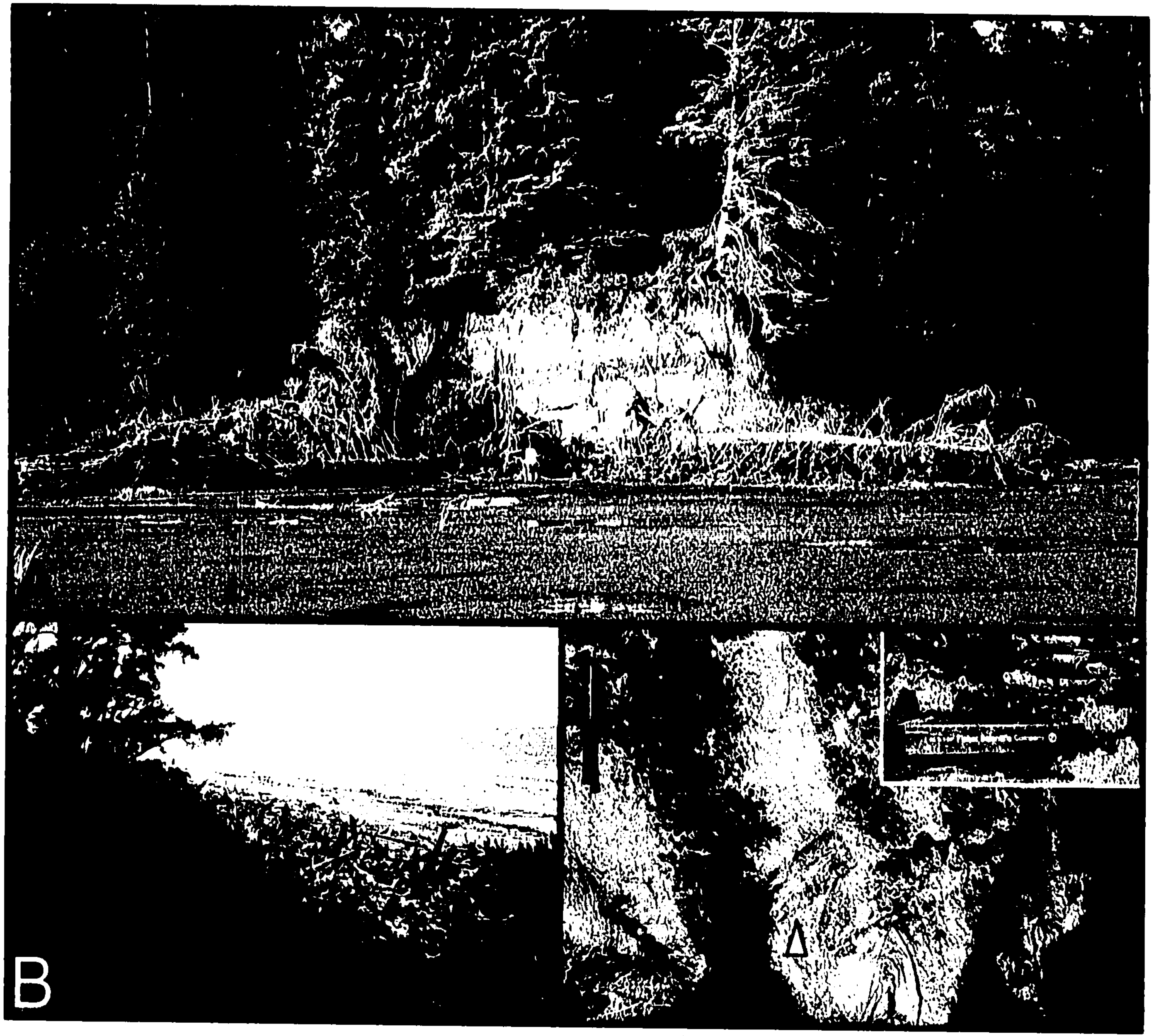
A similar woodground scenario was reported by Burgess (1977) a mile and a half off the coast of Panama City, Florida in sixty feet of water. Slash pine trees were observed to be standing upright on the sea floor at an average density of one tree per m^2. The wood was observed to be heavily bored above the mud line. As these trees originated from terrestrial sources, Burgess was able to infer that sea level has risen approximately 20 meters in this area. The wood was carbon dated at 28000 years old. They are *in situ* and mark the former position of a forest. The trees were reported to be unmineralized but if they pass through the fossilization barrier, the bored stumps signify a significant stratigraphic surface.

FIGURE III-7 **Development of modern and ancient log-grounds in transgressive settings.**

A) Wave-eroded cliffs undercutting trees in Willipa Bay Washington. This mechanism for supplying wood into marine settings supports the observation of Savrda (1993) that transgressions are often characterized by pulse of xylic material. People in center foreground provide scale.

B) Wave-tossed timber, The Inlet, Willapa Bay, Washington. This represents an accumulation that is not *in situ*. This material would represent a transgressive lag if it were to pass into the rock record.

C) Allocthonous, bored logs (arrowed) comprising the basal portion of a transgressive systems tract. *Teredolites clavatus* (arrowed) excavated into the wood (inset). Lower Six-Mile Canyon Formation, Six Mile Canyon, near Sterling, Utah. This corresponds to the U6 sequence boundary of Schwans and Campion, 1997.


B

TEREDOLITES AS AN INDICATOR OF CONCEALED BED JUCTIONS AND THE AMALGAMATION OF ICHNOLOGICALLY DEMARCATED SURFACES

Autocthonous woodgrounds represent surfaces that enable stratal packages to be evaluated in an allostratigraphic framework. High-frequency base level changes may be responsible for generating sedimentologically and stratigraphically complex surfaces. The juxtaposition of surfaces due to multiple burial and exposure events can produce complex ichnological tiering relationships in palimpsest substrates (Lavigne *et al.*, 1998). Two examples have been chosen to demonstrate important stratigraphic concepts that have not been applied previously to *Teredolites*.

AMALGAMATED SURFACES; DINOSAUR PARK FORMATION, IDDESLEIGH, ALBERTA

A locality near Iddesleigh in southern Alberta (see Figure III-1) can be interpreted as an amalgamation of *Teredolites* surfaces (Figure III-8 a&b). The Judith River Group outcrops throughout southern Alberta. At the top of the Red Deer River Valley near Iddesleigh, it records the transition from the fluvial-estuarine deposits of the Dinosaur Park Formation to the upper coaly portion referred to as the Lethbridge Coal Zone that marks the initial phase of the Bearpaw transgression.

At this locality, brackish bay deposits erosionally overly a coal. The bay deposits are characterized by heterolithic sandstone and mudstone layers and contains diminutive *Planolites* with a sharp, erosional base with abundant coal rip-ups. Into the top of the coal

Figure III-8 (A,B) **Woodground association from the Dinosaur Park Formation near Iddesleigh, Alberta.**

A) Bedding plane view of amalgamated suites of *Teredolites*. The surface is characterized by *T. clavatus* (large boring) subtending into a coal. Above this, *T. longissimus* occur as clusters of essentially parallel borings interpreted to represent individual pieces of bored wood accreted onto the surface demarcated by the *T. clavatus*.

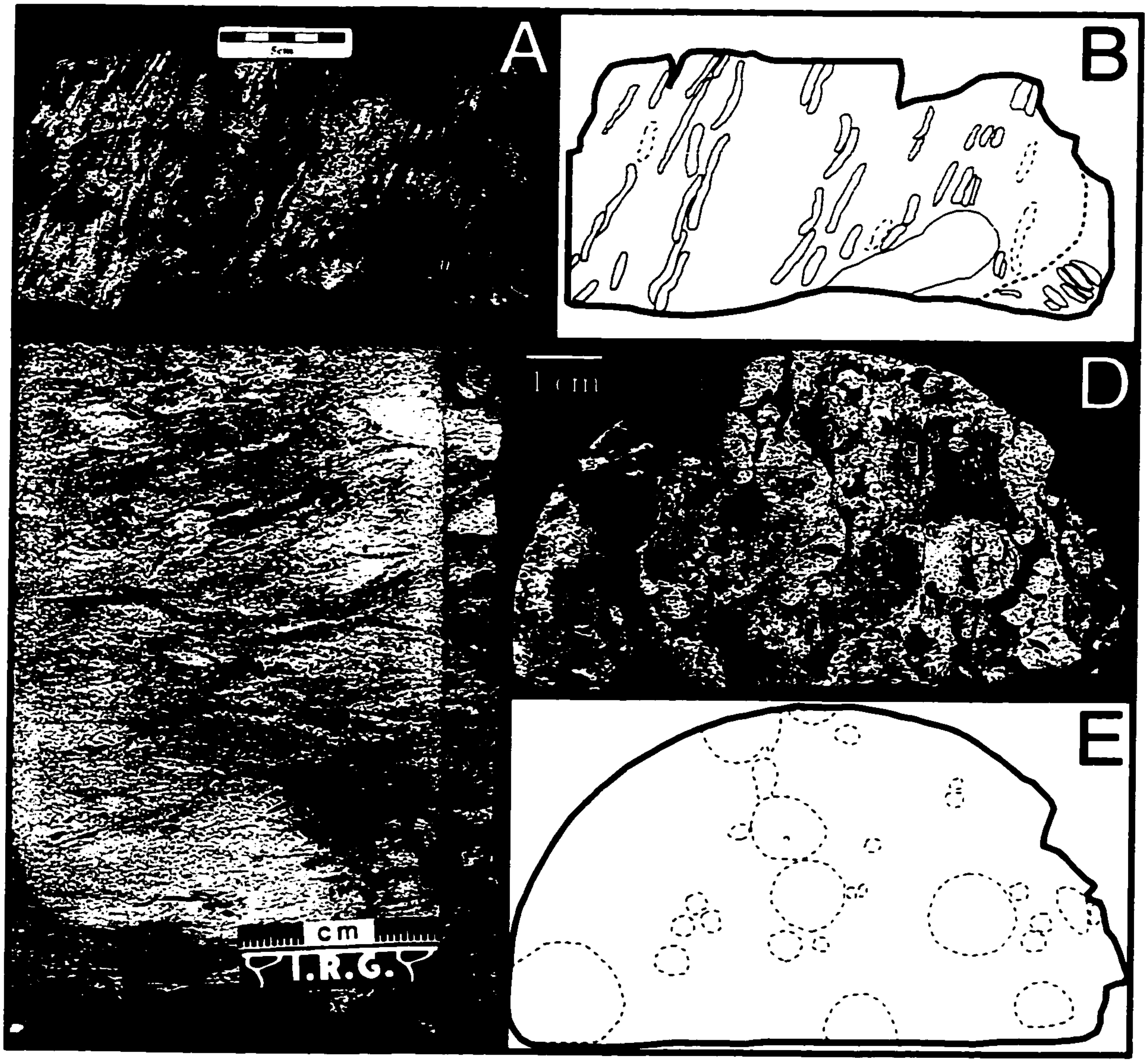
B) Tracing of figure (A) showing the relationships of individual borings.

FIGURE III-8 (C,D,E) **Concealed bed junction demarcated by *Teredolites clavatus*, Horseshoe Canyon Formation, Drumheller, Alberta.**

C) Core sample from well 14-07-24-18W4 showing brackish deposits overlying a thin veneer of coal.

D) Bedding plane view at the base of sample (C) showing the distal terminations of *T. clavatus*, often identified on the basis of residual coal rinds on the edges of the borings.

E) Tracing of sample (D) showing the position of the numerous borings.


5cm
A
B
1 cm
D
E
cm
T.R.G.

are excavated a low-density suite of highly compressed *T. clavatus*. A second suite of higher density *T. longissimus* is also present. Occurrences of *T. longissimus* are dominated by borings that run parallel to the grain of the wood. These traces consist of clusters of essentially parallel borings. With respect to each other however, the clusters do not show a clear preferential orientation.

The larger, clavate borings are interpreted to represent an autochthonous woodground. The randomly oriented *T. longissimus* are excavated into pieces of allochthonous wood that were colonized in marine conditions as flotsam and deposited in their present location.

Examined in an allostratigraphic context, the occurrence is representative of coeval lowstand and transgressive surfaces of erosion. Transgressive erosion exhumed a buried, coastal peat. Initial transgression flooded this horizon with brackish water allowing colonization by the *T. clavatus* trace-making organism (probably a pholad bivalve). Coastal ravinement also supplied abundant wood to the basin (*sensu* Savrda *et al.*, 1993) in the form of both plant material from the hinterland and woody material eroded off of the top of the coal. This wood became colonized as flotsam by the *T. longissimus* trace-making organism (probably a teredinid bivalve).

As transgression continued, coastal onlap began and bored wood was deposited on the top of the colonized peat. The area became fully inundated and the brackish bay succession was deposited. Examined in this context, the complex trace fossil assemblage can be explained as an expression of relative base level fluctuations. The occurrence of the *T. clavatus* represents a autochthonous woodground (*sensu* Bromley *et al.*, 1984) while the occurrences of *T. longissimus* represents an allochthonous log-ground (this paper).

CONCEALED BED JUNCTIONS; HORSESHOE CANYON FORMATION, DRUMHELLER, ALBERTA

Complications to ichnofacies models arise due to erosional removal of colonized substrates. Often this results in the preservation of the lower portions of burrows without the preservation of the surface that they subtend from. Referred to as concealed bed junctions (Simpson, 1970), they are identified primarily on the basis of a contrast of burrow fill to the surrounding matrix.

In the Horseshoe Canyon Formation, *T. clavatus* occurs in cored interval in a well located at 14-07-24-18W4 at a depth of 123m (Figure III-8 c,d,e). The traces occur on a bedding plane consisting of a 3mm coal laminae. The bedding plane contains the 1cm in diameter distal terminations of the borings. Since wood-boring bivalves attach to wood substrates as spat and enlarge the boring throughout their lives, it is unreasonable to assume that the small laminae would have provided enough substrate to sustain the colony of bivalves until they reached the growth stage represented.

This surface is more parsimoniously interpreted to represent an erosional remnant of an originally thicker coal deposit. Peat horizons provide a resistant substrate that mitigates the downcutting of channel deposits as in the case of the mud-filled channel described by Bromley *et al.*(1984). While this relationship acts as a predictive tool it does not imply woody substrates cannot be erosionally thinned during either transgressive erosion or fluvial downcutting.

DEVELOPMENT OF COMPOSITE ICHNOFABRICS IN XYLIC SUBSTRATES

In modern woody substrates, there are a plethora of organisms that occupy abandoned teredinid borings. In Willapa Bay, Washington, creatures such as mussels, crabs, polychaetes and isopods can be frequently observed occupying borings as refuge habitats. Also as many incipient-*Teredolites* become filled with organic-rich sediment soon after abandonment, the potential for other organisms to rework the sediment infill is high.

Miller (1996) suggested a sabellariid polycheate origin for sand-lined tubes found within pholad-bored driftwood. The specimens were collected from beaches in North Carolina after a series of tropical storms. He postulated that this might be a mechanism to produce composite ichnofabrics in *Teredolites*. Similar specimens were collected from the West Coast in Willapa Bay, Washington that show similar sabellariid polycheate tubes constructed in abandoned borings attributed to the teredinid bivalve *Bankia* sp. (Figure III-9a). This would suggest that sabellarid “squatters” are not uncommon in the modern and uphold Miller’s conjectures regarding the rock record.

Small (7mm diameter), sideritized *T. clavatus* from the Horseshoe Canyon Formation (Campanian/Maastrichtian) of southern Alberta may represent a fossil example of this relationship. The composite ichnofabric is expressed as small 2mm tubes within the *T. clavatus*. They are recognized on the basis of higher degree of resistance to erosion and slightly coarser grain size. They are interpreted to represent sand-lined tubes within the borings (Figure III-9b).

Meyers and Reynolds (1957) noted that fungal attack weakens wood in the present day and makes it more susceptible to attack by bivalves. Certain types of fungi attack wood during the winter thereby weakening it and enable boring bivalves to colonize it when they proliferate in the late spring. Fungal attack on wood is documented in the rock record (*i.e.* Crebar and Ash, 1990). The destruction of wood tissues by fungi could also be a component of a composite ichnofabric involving *Teredolites*.

CONCLUSIONS

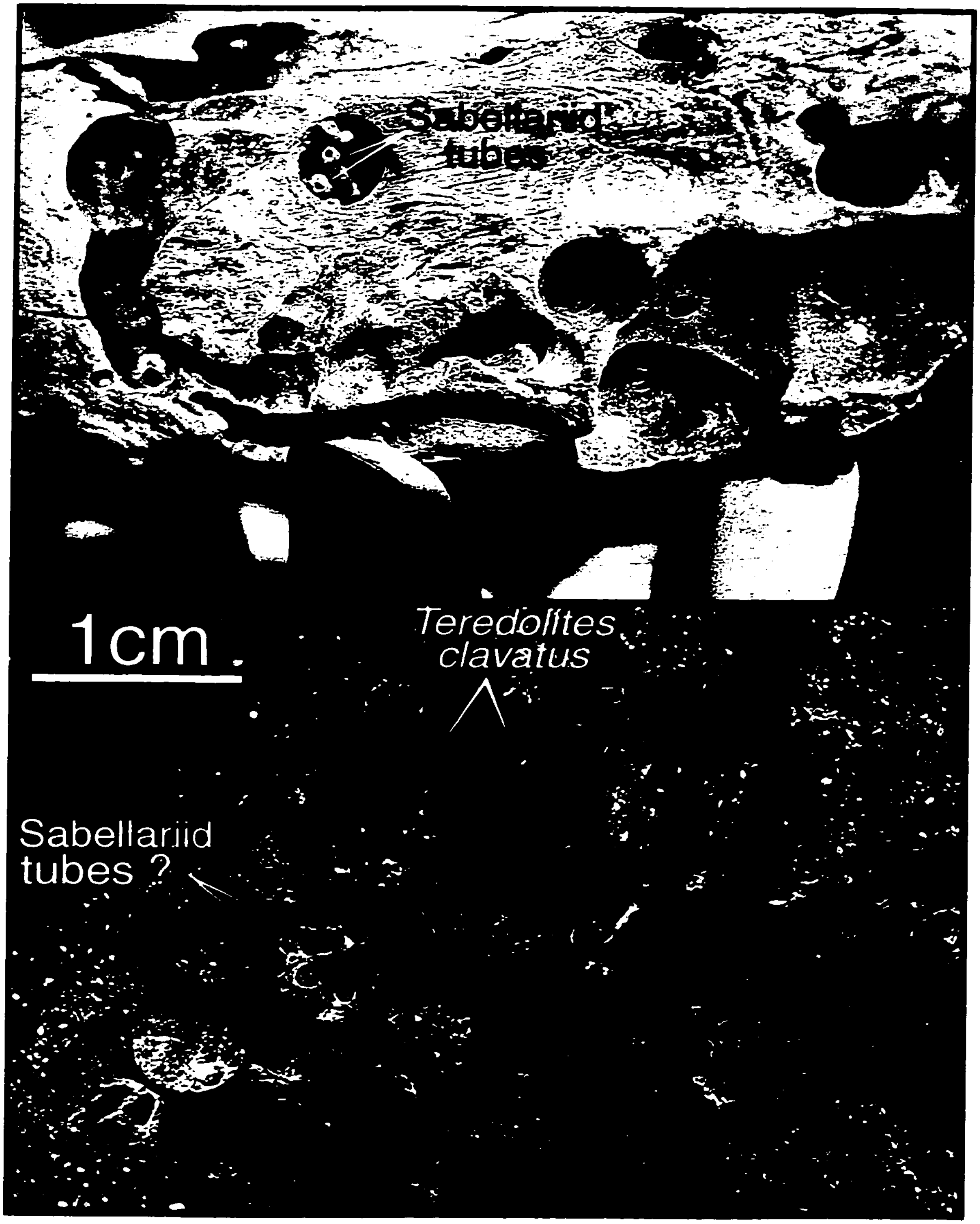
When assessing the stratigraphic significance of any trace fossil assemblage it is imperative that it be done in conjunction with a detailed sedimentological framework. Trace fossils are generally regarded as excellent environmental indicators because they are almost exclusively *in situ*. As *Teredolites* are excavated into pieces of wood that are fully transportable, the stratigraphic and environmental significance of the borings is drastically diminished.

Pholad and teredinid bivalves are typical *Teredolites*-trace makers. These organisms are exclusive to marine and slightly brackish waters. Due to the transportability of the colonized wood, these clasts can be found in depositional settings that are distinctly different from the environment of colonization. The occurrence of *Teredolites* within a stratal succession does not attest to marine deposition, merely a connection to a marine source.

FIGURE III-9 **Modern analogue and ancient example of the development of complex ichnofabric in *Teredolites*.**

A) Modern bored wood from Willapa Bay, Washington. Arrows highlight sand lined tubes of sabellariid polychaetes occupying the boring as a refuge habitat.

B) Composite ichnofabric consisting of *Teredolites clavatus* that is reburrowed, resulting in a fabric similar to one that would be expected if the specimen in (A) above were to pass into the rock record. Sample is from the Maastrichtian Horseshoe Canyon Formation, at East Coulee, Alberta.


Sabellariid tubes
1cm
Teredolites clavatus
Sabellariid tubes ?

Woodgrounds are mappable horizons characterized by borings into a substrate composed of wood and/or peat. They can occur at surfaces that can have stratigraphic significance because woody substrates are difficult to erode and bounding surfaces often bottom out on such horizons. In contrast, log-grounds have been defined as any piece of wood that exhibits borings. This concept has incorrectly placed the significance of the trace fossil on a single specimen rather than on the assemblage of wood and associated traces. In the same way that an isolated shell is not a shell bank, neither is a single piece of wood a woodground.

It would be more beneficial to define log-grounds as *accumulations* of bored wood. Like woodgrounds, these can be useful in stratigraphic studies, as bored wood may be concentrated at surfaces such as transgressive surfaces of erosion or sequence boundaries. This usage also maintains a hierarchical ranking that is useful and distinct from the related woodground concept.

While many studies have dealt with morphology of bivalve borings in wood, few have focussed on the potential stratigraphic significance. *Teredolites* can occur in complex associations representing coeval surfaces. Wood substrates provide a horizon that is resistive to erosion. It is therefore quite reasonable to suspect that these surfaces may be prone to multiple re-exposures, and the sedimentologist should be aware that these surfaces represent temporal discontinuities that may or may not be of stratigraphic significance.

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TABLE III-1 Worldwide *Teredolites* Occurrences.

LOCALITY/ FORMATION	AGE	REFERENCES	COMMENTS
Neslen Formation, Book Cliffs, Utah	Campanian	Anderson *et al.*, 1995	Log-ground. Bored carbonaceous material associated with hadrosaur skin impressions
Mamu Formation, Southest Nigeria	Maastrichtian	Arua, 1989	Wood ground. *Teredolites* penetrating from a silty sandstone into a coaly layer
Ameki Formation, Southwest Nigeria	Eocene	Arua, 1991	*T. longissimus* in calcareous concretions
Enys Formation, Canturbury, New Zealand	Miocene- Pliocene	Bradshaw, 1980	*Gastrochaenolites* incorrectly identified as *Teredolites*
Svartenhuk Penninsula, West Greenland	Upper Cretaceous	Bromley and Asgaard, 1991	Isolated bored log
Basal Horseshoe Canyon Formation, Alberta	Maastrichtian	Bromley *et al.*, 1984	Wood ground. *Teredolites* penetrating the top of a coal. Also abundant isolated bored wood fragments
Badheart Formation, NW Alberta, Canada	Coniacian	Collum, C.J., pers. comm., 1998.	Sulfide-rich rocks, bored wood, calcite linings, preserved valves
Maungataniwha Sandstone, New Zealand	Campanian-Maastrichtian	Crampton, 1990	Bored logs in concretions in transgressive setting
Eutaw Formation, Mississippi	Coniacian-Campanian	Dewey and Keady, 1987	Allochthonous logs preserved on lateral accretion beds
Kolosh Formation, Iraq	Paleocene- Lower Eocene	Elliot, 1963	Dicotyledonous wood with calcite filled borings. Good preservation of body parts.
Lopez de Bertodano Formation (?), James Ross Island, Antarctica	upper Lower to Middle Campanian (disputed, see Francis, 1986)	Francis, 1986	Isolated bored logs, some shell material
Vega Island, Antarctica	Campanian-Maastrichtian	Francis, 1986	Isolated bored logs
Seymour Island, Antarctica	Lower Tertiary	Geikie, 1898	"Petrified Worms" in well-preserved wood from deciduous trees.
Eagle Sandstone, Billings Montana	Campanian	Hansen, 1989	Isolated wood in a channel point bar sequence
Trichinopoly Group, SE India	Turonian	Hart and Tewari, 1995	Logs with encrusting oysters. Lined Tubes.
Star Point Formation, Utah, U.S.A.	Campanian	Howard and Frey, 1984	Locally in bored logs in upper shoreface setting

TABLE III-1 Worldwide *Teredolites* Occurrences.

LOCALITY/ FORMATION	AGE	REFERENCES	COMMENTS
Bluesky Formation, north-central Alberta	Aptian	Hubbard, 1999a&b	Preseved shell material of teredinids (?)
London Clay, U.K.	Eocene	Huggett and Gale, 1995; Gale, 1995; Stinton 1956;	Isolated wood, *T. longissimus*, calcite linings and hard parts preserved
Blackhawk Formation (Springer Canyon Member)	Upper Cretaceous (Campanian)	Kamola, 1984; Kamola and Howard, 1984; Howard and Frey, 1984	Woodgrounds, channels bottom out on coal. Incorrectly identified as *Thalassinoides* (fig. 13).
Kotick Point Formation, Antarctica	Tithonian to Albian	Kelly,1988(a)	Drifted, scattered plant remains.
Marambio Group, Antarctica	Late Cretaceous	Kelly,1988(a)	Isolated wood.
Shotover Grit Sands, Oxfordshire, U.K.	Volgian/Kimmeridgian (Jurassic)	Kelly,1988(b)	Shells associated with traces.
Carter Sandstone Member, Colorado, U.S.A.	Campanian	Kiteley and Field, 1984	Borings present at base of lenticular Sandstone within non-marine shale.
Fox Hills Formation, Wyoming	Maastrichtian	Land, 1972	Isolated borings in wood in estuarine sandstone
Dinosaur Park Formation, Alberta	Campanian	.M.L., this paper	Woodground. At the base of a Brackish bay fill erosively overlying a coal.
Wangaloa Formation, New Zealand	Paleocene	Lindqvist, 1886	Bored wood in a concretionary shell bed. Some Carbonate lined.
Lambert Formation,Hornby Is., British Columbia, Canada.	Cretaceous	Ludvigsen and Beard, 1994	Isolated bored logs.
Korycany Sandstone, Prague, Czech. Republic	Cenomanian	Mikulas, 1993	Dense Concentrations of bored logs.
Near Shark's Bay, Western Australia.	Upper and Middle Lias?	Moore, 1870	Pholads preserved despite disintegration of wood substrate. Very iron rich.
Bracklesham Formation, southern U.K.	Middle Eocene	Plint and Pickerill, 1985	Allochthonous bored wood. Questionable report of non- marine *Teredolites*.
Ferron Formation, Utah, U.S.A.	Upper Cretaceous (Campanian)	Ryer, 1980	Logs at the basal portion of channel fill. Wood ground at the base of Ferron "C".

TABLE III-1 Worldwide *Teredolites* Occurrences.

LOCALITY/ FORMATION	AGE	REFERENCES	COMMENTS
Mooreville Chalk, Alabama, U.S.A.	Upper Cretaceous (Campanian)	Savrda and King, 1992	Log-ground, transgressive lag, *T. longissimus*, calcite-lined tubes
Clayton Formation, Alabama, U.S.A.	Lower Paleocene	Savrda *et al.*, 1993	Allochthonous logs, calcite linings, rare bioglyphs.
John Henry Member, Straight Cliffs Formation, Utah, U.S.A.	Campanian through Turonian	Shanley and McCabe, 1990	Bored logs.
Seymour Island, Graham's Land, Antarctica	"Lower Tertiary"	Sharman & Newton, 1898	Isolated borings in wood, Rare linings.
Dakota Formation, Kansas	Upper Cretaceous	Siemers, 1976	Isolated limonitized logs.
Tallahatta Formation, Alabama, U.S.A.	Eocene	Smith and Savrda, 1995	*T. longissimus*; branching; calcite tube linings.
Garudamangalam Sandstone, SE India	Turonian-Coniacian	Tewari *et al.*, (*in press*)	Log-grounds in estuarine settings; calcite tube linings
Johannistal, Germany	Lower Eocene	Tufar *et al.*, 1966	Pyritized log.
La Frontera Formation, Columbia.	Late Turonian	Villamil and Hasiotis, 1993	Miniature *Teredolites* in Amber from Concretions. Transgressive systems tract.
La Meseta Formation, Antarctica	Eocene	Wiedman and Feldmann, 1988	Isolated Pieces of wood.
Barton Beds, Middle Headon Beds; Paris Basin	Ledian	Wrigley, 1929	Borings both parallel and perpendicular to grains
Upper Hamstead Beds, Paris Basin	Ledian	Wrigley, 1929	Calcareous tubes.
Castlegate Sandstone, Utah	Campanian	Yoshida *et al.*, 1996	Bored logs.

CHAPTER IV

SUMMARY AND CONCLUSIONS

This thesis has sought to examine aspects of the sedimentology and ichnology of marginal marine depositional systems as they pertain to genetic stratigraphic studies. Ichnological models, particularly substrate-controlled, provide a powerful tool when applied synergistically with detailed sedimentological and stratigraphical studies ichnofacies (Pemberton and MacEachern, 1995).

Chapter II examined the basal Horseshoe Canyon Formation and found that estuarine deposits reflect deposition in deltaic distributary channels. This is in contrast to Ainsworth (1994) who considered the channels to be part of a larger incised valley complex. Incised valley complexes are an important concept to emerge in genetic stratigraphic studies. Recgonition of these systems is often aided by ichnological studies (MacEachern and Pemberton, 1994). It is imperitive that sufficient evidence exists to invoke this model however. The outcrops in the Lower Horseshoe Canyon Formation do not contain sufficient evidence of an unconformity.

At the Hoodoos Recreation Area, the interval consists of a coarsening upward succession of interbedded siltstones and mudstones sharply overlain by relatively massive sandstones reflecting a sharp progradation of delta front sandstones over prodelta fines. This contact is not an unconformity as implied by Ainsworth (1994) and therefore does not represent a sequence boundary.

The delta front sandstones are sharply and erosively overlain by a siltstone pebble conglomerate that represents the base of a distributary channel system. The distributary system contains four previously described channel units that are distinguished on sedimentological and ichnological criterion. This work has also identified a fifth channel unit beneath the four previously described ones. The addition of this unit does not fundamentally change the interpretation of the origin channel system.

The interpretation of these units does not require invoking allocyclic processes to explain the geometry of the outcrop units. The succession exactly conforms to the idealistic succession expected in fluvial distributary systems.

Chapter III deals with the stratigraphic significance of the trace fossil *Teredolities*. This trace has frequently been viewed with a "stamp collector" mentality, with very few studies placing the traces into a stratigraphic context. With the intoduction of the woodground concept, the work of Bromley *et al.* (1984) pioneered the application of *Teredolites* occurrences in genetic stratigraphy.

The introduction of the term "log-ground" by Savrda and King (1993) clouds the usefulness of the presence of borings in xylic substrates. Due to the fact that many wood substrates such as isolated logs are fully transportable, their stratigraphic significance is minimal. As opposed to regarding an isolated piece of bore wood as a "log-ground", the term should be reserved for concentrations of bored logs such as at transgressive surfaces of erosion.

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