UNIVERSITY OF ALBERTA

ICHNOLOGY, SEDIMENTOLOGY AND STRATIGRAPHY OF THE OSTRACODE ZONE, BELLSHILL LAKE - KILLAM AREA, EAST CENTRAL ALBERTA

BY

MICHAEL HOWARD GEIER ©

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THE UNDERSIGNED CERTIFY THAT THEY HAVE READ, AND RECOMMEND TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH FOR ACCEPTANCE, A THESIS ENTITLED **ICHNOLOGY, SEDIMENTOLOGY AND STRATIGRAPHY OF THE OSTRACODE ZONE, BELLSHILL LAKE - KILLAM AREA, EAST CENTRAL ALBERTA**, SUBMITTED BY MICHAEL HOWARD GEIER IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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Date: Aug 28, 1995

DEDICATION

To Elizabeth (Bessie) and Helene
There is a spirit which guides us,
though intangible, it is no less real.

ABSTRACT

Siliciclastic and carbonate facies from the Ostracode Zone were studied in detail in 45 cored wells, to complete the data 1640 geophysical well logs were analysed. The study area is located in the Bellshill Lake - Killam area of east central Alberta Twp. 39-44, Rng. 11W4 - 17W4. Hydrocarbons are produced from the Ostracode Zone in the Bellshill Lake, Thompson Lake and Forrestburg fields.

The Ostracode Zone contains a mixed siliciclastic - carbonate succession, consisting of 13 facies. These facies are arranged into 5 recurring facies associations. The Ostracode Zone consists of a regionally extensive succession (FA1 and FA4) and an incised valley succession (FA2, FA3 and FA5). The regional succession is comprised of storm influenced brackish bay, lacustrine and coal swamp environments. The valley fill succession is composed of point bar, bay and mud flat environments. The ichnology and sedimentology of the valley fill deposits demonstrate that the environment of deposition was subject to brackish water conditions, fluctuating salinities, and high sedimentation rates, indicating that the valley was occupied by an estuary during the deposition of the valley fill. The predominance of tidally generated features such as inclined heterolithic stratification and tidal flat deposits, among other features, indicate that the estuary that occupied the valley was tidally dominated.

The valley was incised in late Ostracode time (Late Aptian) during a relative lowstand of sealevel. In the study area, three subsequent, smaller lowstands resulted in the re-incision of the valley deposits and the development of a compound incised valley fill.

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Most importantly, I must acknowledge the supervision that I received during the preparation of this thesis from Dr. S. George Pemberton. Without his input and guidance I am certain that I would not have attempted this thesis, let alone complete it. PanCanadian Petroleum is gratefully acknowleged for their financial support of this thesis.

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Special thanks are due also to my family for their unfailing support and for showing me that there is no hardship that cannot be endured and overcome.

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CHAPTER 1

INTRODUCTION, STUDY AREA, RATIONALE FOR STUDY, DATABASE AND STUDY METHODS.

1.1 INTRODUCTION

The scope and objective of Mannville Group studies have changed through time from the regional and general, to the local and specific. Badgley (1952), Glaister (1959), Williams (1963) and Mellon (1967) conducted regional studies concerned with the identification and description of the major lithostratigraphic units within the Mannville Group. Local and specific studies, conducted within the framework developed by these early workers, were undertaken in many regions of the Western Canada Sedimentary Basin (W.C.S.B.) during the next decade. One such study was that of Cartier (1976) who examined the sedimentology and stratigraphy of the Bellshill Lake oil field.

The last decade has seen refinements in sedimentology, fundamental advancements in ichnological applications to facies analysis (Frey and Pemberton, 1984; Pemberton *et al.* 1992; *etc.*), and the development of high resolution sequence stratigraphy (Van Wagoner *et al.* 1990; Posmentier *et al.*, 1992). Consequently, it is a useful exercise to re-examine the studies of these early workers in the light of these recent developments.

Sedimentology, while necessary for the interpretation of physical processes at work in an environment, is not sufficient for detailed paleoenvironmental reconstructions of the rock record. Significantly more information about the environment of deposition may be discerned when detailed ichnological analysis is combined with the available sedimentological information (*e.g.* Moslow and Pemberton, 1988; Beynon *et al.*, 1988; Pemberton *et al.*, 1992; Ranger and Pemberton, 1992; MacEachern and Pemberton, 1994). Benthic organisms are exceedingly sensitive to the environment, and even subtle environmental changes may result in profound changes in the behaviour of organisms. Some important environmental conditions include substrate coherence and stability, fluctuating energy levels, salinity levels, temperature fluctuations, oxygenation, bathymetry and the nature of food resources (Pemberton *et al.*, 1992). Integration of this ichnological data with the more conventional aspects of physical sedimentology is crucial to the development of an accurate paleogeographic and paleoenvironmental reconstruction of the Bellshill Lake area.

The development of high resolution sequence stratigraphy has led to a major revolution in the way that sedimentary successions are viewed. Previously, rocks were examined from a lithostratigraphic viewpoint and correlations were made based on the lithologic similarities of rock types. Sequence stratigraphy, conversely, places the emphasis on bounding discontinuities and unconformities, relating them to relative sea level fluctuations (Van Wagoner *et al.* , 1990). This stratigraphic paradigm is a valuable framework for the organisation and interpretation of facies observations.

In addition to the advancements discussed above, much additional drilling has occurred in the last twenty years, yielding a larger data base than was available to early researchers for subsurface studies. In fact, the amount of data now available in many areas of the W.C.S.B. necessitates the use of computers in order to store and manipulate this information.

1.2 STUDY AREA

The study area is located in the Bellshill Lake - Killam area of east - central Alberta (Fig. 1.0). Specifically, the study area spans Townships 39 - 44 and Ranges 11 - 17 West of the Fourth Meridian and covers an area of 3900 km^2.

The stratigraphic interval of interest comprises a succession of shales, sandstones, limestones and coals informally refered to as the Ostracode Zone. Farshori (1990) reported that this zone occupies a stratigraphic position in the uppermost part of the Lower Mannville Group (Fig. 2.0). Biostratigraphic studies of ostracode fauna found in the rocks indicate that the Ostracode Zone likely spans the Aptian/Albian boundary (Finger, 1983). Within the study area, the stratigraphy of the Ostracode Zone has been complicated by the incision and subsequent filling of several valleys of differing ages. These incised valleys cut stratigraphically important horizons and mask the precise stratigraphic relationship of the deposits in the Bellshill Lake - Killam area.

1.3 RATIONALE FOR STUDY

Much confusion has arisen regarding the stratigraphy of the Bellshill Lake - Killam area. One goal of this study was to unravel the complex stratigraphy of the Ostracode zone in the study area. It is anticipated that examination of this zone in the Bellshill Lake - Killam area will aid in the exploration for economic accumulations of hydrocarbons in the Ostracode Zone of the study area and in other areas of the W.C.S.B. In the study area, economic accumulations of hydrocarbons in this zone occur in the Thompson Lake, Bellshill Lake and Forestburg.

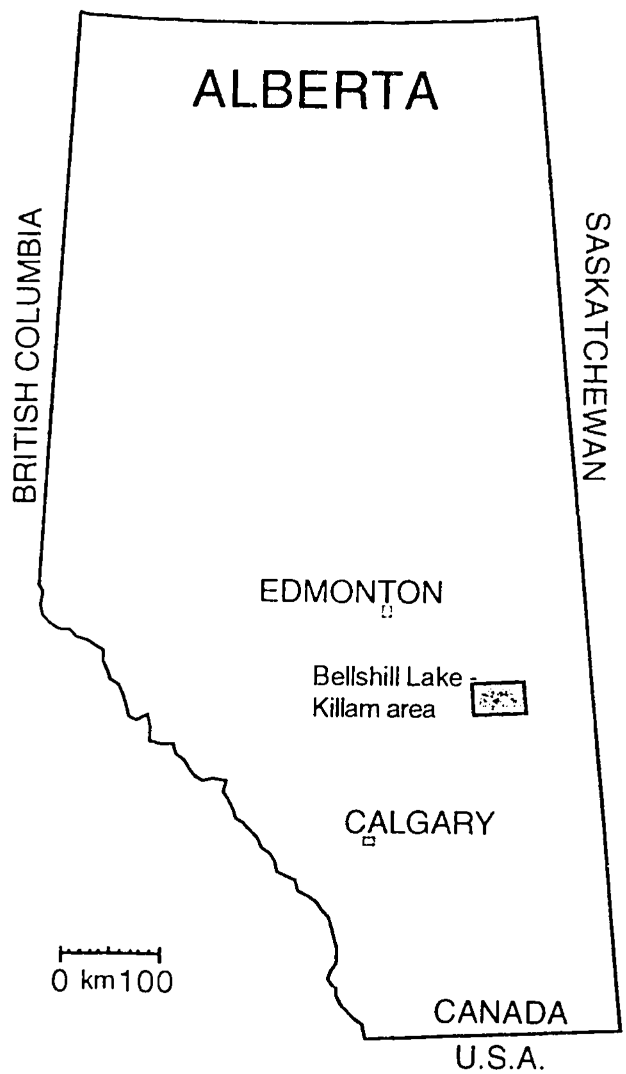


Figure 1.0 Location of the Bellshill Lake - Killam study area.

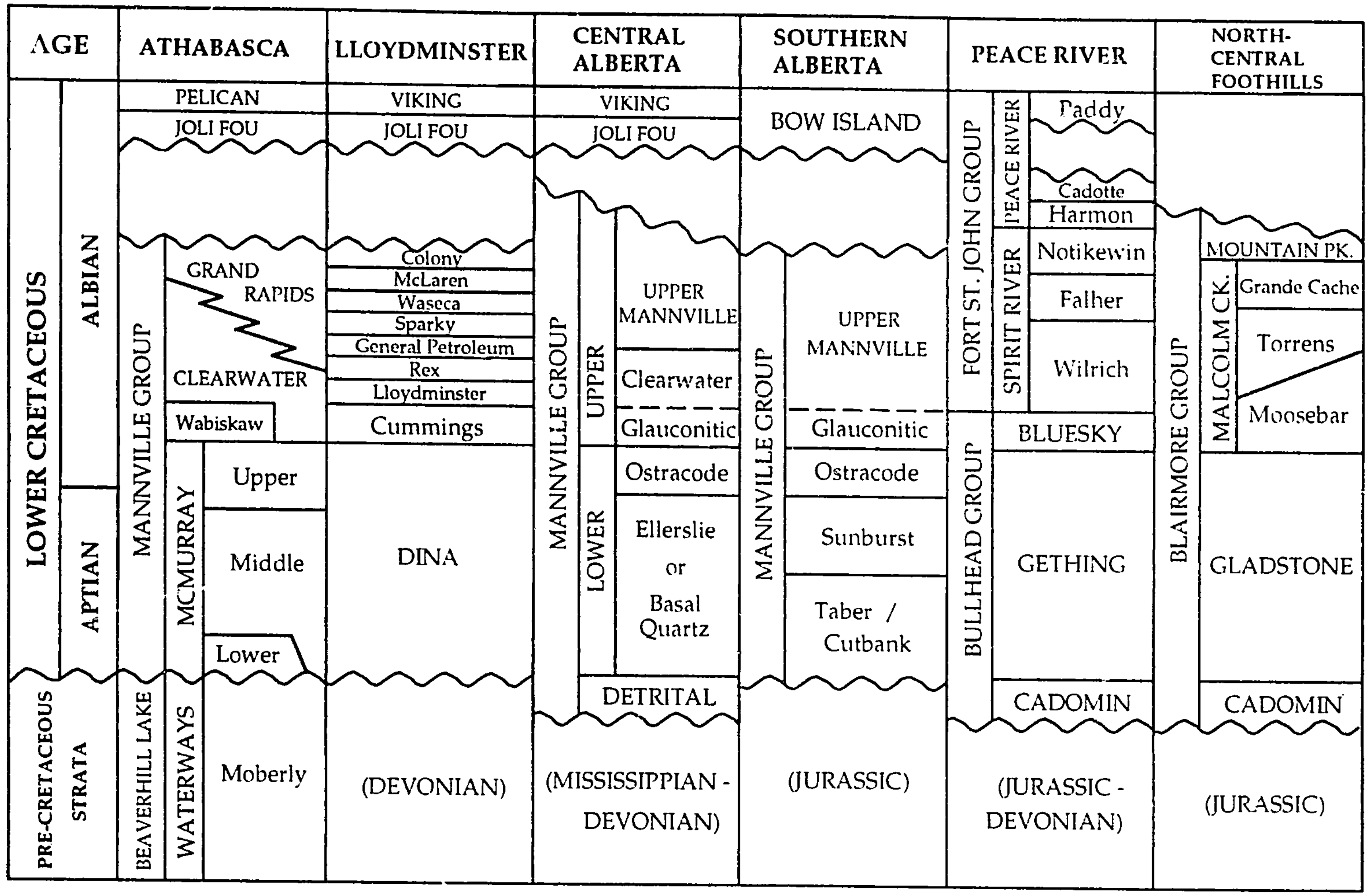


Figure 2.0. Stratigraphic correlation chart of the Lower Cretaceous in Alberta (from Williams, 1963; Glaister, 1959; AGAT, 1987). Parentheses indicate ages, not formation names.

fields, which have combined total initial reserves in excess of $5 \times 10^7\ m^3$ (E.R.C.B., 1992). These oilfields are located in stratigraphic traps that are typically quite subtle. Successful exploration for other oilfields of this nature and the exploitation of existing fields in the Bellshill Lake - Killam area will require a detailed understanding of the local stratigraphy, sedimentology and facies distribution.

1.4 DATABASE AND METHODS

The goals set out above were accomplished by the examination of selected drill cores through the zone of interest, use of industry databases and by the examination of geophysical well logs. From this information, cross sections (Fig. 3) and maps of important horizons were constructed (Fig. 4).

In the preparation of this study, 45 drill cores through the Ostracode Zone were examined in detail. Sedimentological and ichnological characteristics and stratigraphically important surfaces were noted. Due to its value in paleoenvironmental interpretation, particular attention was paid to the examination of the ichnological elements of the deposits. Application of ichnology, in conjunction with conventional sedimentologic analysis, has proven fruitful in the past as a means of characterising environments of deposition (*e.g.* Beynon *et al.*, 1988; Moslow and Pemberton 1988; Pemberton *et al.*, 1992; MacEachern and Pemberton, 1992). These observations were entered into a computer core logging program courtesy of Dr. Michael J. Ranger so that lithologs of cored intervals could be drafted and compared to each other and their associated geophysical well logs. Core lithologs permitted correlations between the rocks and the geophysical well log

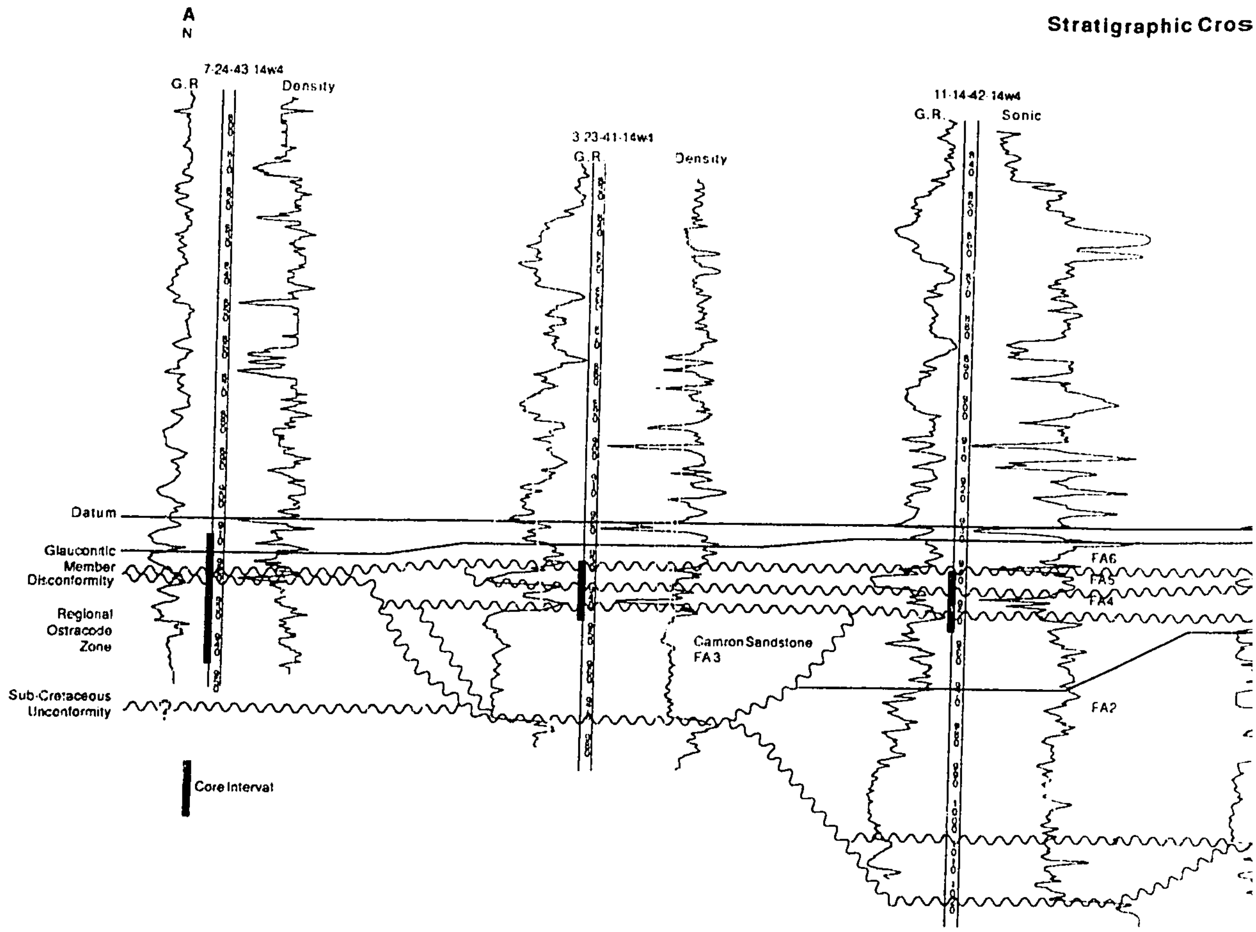
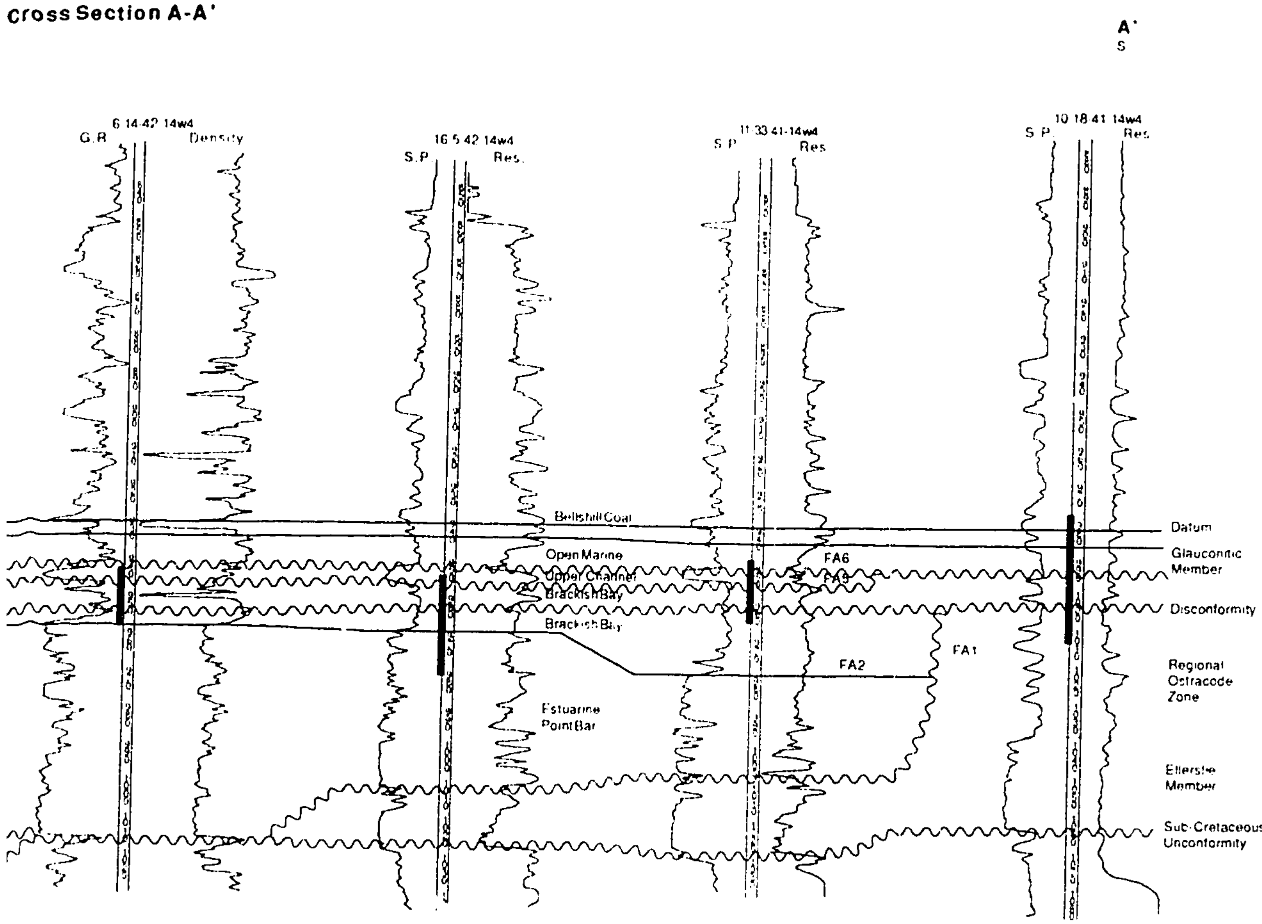


Figure 3.0 Stratigraphic cross section through the Killam area.

Cross Section A-A'



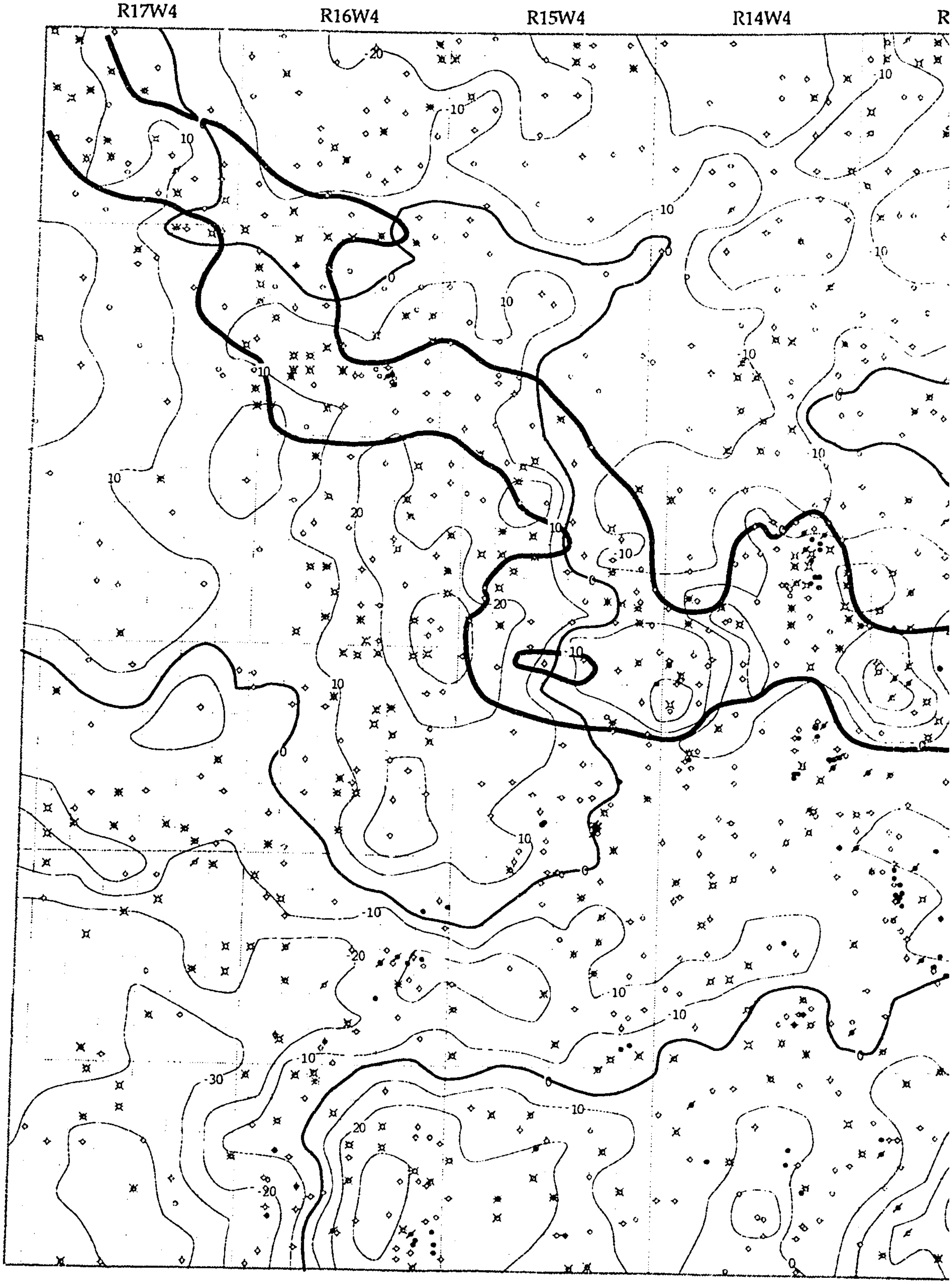
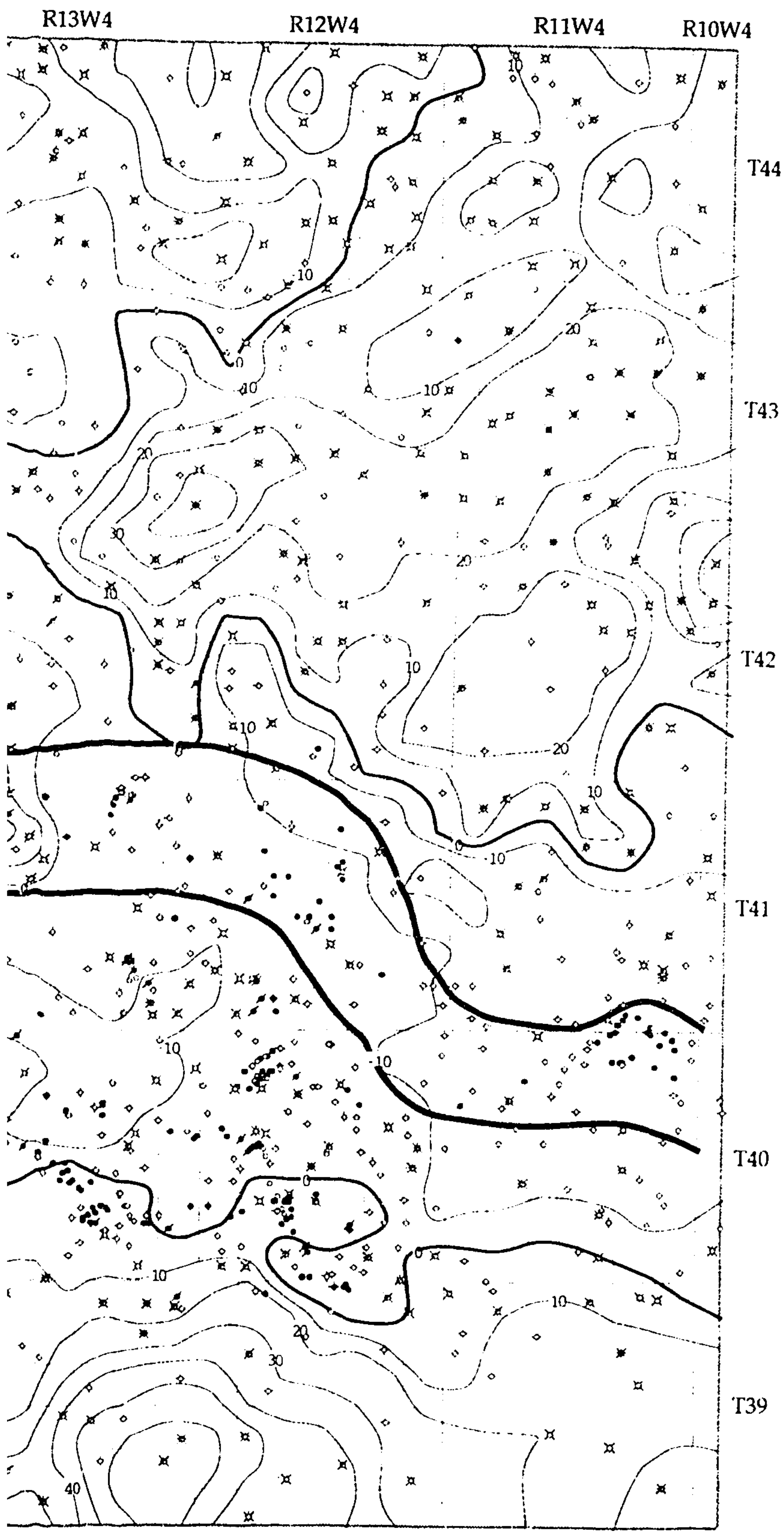


Figure 4.0 Second order residual structure map of the top of the sub-Cretaceous unconformity. C
developed on the unconformity surface. The trend of the Ostracode Zone paleovall
highlighted to show regions that were relativly low and likely acted as a locus for va



Legend

- Oil well
- Suspended oil
- Abandoned oil
- Gas well
- Suspended gas
- Abandoned gas
- Service well
- Dry Hole
- Location
- Suspended location

Scale 1: 275000

Contour interval - 10 units

:y. Computer generated contours show the relative structure
›valley is highlighted in heavier pen weight. The 0 contour is
›r valley incision.

responses over the cored interval. Geophysical well logs, while providing information on certain rock properties such as natural radioactivity, resistivity to an induced electric current and density, give little specific information about the environment of deposition and nature of stratigraphically-important surfaces, such information can be gleaned, however, from careful examination of drill cores. Cross-cutting relationships were determined by constructing a suite of stratigraphic cross sections through the study area. Based on these relationships, a stratigraphic model of the Bellshill Lake - Killam area can be developed.

Isopach and residual structure maps of important geologic units and horizons examined in the study area were generated in order to establish their spatial relationships. Construction of these maps was achieved by downloading an industry database (AccuMap EnerData Corp.) containing all the wells in the study area that penetrated the Paleozoic. The resulting file contains surface locations and geologic information on 1640 wells. The information was then entered in a computer mapping program. By using large numbers of wells, problems associated with "bad" data points would be avoided since erroneous points would show up as so-called "bulls-eyes" on the contoured map. Geologic tops along the trend of the interpreted incised valley were "picked" by examining well logs in that area. A total of 473 geophysical well logs were examined along the trend of the valley and the pertinent geologic tops were "hand-picked" and re-entered into the database. Maps constructed in this study may be classified into two categories. The first category contains those maps where values were posted and contoured by computer methods. The second category comprise those maps that were posted by the computer but contoured by hand. Geologic tops such as the

Paleozoic surface (Fig. 4.0) were of sufficient precision and quantity that computer generated contours gave a reasonably accurate map of that surface. Geologic tops that were "hand-picked" required geologic interpretation and were contoured by hand. Structure maps were constructed by performing residual analysis on the values. The second order residuals of the data sets were calculated in order to remove the effects of regional dip. Second order residual values for geologic tops were then contoured to give a representation of the inferred paleotopography of the surface without the effects of regional dip.

CHAPTER 2

THE MANNVILLE GROUP AND PREVIOUS WORK

2.1 INTRODUCTION

During the Late Jurassic, a major transformation in the tectonic regime of the western margin of North America resulted in the formation of a foreland basin. It is within this basin that the heterolithic deposits of the Mannville Group accumulated. This section discusses the formation of the foreland basin and the effect this basin has had on Mannville Group sedimentation. This section also discusses the previous work that has been done on the Mannville Group in the study area.

2.2 OVERVIEW OF THE MANNVILLE GROUP

Late Jurassic time in Western North America witnessed a major shift in tectonic regime from a passive continental margin to a foreland basin. The Western Canada Sedimentary Basin (W.C.S.B.) developed as the first of several allochthonous terrains accreted with the North American craton, resulting in the Columbian Orogeny (Smith, 1994). Downwarping of the craton due to orogenesis resulted in an elongate low, parallel to the present day Rocky Mountains.

The first sediments to accumulate in the foreland basin were dominated by shales, and are known as the Passage Beds and their equivalents. Deposition in the foreland basin was confined to a narrow foredeep trough extending from late Oxfordian time to the end of Valanginian time (Late Jurassic to Early Cretaceous) (Smith, 1994). During Hautervian to Late Barremian time, a major lowstand of relative sea level resulted in basin-wide erosion and incision of deep valleys on the exposed Paleozoic to earliest Cretaceous surface (Smith, 1994).

These valleys are organised into three major drainage systems, the distribution of which was controlled by differential erosion of the Paleozoic succession (Ranger, 1994). The Paleozoic succession dips southwest, exposing progressively older strata to the northeast. Due to the southwestern dip, ridges of resistant Paleozoic carbonates trend northwest. These ridges, in concert with other major structural elements, combine to divide the W.C.S.B. into the Spirit River, Edmonton and McMurray drainage systems (Ranger, 1994). The Bellshill Lake - Killam area is located in the upper reaches of the Edmonton drainage system. This system drained the Swift Current Platform, and ultimately emptied into the Boreal Sea to the North (Ranger, 1994).

Figure 4.0 is a second-order residual map of the sub-Cretaceous surface in the study area. The map shows a pronounced erosional low through the middle of the map defined by the 0 to -30 contours. The outline of the Ostracode-aged channel system is superimposed. The system follows the low through most of the study area, but can be seen to deflect around a high on the sub-Cretaceous surface in the western portion of the study area. At the end of Barremian time, relative sea level rose once again. This transgression was the result of further terrain accretion and subsequent downwarping of the crust. This relative rise in sea level was responsible for the deposition of the Mannville Group (Hayes *et al.* , 1994). The youngest deposits of the Mannville Group comprise the alluvial sandstones and conglomerates of the Cadomin Formation, which accumulated on the western flank of the Spirit River Channel. In other regions, fluvial and estuarine deposits aggraded in response to rising base level. The Gething Formation accumulated in the

Peace River area, the Ellerslie Formation and equivalents were deposited in the Edmonton Valley system and the McMurray Formation infilled the McMurray Valley system (Hayes *et al.* , 1994).

These deposits are composed of nearly pure quartz laid down under fresh and brackish-water conditions. The nearly pure quartz sandstone, found in the early Mannville Group deposits, is thought to have been sourced from the western United States with lesser contributions from the Canadian Shield, particularly on the western flank of the W.C.S.B. (Hayes *et al.* , 1994). Brackish-water influence on the Lower Mannville Group is interpreted to be due to deposition in estuarine valleys and embayments of the shoreline during transgression. The location of these estuaries was controlled by paleotopography generated on resistant Paleozoic carbonates, much of which remained emergent at this time (Ranger, 1994). The locus of the estuarine-fill likely shifted up the major valleys with rising sea level.

Deposits of the Ostracode Zone and its equivalents represent the last stages of Lower Mannville Group deposition. Ostracode Zone sediments throughout most of the W.C.S.B. are composed of limestones, calcareous shales and sandstones. These deposits are believed to have been deposited in brackish bays (Hayes, *et al.* , 1994) or fresh water lakes (Holmden, 1994) Locally, however, the Ostracode Zone contains thick sandstone deposits that have incised into underlying sediments. Examples include the Peace River, Edson, Lanaway and Bellshill Lake - Killam areas of Alberta and the Aitken Creek area of British Columbia (Smith, 1994). Typical or "regionally-extensive" Ostracode Zone deposits are absent in the McMurray drainage system, suggesting that the paleotopography of the W.C.S.B. had a marked effect on the deposition of the Ostracode Zone (McPhee, 1994). In addition, the Ostracode Zone is not found in central Alberta north of Township 60. It has been suggested that a barrier island existed in this area and that the Ostracode zone reflects deposition behind this barrier (Hayes *et al.* , 1994). In the Peace River area of Alberta, the Ostracode Zone is correlateable with parts of the upper Gething Formation (Fig. 2.0). Sediment influx in this region was sufficient to permit continued fluvial/deltaic aggradation (Hayes *et al.* , 1994).

Maximum transgression of the Moosebar/Clearwater Sea and subsequent progradation of shore-face deposits mark the base of the Upper Mannville Group (Smith, 1994). The first deposits of the Upper Mannville Group include the Glauconitic Member and its equivalents. Glauconitic Member deposition was punctuated by several relative sea level lowstands and subsequent periods of valley incision (Hayes *et al.* , 1994). The first of these incised valley deposits is filled with quartzose sandstones, while later incised valley deposits consist of lithic sandstones (Hayes *et al.* , 1994). Changes in sandstone composition suggests a major change in provenance during deposition of the Glauconitic Member.

The late Upper Mannville Group was characterised by continued supply of volcanic - felspathic sediments to the basin (Smith, 1994). Sediment influx displaced shorelines to the north and north east transforming the W.C.S.B. into a vast floodplain (Smith, 1994). These deposits are referred to as the undifferentiated Upper Mannville Group in central Alberta. In the McMurray sub basin, equivalent strata include the Clearwater and Grand Rapids formations. The Spirit River Formation constitutes equivalent Upper Mannville strata in the Peace River area. In the Lloydminster area, the Upper Mannville Group is represented by the Rex, General Petroleums, Sparky, Waseca, McLaren and Colony informal units (Fig. 2).

2.3 PREVIOUS WORK

Previous work in the study area dates back to 1959. This section discusses the various models proposed to explain the occurrence of the anomalously thick build-up of sandstone in the Bellshill Lake - Killam area.

After the discovery of the Bellshill Lake oilfield in 1955, Rudolph (1959) outlined the stratigraphy of the Mannville Group in the area. He noted that there was a major erosional low in the Bellshill Lake area and suggested that the surrounding uplands contributed to the sediments deposited in the low. Configuration of these highlands was interpreted to have affected the development and emplacement of the sand bars in the Basal Quartz (Ellerslie Member equivalent). In addition, a brackish component to the sediments was noted, and Rudolph (1959) proposed that deposition took place as sand bars in a fresh water to brackish arm of the sea. Conybeare (1964) and Martin (1966) invoked an eroded fluvial terrace model to explain the anomalously thick sandstone deposit in the Bellshill Lake area.

The first thorough study of the Bellshill Lake area was conducted by Cartier (1976), who attributed the sandstones of the area to channel incision. He noted that the sandstones cut Calcareous Member (Ostracode Zone) markers and had a sinuous geometry. From this evidence he concluded that the anomalous sandstone body was the result of post-Ostracode Zone emergence and subsequent channelling. Fill of this channel was interpreted as "Fort Augustus Formation"-age (Glauconitic Member equivalent). Cartier (1976) also observed that the deposits had "...worm tracks and borings..." and that locally, the sandstone body was overlain by dark shales containing ostracodes. This evidence lead Cartier (1976) to interpret a possible tidal or estuarine origin for the sandstone body, and that following deposition of the sandstone, lacustrine conditions prevailed until the establishment of fully marine conditions. Petrologic studies by Cartier (1976) determined that the Ellerslie Member is composed of quartz sandstones. Sandstone in the "Calcareous Member" (Ostracode Zone) and in the channel deposits ("Lower Fort Augustus Formation") are reported as transitional between quartzose and lithic sandstones, while sandstone of the "Fort Augustus Formation" (Glauconitic Member) are lithic with a low rock fragment content (Cartier, 1976).

Karvonen (1989), worked on the Ostracode Zone in the Bellshill Lake area and agreed with Cartier's (1976) interpretation of a channel incision origin for the anomalous sandstone body. Karvonen (1989), however, assigned the incision to late Ostracode Zone (Late Aptian) time rather than "Fort Augustus Formation" (Glauconitic Member) (Early Albian) time. Karvonen (1989) also undertook a more detailed study of the ichnology of the deposit. A mixed *Skolithos -Cruziana* assemblage was reported and interpreted to reflect an estuarine depositional environment, in accordance with Wightman *et al.* (1987), Beynon *et al.*, (1988) and Ranger and Pemberton, (1992).

The most recent study of the Ostracode Zone in the Bellshill Lake - Killam area is that of Geier and Pemberton (1994), who studied the ichnology and sedimentology of the Ostracode Zone further west, in the vicinity of the Forrestburg oil field. Their findings were in agreement with Karvonen (1989) as to the estuarine nature of the deposits. No attempt was made to refine the stratigraphy of the Ostracode Zone in their study.

CHAPTER 3

FACIES DESCRIPTIONS

3.1 INTRODUCTION

The term facies was originally defined by Gressly in 1838 as the sum of the lithologic and paleontologic characteristics of a sedimentary rock from which its origin and the environment of deposition may be inferred (Teichert, 1958b). This definition is etymologically correct as facies, in Latin, means "face", "figure", "appearance", "aspect" or "look". Modern usage of the term facies is based on Gressly's definition of 1838. Johannes Walther, (1893 - 1894), made important contributions to the manner in which facies are viewed in context and subsequently interpreted. Walther correctly defined facies as the sum of all primary characteristics of a sedimentary rock and went on to define a *faciesbezirk* (facies tract) as a system of different but genetically interconnected facies. This has subsequently been reinvented in sequence stratigraphic nomenclature as a systems tract (*cf.* Van Wagoner *et al.*, 1990) Walther also put forth his law of correlation of facies which, paraphrased, reads that: only those facies can be superimposed which can be observed beside each other today (Teichert, 1958b, Middleton, 1978). Without Walther's Law of the correlation of facies, successions of facies could not be resolved into a three-dimensional understanding of facies architecture, nor could the paleogeography of an interval be resolved.

In the following section, an integrated approach for facies designations is used. This approach combines: i) physical elements such as sorting, bedding style and texture, ii) primary physical structures, iii) penecontemporaneous physical structures and iv) biogenic elements including burrow intensity, degree of burrowing uniformity, ichnogenera present, distribution of ichnogenera, and ichnologic assemblages within the ichnofacies paradigm. In addition, some facies (*e.g.* Facies 9, 13) show pedogenic modification during subaerial exposure. Such features, being imparted by the terrestrial environment, constitute a valid facies designation in accordance with Gressly's 1838 definition.

3.2 FACIES DESCRIPTIONS

3.2.1 Facies 1 - Weakly Burrowed Silty Shale

Facies 1 comprises weakly burrowed, dark, silty shales with rare, thin, very fine grained wavy parallel and oscillation ripple laminated sandstone laminations (Fig. 5 A, B). Additional sedimentary structures include common synaeresis cracks and rare rip-up clasts associated with the sandstone laminations. Pyrite nodules and carbonaceous detritus are accessory constituents in this facies. Trace fossils are rare, and include small *Planolites*, *Teichichnus* (2-4 mm diameter) and very rare numbers of *Lockeia*. Burrowing intensity is low with sporadically distributed bands of moderate bioturbation.

3.2.2 Facies 2 - Weakly Burrowed Contorted Silty Shale

Facies 2 is composed of silty shale with rare, very fine-grained sandstone laminations (Fig. 5 C, D). Penecontemporaneous soft sediment deformation is characteristic of this facies and includes convoluted laminations and microfaults. Where primary stratification is preserved, it is dominated by wavy parallel and oscillation ripple laminations. Pyrite is present as an accessory component. The ichnology of the deposit consists of

Figure 5 A, B Facies 1 - Weakly burrowed silty shales.

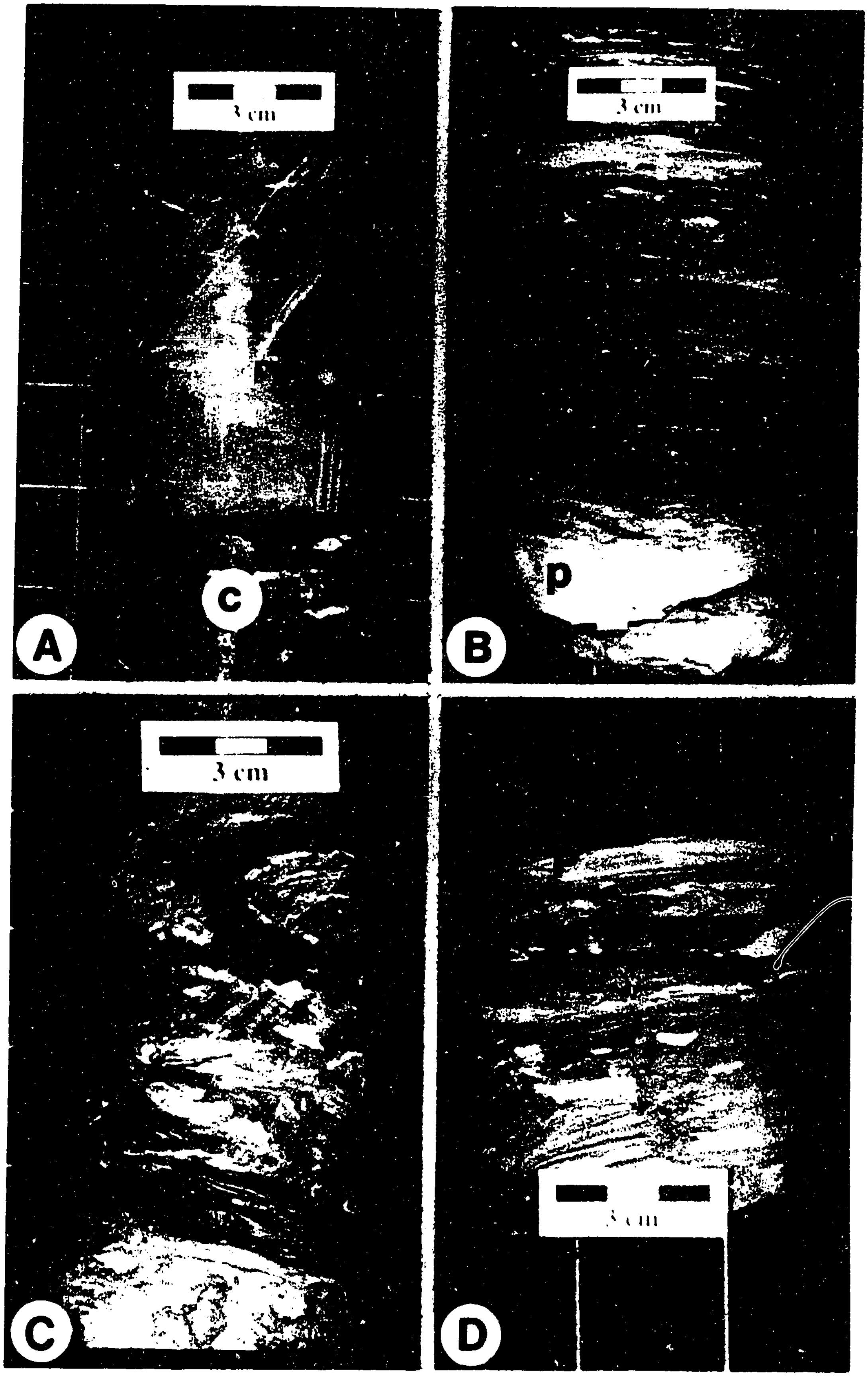
(A) Coal (c) (Facies 4) sharply overlain by unburrowed to weakly burrowed silty shales with rare pyrite nodules (py). From 6-14-42-14W4 depth 942.2m.

(B) Paleosol (p) (Facies 9) sharply overlain by weakly burrowed silty shale with a thin lag of detritus derived from the underlying paleosol. Silty shales are burrowed with rare, small *Planolites* (P) and *Teichichnus* (T). Sandstone stringers increase in frequency and thickness upward. Sandstone bed near the top is parallel laminated. From 7-7-42-12-W4 depth 2996.9 ft. (913.4m).

Figure 5 C,D Facies 2 - Weakly burrowed contorted silty shales.

(C) Highly contorted silty to sandy shale with abundant isoclinal soft-sediment folds obliterating original laminations and obscuring bioturbation. From 6-14-42-14W4 depth 951.2m.

(D) Weakly burrowed silty to sandy shale with moderate convoluted bedding. Some of the original laminations and burrows preserved (*ie. Planolites* (P)). Note the isoclinal soft sediment fold at the top of the photo. From 11-14-42-14W4 depth 953.8m.


3 cm
C
A
3 cm
p
B
3 cm
C
3 cm
D

rare, small (2-4 mm diameter) *Planolites* and locally abundant rootlets. Other trace fossils may have been present but if so, soft sediment deformation has obliterated them. In addition, the original burrowing intensity is unknown due to this penecontemporaneous deformation. This silty shale facies is interpreted to have a restricted trace fossil assemblage.

3.2.3 Facies 3 - Weakly Burrowed Interlaminated Sandstone and Shale

Facies 3 comprises wavy, lenticular and pinstriped beds of very fine to fine-grained sandstone, interlaminated to interbedded with dark, carbonaceous shale and grey, silty shale (Fig. 6 A, B). Sandstone beds are quite thin, ranging from 0.1 - 0.5 cm thick and dominated by wavy parallel laminations, and lesser oscillation ripple laminations. Penecontemporaneous physical sedimentary structures include locally common synaeresis cracks and rare soft sediment deformation in the form of microfaults. Accessory components include carbonaceous detritus, pyrite and smectite. Bioturbation is restricted to low numbers of sporadically distributed, small (2-4 mm diameter) *Planolites*, and *Teichichnus*.

3.2.4 Facies 4 - Carbonaceous Shale and Coal

Facies 4 is composed of black, organic-rich, fissile shale (Fig. 6 C) typically grading into coal (Fig. 5 A). Carbonaceous shales contain rare numbers of synaeresis cracks as well as pyrite and smectite. Locally, high concentrations of smectite imparts a fissility to the carbonaceous shale, masking physical and biogenic structures. Coals tend to be both argillaceous and pyritic. Trace fossils are restricted to rootlets, in rare to moderate

Figure 6 A,B Facies 3 - Weakly burrowed interlaminated sandstone and shale.

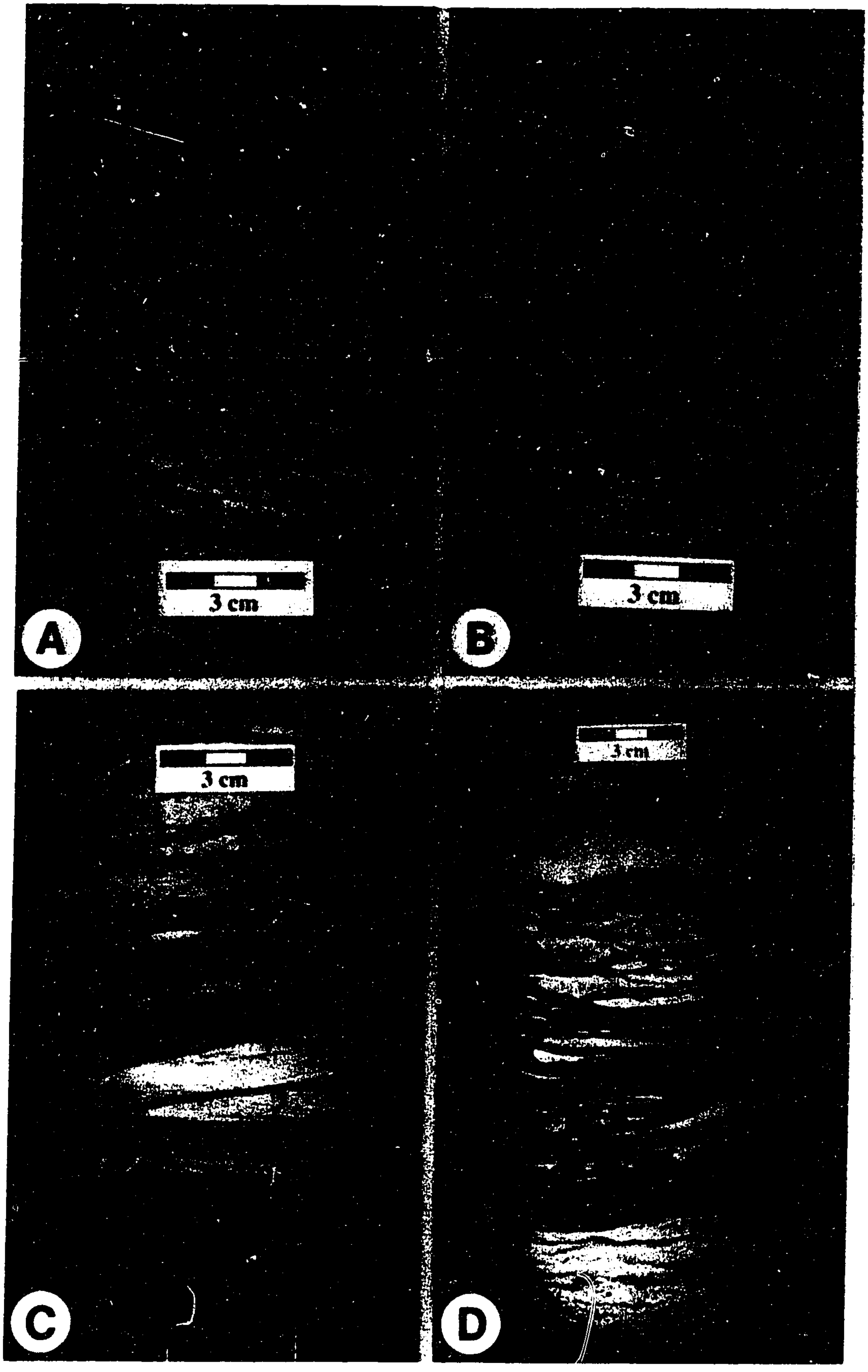
(A) Unburrowed shale overlain by thinly interlaminated (pinstriped) sandstone and shale with common microfaults disrupting laminations.

(B) Weakly burrowed (possible *Planolites* centre left of photo) thinly interlaminated sandstone and shale with rare microfaulting. Possible load cast at the base of the photo. Inclined, truncated laminae at the top may be due to rotational slumping and subsequent erosional truncation.

Figure 6 C,D Facies 5 - Interbedded sandstone and black shale.

(C) Carbonaceous shale (Facies 4) overlain by wavey interbedded sandstone and black shale. Abundant synaeresis cracks associated with the sandstone interbeds. Sandstone interbeds have oscillation ripple laminations or parallel laminations and typically display a sharp base and grade into black shale at the top. Trace fossils are restricted to very rare *Planolites* (P). From 6-27-41-13W4 depth 3035.2 ft. (925.1m).

(D) Wavey interbedded sandstone and black shale with moderate microfaults and rare contorted beds. Synaeresis cracks are rare. Sandstone beds typically have sharp bases and gradational tops. From 7-24-42-14W4 depth 3072.2 ft. (936.4 m).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abundances, typically associated with the carbonaceous shales. No burrows were observed.

3.2.5 Facies 5 - Interbedded Sandstone and Black Shale

Facies 5 consists of fine to very fine-grained sandstone, interbedded with black shale (Fig. 6 C, D). Bedding is typically lenticular to wavy. Sandstone beds are commonly oscillation ripple laminated and wavy parallel laminated and range in thickness from 10 - 20 mm. Shale beds are highly carbonaceous, fissile and typically contain sand-to-silt filled synaeresis cracks. Smectite, pyrite and organic material are locally abundant. The sandstone/shale ratio of Facies 5 is variable, ranging between 25% and 75% sandstone. Locally, the facies may also contain significant amounts of bivalve or gastropod shell material as discrete interbeds. Normally graded beds are commonly observed within the sandstones. Successions of oscillation rippled sandstone or shell debris grading into synaeresis-cracked black shale are common. Locally, the deposit grades upward into a weakly burrowed, fine-grained sandstone, interbedded with dark grey shale. The trace fossil assemblage of Facies 5 is restricted to rare rootlets and rare, small (2-4 mm diameter) *Planolites*, and *Teichichnus*. Burrowing intensity is typically low, with local zones displaying moderate degrees of bioturbation.

3.2.6 Facies 6 - Weakly to Moderately Burrowed Interbedded Sandstone and Shale

Facies 6 consists of wavy bedded fine to very fine-grained sandstones interbedded with shale (Fig. 7 A-D). In contrast to facies 3, sandstone beds are typically 0.2 - 2 cm thick, predominantly oscillation ripple laminated and

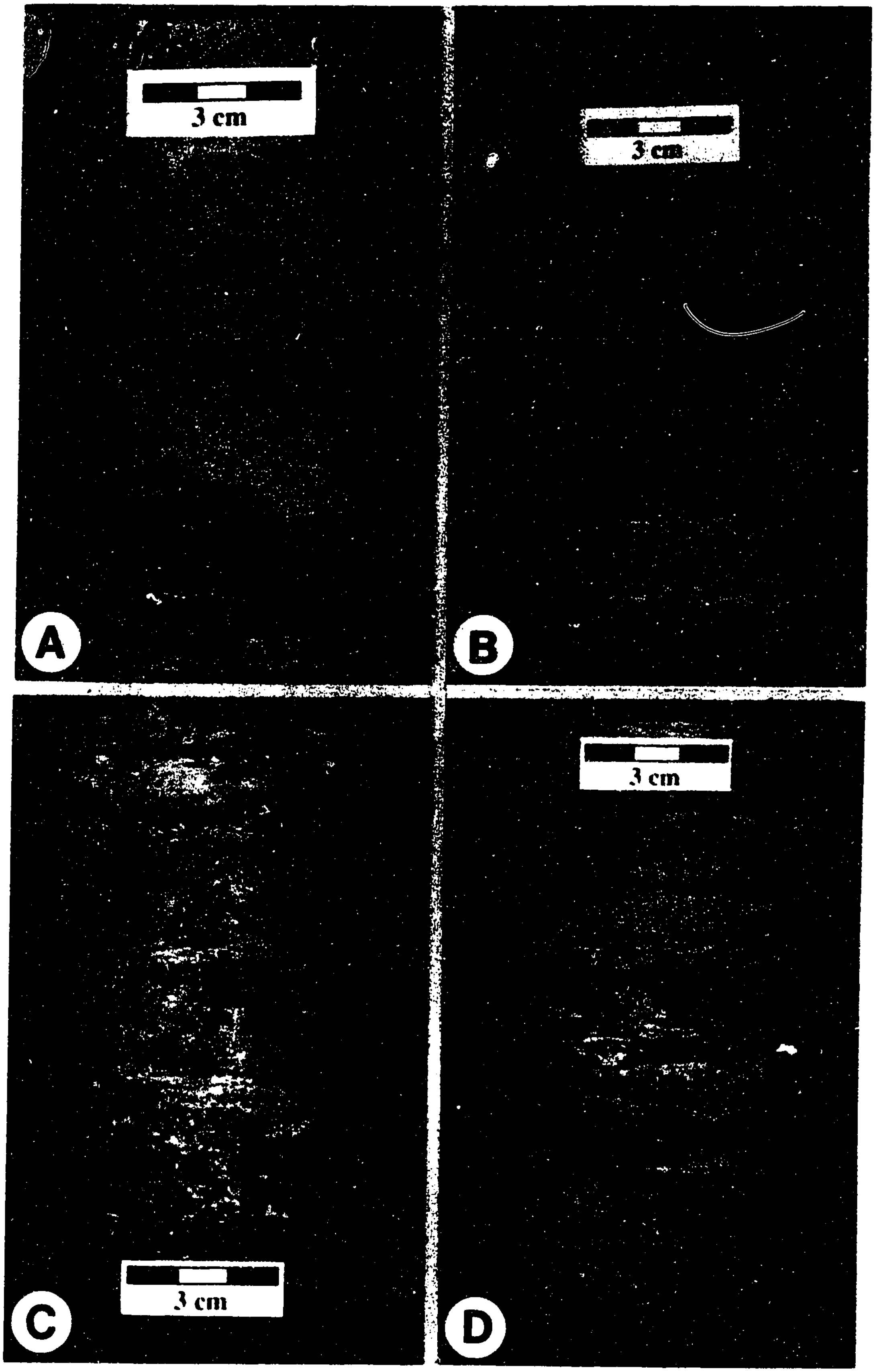
Figure 7 A-D Facies 6 - Moderately burrowed interbedded sandstone and shale.

(A) Interbedded sandstone and shale with flame structures at the base of the sandstone bed (arrows). Note also the sandstone rip up clast below the flame structures likely derived from the underlying sandstone interbed. Shale bed in the middle of the photo has been thoroughly burrowed by some variety of benthic mieofauna (m). These mieofauna are displaying an opportunistic behaviour pattern possibly taking advantage of temporarily oxygenated substrates. Carbonaceous detritus is common, particularly at the base of the upper sandstone bed. From 11-14-42-14W4 depth 932.8m.

(B) Moderately burrowed wavey bedded sandstone interbedded with shale. Sandstone interbeds are parallel laminated but typically disrupted by bioturbation. *Planolites* (P) is present in rare numbers and associated with the shale beds. *Cylindrichnus* (Cy) and *Palaeophycus* (P) are common and associated with the sandstone interbeds. From 7-15-42-12W4 depth 3099.7 ft. (944.8m).

(C) Well burrowed wavey bedded sandstone interbedded with shale. Trace fossil assemblage dominated by *Gyrolithes* (G) with rare *Planolites* (P) and *Teichichnus* (T). *Gyrolithes* are mud filled and associated with sandstone interbeds. From 7-24-43-14W4 depth 3026.4 ft. (922.4).

(D) Moderately burrowed wavey bedded sandstone interbedded with shale. There is a distinctly bimodal sandstone grainsize present highlighting the variability in energy conditions present in the depositional environment. Well preserved oscillation ripples at the base of the photo are associated with synaeresis cracks (sy). *Planolites* (P) are present in moderate numbers in the shale beds and *Teichichnus* (T) are rare and associated with the sandstone interbeds. From 10-20-42-13W4 depth 914.8m.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more rarely, current ripple laminated. Shale beds typically display synaeresis cracks and thin (1-2 grain thick) sand and silt stringers. Soft sediment deformation structures such as microfaults, convoluted beds and load casts are common in this facies. Accessories include rare to moderate smectite and pyrite. Characteristic trace fossils include small (2-4 mm diameter) *Cylindrichnus, Teichichnus, Planolites, Palaeophycus* and rootlets; *Gyrolithes* and *Bergaueria* are present locally. Trace fossil abundances in this facies are generally low and the distribution of ichnofossils is sporadic. Most thoroughly burrowed horizons are dominated by a single ichnogenus such as *Cylindrichnus* or *Gyrolithes*. This facies locally contains intervals of cryptic bioturbation. In such intervals, the sediments show evidence of disruption presumably by meio - sized infaunal organisms. The structures they produce, however, are indistinct and unidentifiable due to their small size and the high density.

3.2.7 Facies 7- *Teichichnus* -Dominated Silty Shale

Facies 7 is composed of silty to sandy shales (Fig. 8 A,B). Rare sand beds locally display oscillation ripple laminations or wavy parallel laminations. Synaeresis cracks are sporadically present and accessory components include rare pyrite and carbonaceous detritus. Facies 7 is thoroughly burrowed by robust (5-10 mm diameter) *Teichichnus*, as well as low numbers of small (2-4 mm diameter) *Palaeophycus* , *Planolites* and *Ophiomorpha*.

3.2.8 Facies 8 - Trough Cross Stratified Sandstone

Facies 8 consists of upper fine to medium-grained sandstone.

Figure 8 A,B Facies 7 - Teichichnus dominated silty shale.

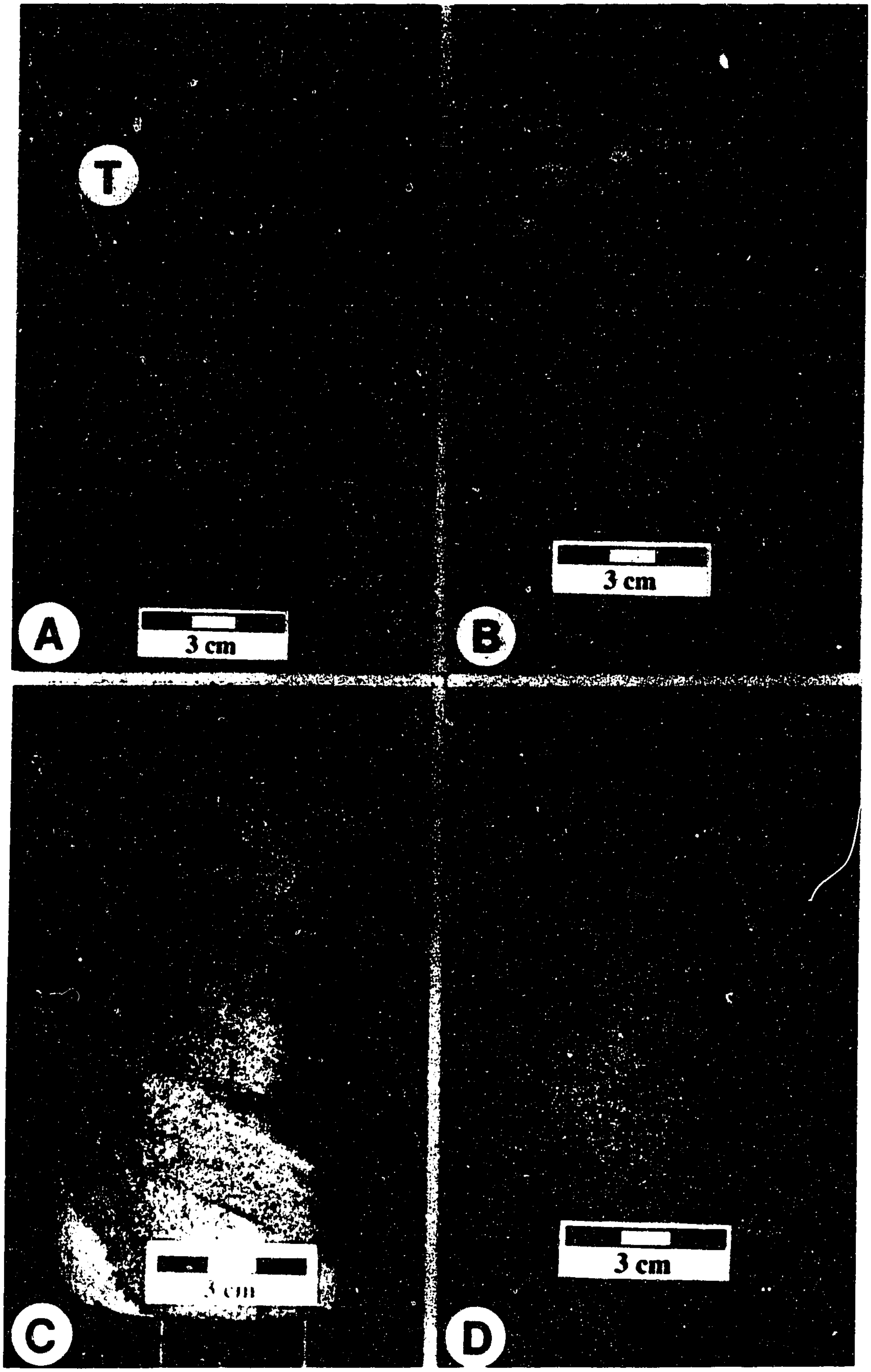
(A) Silty to sandy shale dominated with abundant, robust Teichichnus (T) and rare *Planolites* (P). Rarely burrowed sandstone interbed in the photo is parallel laminated and likely storm derived. From 3-23-42-14W4 depth 940.2.

(B) Shaley sandstone dominated by robust Teichichnus (T) to the exclusion of other ichnofauna. Shaley sand is overlain by carbonaceous shale (Facies 4). From 7-24-43-14W4 depth 3009.4 ft (917.3m).

Figure 8 C,D Facies 8 - Trough cross stratified sandstone.

(C) Trough cross bedded medium grained sandstone with characteristic steepening upward beds. Forsets are highlighted by carbonaceous detritus. From 7-15-41-12W4 depth 3127 ft. (953.1m).

(D) Trough cross bedded medium grained sandstone with steepening upwards forsets and a reactivation surface at the very top of the photo. Carbonaceous detritus present in rare abundances. From 11-33-41-14W4 depth 951.5m.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Sandstone beds are generally 10 - 15 cm thick (Fig. 8 C,D). Physical structures are dominated by trough cross beds, with lesser high angle planar laminations, current ripple laminations, reactivation surfaces and climbing ripples. Common accessory components include, carbonaceous detritus, rip-up clasts and rare muddy laminations. No rootlets were observed in this Facies 8. Rare *Planolites* are present in some shale laminations.

3.2.9 Facies 9- Waxy Mudstone Facies

Facies 9 is composed of waxy, smectite-rich blocky, crumbly mudstone with abundant rootlets, pyrite and pedogenic slickensides (Fig. 9 A-D). Variations in this facies exist in the relative development of glutins in the rock and the degree of host rock alteration. Spherulitic siderite and sulfur residue are locally abundant. Burrows in this facies are restricted to very rare small (2-4 mm diameter) *Planolites*. Other ichnogenera may have been present but, if so, are obscured by pedogenic alteration of the rocks. It is important to note that these ichnogenera are not genetically related to Facies 9 *per. se.* These burrows reflect faunal activity contemporaneous with the original depositional environment of the host rock. On the other hand, rootlets are associated with subaerial exposure, and therefore, are contemporaneous with the pedogenic modification of the host rock. Rootlets are typically preserved as carbonaceous films or by replacement of the root system by pyrite (Fig. 9 A).

3.2.10 Facies 10 - Low Angle Parallel Laminated Sandstone

Facies 10 consists of fine-grained, low angle parallel laminated sandstone (Fig. 10 A-D). This facies typically displays oscillation ripple

Figure 9 A-D Facies 9 - Waxy mudstone.

(A) Incipiently podzolized sandy shale with vague, poorly preserved sandstone laminations. Abundant pyrite (py) as noduals and replacing a root system (r). From 11-32-41-12W4 depth 911.4 m.

(B) Well developed paleosol composed of smectite rich claystone. Moderate amounts of pyrite as noduals and possibly preserving a rootlet. Abundant spherulitic siderite (s) as 0.5 mm diameter "pinpoints". From 6-12-42-15W4 depth 3251.8 ft. (991.1m).

(C) Pedogenically altered silty shale with oil stained sandstone bed at the base of the photo. Moderate amounts of pyrite (py) as nodules and possibly replacing a rootlet. From 11-14-42-14W4 depth 948.7m.

(D) Well developed paleosol composed of waxy, smectite rich mudstone with slickensides on the lower surface of the core. Overlying the paleosol above a sharp, undulatory contact is a carbonaceous shale (Facies 4). near the base of the carbonaceous shale is a lag deposit consisting of bivalves and other shell debris. Note the concave down orientation of the bivalve shell indicating deposition by fairly vigorous currents.

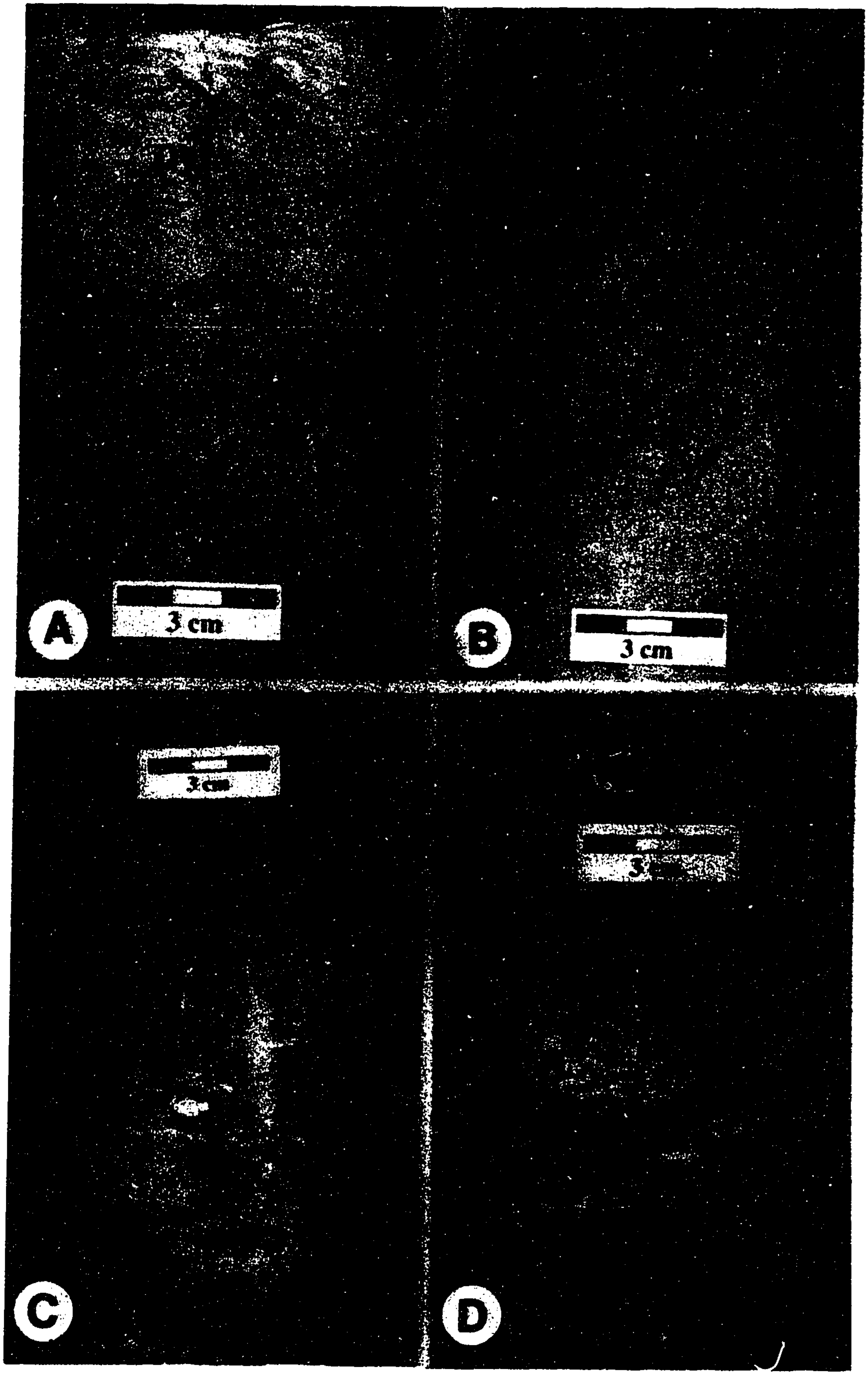
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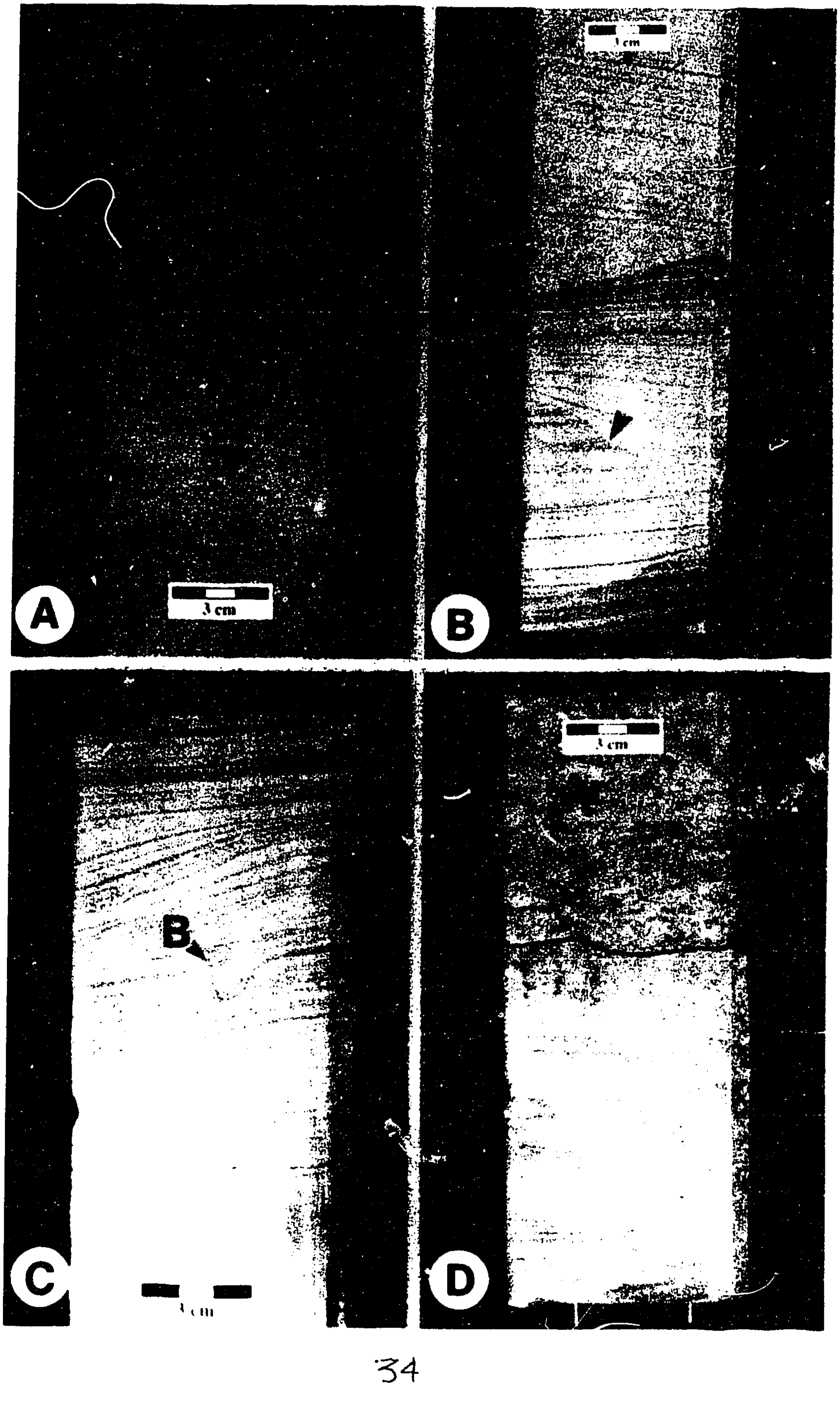
Figure 10 A-D Facies 10 - Low angle parallel laminated sandstone.

(A) Low angle parallel laminated fine grained sandstone. Laminae overlying low angle truncations are parallel to the truncation surface (arrow) and are progressively flater upwards. These successions are characteristic of HCS in which laminae drape over the hummocks and thicken into the lows. Carbonaceous detritus highlites the laminations. From 10-18-41-14W4 depth 3308.5ft. (1008.4m).

(B) Succession of stacked, low angle parallel laminated fine grained sandstones similar to HCS but with concave up laminations filling and thickening into the scours. This is characteristic of SCS where the hummocks are scoured off preserving the swales or lows. From 10-18-41-14W4 depth 3300.5 ft (1005m).

(C) Similar low angle parallel laminated succession with *Bergaueria* (B) possibly representing opportunistic colonisation of the deposits. From 10-18-41-14W4 depth 3310.5 ft. (1009m).

(D) Oscillation ripple laminated fine grained sandstone with no burrows overlain by a biogenically scrambled succession. This laminated to scrambled succession represents opportunistic colonisation of storm beds by trace makers. High degrees of biogenic reworking obscures most individual ichnofossils however *Arenicolites* (Ar)is preserved. From 10-18-41-14W4 depth 3293.0 ft. (1003m).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laminated beds, hummocky cross stratification (HCS) or swaley cross stratification (SCS). Beds are 2 - 15 cm thick and erosionaly amalgamated into bedsets 20 - 150 cm thick. Scour surfaces between beds range from 2 - 30 degrees in inclination but are typically less than 15°. Laminae occur on the scale of mm, and are parallel to subparallel to lower set boundaries. Laminae typically display an upward decrease in inclination, and thicken into lows or swales (Fig. 10 B). Some laminae display convex upward inclinations (Fig. 10 A), characteristic of HCS. Bedsets of HCS and SCS sandstone are locally overlain by oscillation ripple laminated bedsets. Accessory components include rare carbonaceous detritus and shale laminae. Bioturbation within this facies is typically low to moderate in abundance, sporadically distributed and fairly diverse. Forms present include rare small (2-4 mm diameter) *Planolites, Palaeophycus, Teichichnus, Cylindrichnus, Skolithos, Ophiomorpha, Bergaueria* and moderate numbers of fugichnia. Portions of Facies 10 locally displays HCS, SCS or oscillation rippled bed sets that are laminated at the base and biogenically scrambled at the top.

3.2.11 Facies 11 - Inclined Heterolithic Stratification (IHS) Deposits

Facies 11 is composed of fine-grained, cross stratified sandstone interstratified with muddy zones of interlaminated sandstone and shale (Fig. 11 A-D). Sandstone beds are typically 3 - 10 cm thick and current ripple laminated to low angle parallel laminated. Double mud drapes are locally developed on the foresets of low angle parallel laminated units. Muddy zones are typically 3 - 5 cm thick and wavy parallel laminated. Synaeresis cracks are common in the muddy zones. Bedding plane inclinations decrease

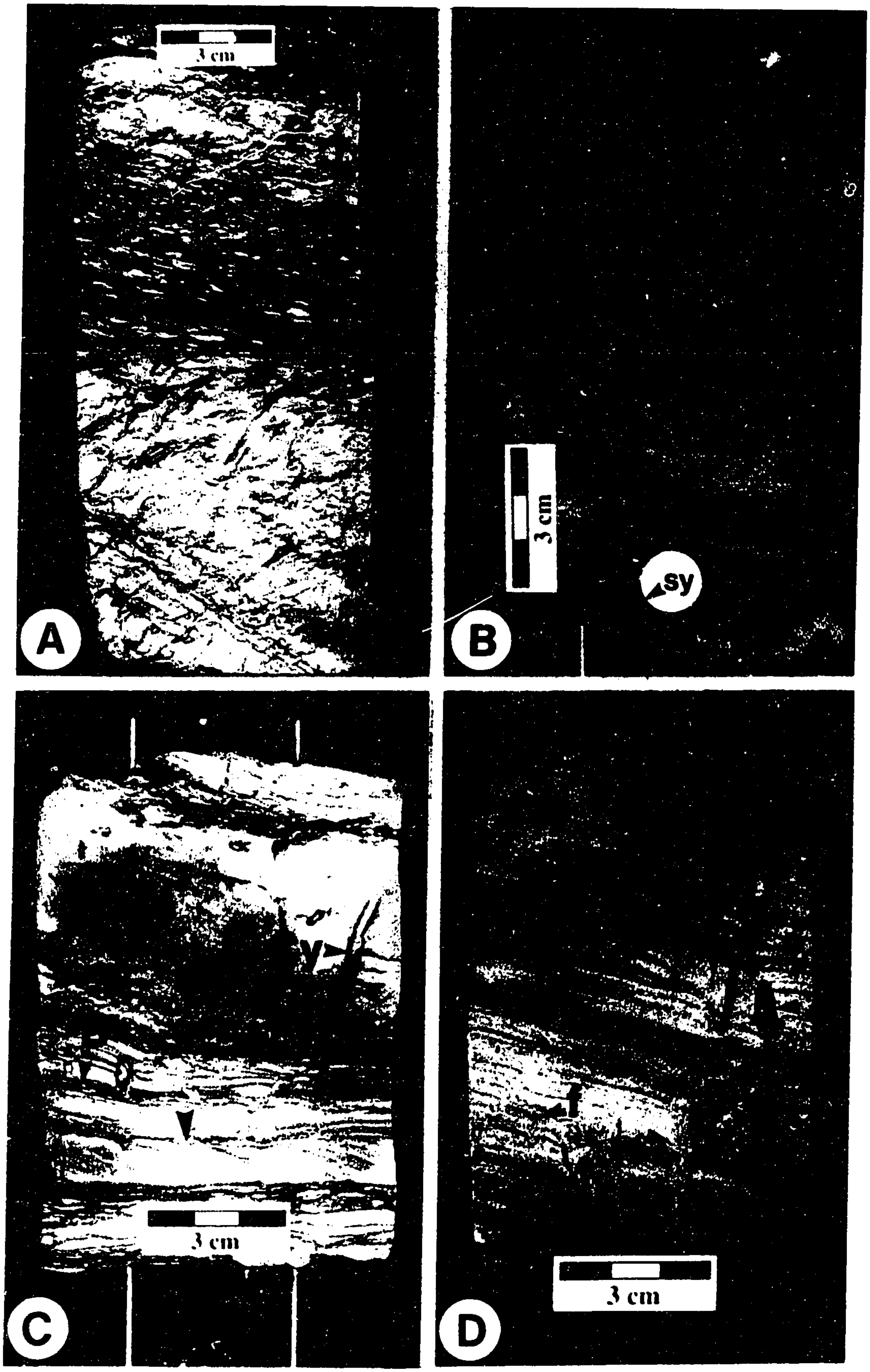
Figure 11 A-D Facies 10 - Inclined heterolithic stratification.

(A) Fine-grained, cross stratified sandstone interbedded with muddy zones of interlaminated sandstone and shale. Note that the inclination of the forsets in the sandstone beds and the inclination of the sandstone interlaminations in the muddy units form a continuous, flattening upward trend from 25-30° to 3-5° reflecting the depositional slope of the point bar. The trace fossil assemblage is dominated by *Cylindrichnus* and *Planolites* (P). *Cylindrichnus* is restricted to the sandy portions while *Planolites* dominates the muddy intervals. From 16-5-42-14W4 depth 3170.8 ft. (966.5m).

(B) This photo is a detail of the lower portion of photo (A). Note the synaeresis cracks (sy) in the shale at the base of the photo. Arrow points to double mud drapes on the forsets of the sandstone beds. Sandstone beds are well burrowed by *Cylindrichnus* (Cy) displaying a forset perpendicular orientation. From 16-5-42-14W4 depth 3170.8 ft. (966.5m).

(C) IHS somewhat sandier than (A) and (B), from lower in the same core indicating that the IHS is muddier upwards. Note the current ripple laminations (arrow) at the base of the photo. From 16-5-42-14W4 depth 3183.8 ft. (970.4m).

(D) Sand dominated IHS note similar trace fossil assemblage and behaviours compared with the muddier IHS. *Cylindrichnus* (Cy and arrows) robust and well developed with forset perpendicular orientation. Fugichnia (f) indicates organism response to high sedimentation rates. From 11-21-41-12W4 depth 981.0m.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upward from 25 - 30° in the lower portions of sandy zones, to 3 - 5° in the overlying muddy zones (Fig. 11 A). Units of IHS are organised into 50 - 100 cm thick bed sets of interstratified sandy and muddy units. These bedsets typically become more mud-dominated toward the top. Carbonaceous detritus is a common accessory constituent. Ichnofossils found in Facies 11 include *Cylindrichnus, Gyrolithes, Planolites* and fugichnia. Trace fossils are unevenly distributed between sandy and muddy zones. *Cylindrichnus, Gyrolithes* and fugichnia are abundant in sandstone units where these traces display a bedding plane perpendicular orientation. *Planolites* is typically found in moderate numbers in the muddy units

3.2.12 Facies 12 - Mottled Carbonate Mudstone

Facies 12 comprises mottled lime mudstone to packstone in intervals 0.2 - 2 m thick (Fig. 12 A,B). Allochems typically consist of gastropod, bivalve, ostracode and more rare bone debris. Allochems range from 0.1 - 4 cm in diameter Locally, shell debris is concentrated into discrete horizons up to 3 cm thick. Bivalves in the shell beds are commonly oriented concave-down throughout most of the unit, but may display a concave-up orientation toward the top of the bed. Pyrite and smectite are rare accessory components in this facies. Lack of lithologic contrast makes burrow identification problematic. The mottled texture of the facies may be attributable to rooting. Alternatively, the mottled texture may be due to burrows, though no biogenic structures could be positively identified.

Figure 12 A,B Facies 12 - Mottled carbonate mudstone.

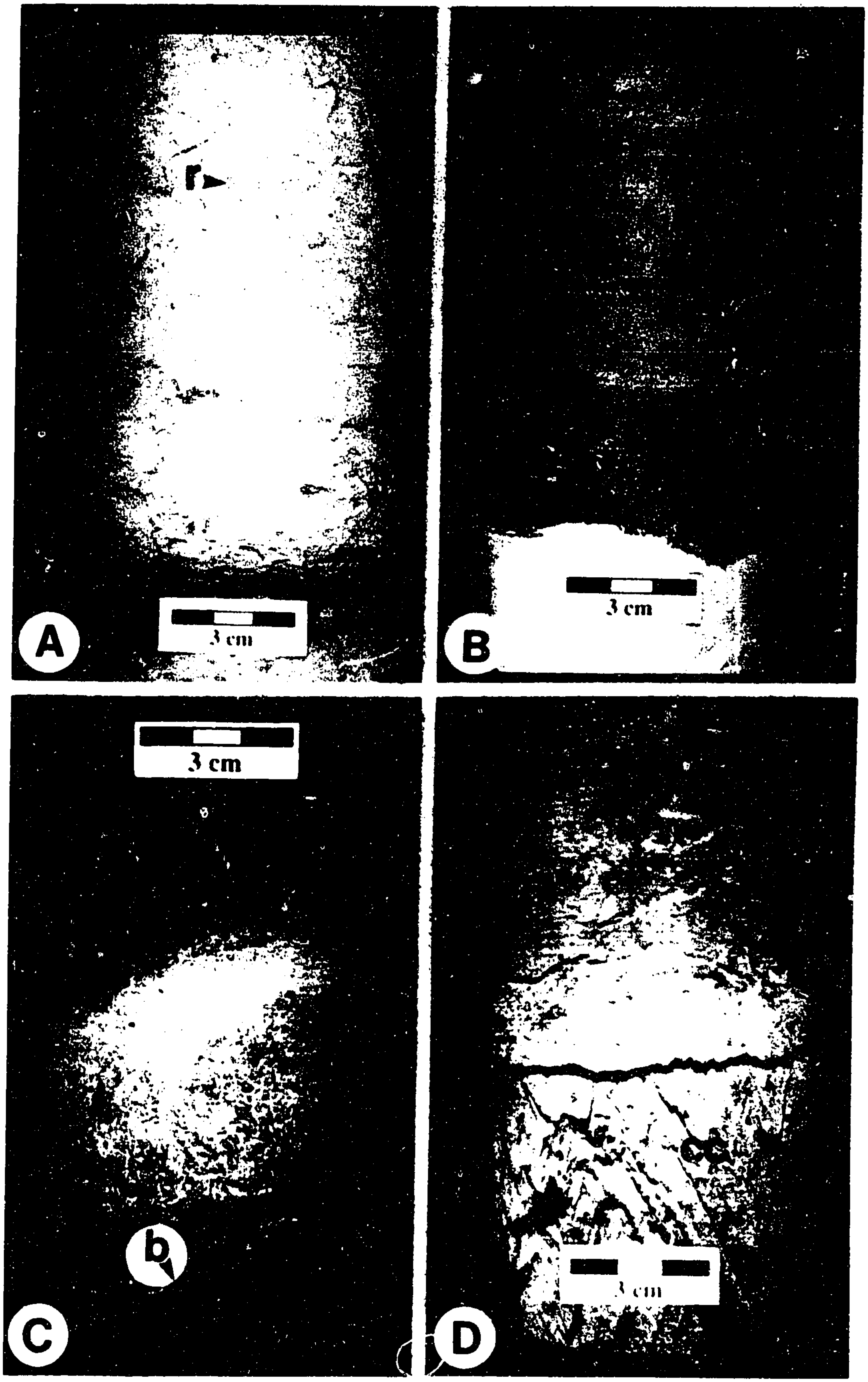
(A) Calcareous mudstone with rootlets (r)? giving the rock a mottled appearance. From 9-3-41-14W4 depth 987.0m.

(B) Tan carbonate mudstone overlain by brown mudstone to wackestone. Note the shell hash (s) due possibly to a storm event. From 7-24-43-14W4 depth 3055.6 ft. (931.3m).

Figure 12 C,D Facies 13 - Recrystallized argillaceous limestone.

(C) Recrystallized calcareous wackestone to rudstone with allochems composed of bone (b) and carbonaceous detritus (upper portion of photo). From 7-24-43-14W4 depth 3074.8 ft (937.2m).

(D) Recrystallized argillaceous limestone with well developed cone-in-cone structures interpreted to be the result of subaerial exposure. Note the thin (2 cm) band in the middle of the photo appears the be composed of more coarse material, possibly represents a storm bed. Cone-in-cone structures do not develop as will in this coarse zone. This suggests that the recrystallized limestone in photo (C) also represents an exposure surface but the cone-in-cone structures did not develop due to the coarse nature of the host rock. From 13-30-40-12W4 depth 3158.0 ft. (962.5m).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3.2.13 Facies 13 - Recrystallized Argillaceous Limestone

Facies 13 is composed of argillaceous lime mudstone to packstone. Recrystallisation has obscured identification of most allochems and only rare shell or bone material is discernible in the facies (Fig. 12 C,D). Sedimentary cone-in-cone structures dominate the fabric of the facies (Fig. 12 D). Cone-in-cone structures resemble a set of concentric cones fitting into one another and are interpreted to develop in response to weathering and subsequent recrystallisation (A.G.I., 1980). Pyrite and smectite are rare accessory components in the facies. No ichnofossils were observed.

CHAPTER 4

FACIES ASSOCIATIONS AND INTERPRETATIONS

4.1 INTRODUCTION

The individual facies that are encountered in the Ostracode Zone of the Bellshill Lake - Killam area have been placed in genetically-related, recurring successions called facies associations. Grouping facies into genetically-related packages enhances the interpretation of the deposits. In this scheme, the same facies may be placed into several different facies associations, depending upon the context in which it occurs. An example of this is Facies 1 which is placed in both Facies Association 1 (FA1) and Facies Association 2 (FA2). Facies 1 is a shaly unit interpreted to be deposited in low energy, brackish water conditions. These conditions exist in both FA1 and FA2, but represent very different environments when examined within the context of the associated facies. Advantages of grouping facies into genetically-related associations include: i) placing emphasis on the context in which a particular facies is found, and ii) the ease with which the deposit can be placed within a sequence stratigraphic context. By placing the emphasis on the association in which a facies is found and how each facies relates to other facies, environmental interpretations are enhanced and refined, in contrast to considering each facies in isolation.

The basic unit in sequence stratigraphy is the sequence which is defined as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchum, 1977). The facies associations outlined below conform to this definition and may be regarded as sequences since each association is bounded by a lowstand surface of erosion.

In addition, by subdividing the deposits into unconformity bound packages, Walther's law of the correlation of facies may be applied within facies associations but not necessarily between successive packages (see chapter 3.1).

4.2 FACIES ASSOCIATION 1

Facies Association 1 (FA1) comprises the regional Ostracode Zone and is variably composed of sandstones, shales, limestones and paleosols. Limestone deposits in the Ostracode Zone have been used as an important marker horizon in the W.C.S.B., dating back to the first exploration wells drilled. Loranger formally defined the Ostracode Zone in 1951, but the term was already in use at that time by Imperial Oil geologists in the Taber area (Farshori, 1990). Though individual markers within FA1 do not correlate well on a regional scale, the facies association as a whole can be correlated through much of the W.C.S.B. west of the Wainwright Ridge (McPhee, 1994). The presence or absence of this regional succession of strata is the main criterion used to map the extent of the incised valley in the study area.

FA1 consists of a series of stacked, coarsening-upwards successions. These successions are variable locally and consist of the facies summarised in Table 1.0. Though there is considerable variability within each coarsening upwards succession, an idealised succession can be constructed based on the detailed examination of 5 drill cores that penetrate FA1 (Fig. 14). A generalised succession begins with 20 - 30 cm of weakly burrowed silty shales (Facies 1). This facies is interpreted to represent distal brackish bay deposits, rarely influenced by storms. Sporadic storm activity is indicated by rare, thin, parallel laminated sandstone stringers. The trace fossil suite consists of rare

Table 1.0 - Facies Association 1

Facies	Name	Physical Structures	Biogenic Structures	Accessories
1	Weakly Burrowed Silty Shale	synaeresis cracks, rip-up clasts	*Planolites*	sandstone laminations, carbonaceous detritus, pyrite
4	Carbonaceous Shale and Coal	synaeresis cracks	rootlets	pyrite, smectite
5	Interbedded Sandstone and Black Shale	lenticular to wavy bedded, oscillation ripple laminations, synaeresis cracks	*Planolites*, *Teichichnus*	carbonaceous detritus, pyrite, smectite
6	Moderately Burrowed Interbedded Sandstone. and Shale	lenticular to wavy bedded, oscillation ripple laminations, microfaults, synaeresis cracks	*Planolites*, *Palaeophycus*, *Teichichnus*, *Cylindrichnus*, *Gyrolithes*, *Bergaueria*	carbonaceous detritus, pyrite, smectite
9	Waxy Mudstone	pedogenic slickensides	rootlets, *Planolites*	carbonaceous detritus, pyrite, smectite, sulphur
10	Low Angle Parallel Laminated Sandstone	HCS, SCS, oscillation ripple laminations	*Planolites*, *Palaeophycus*, *Teichichnus*, *Cylindrichnus*. *Skolithos*, *Ophiomorpha*, *Bergaueria* and fugichnia	carbonaceous detritus, mud laminae
12	Mottled Carbonate Mudstone	N/A	not discernible	shell material, bone fragments, pyrite, smectite
13	Recrystallised Argillaceous Limestone	sedimentary cone-in-cone structures	not discernible	N/A

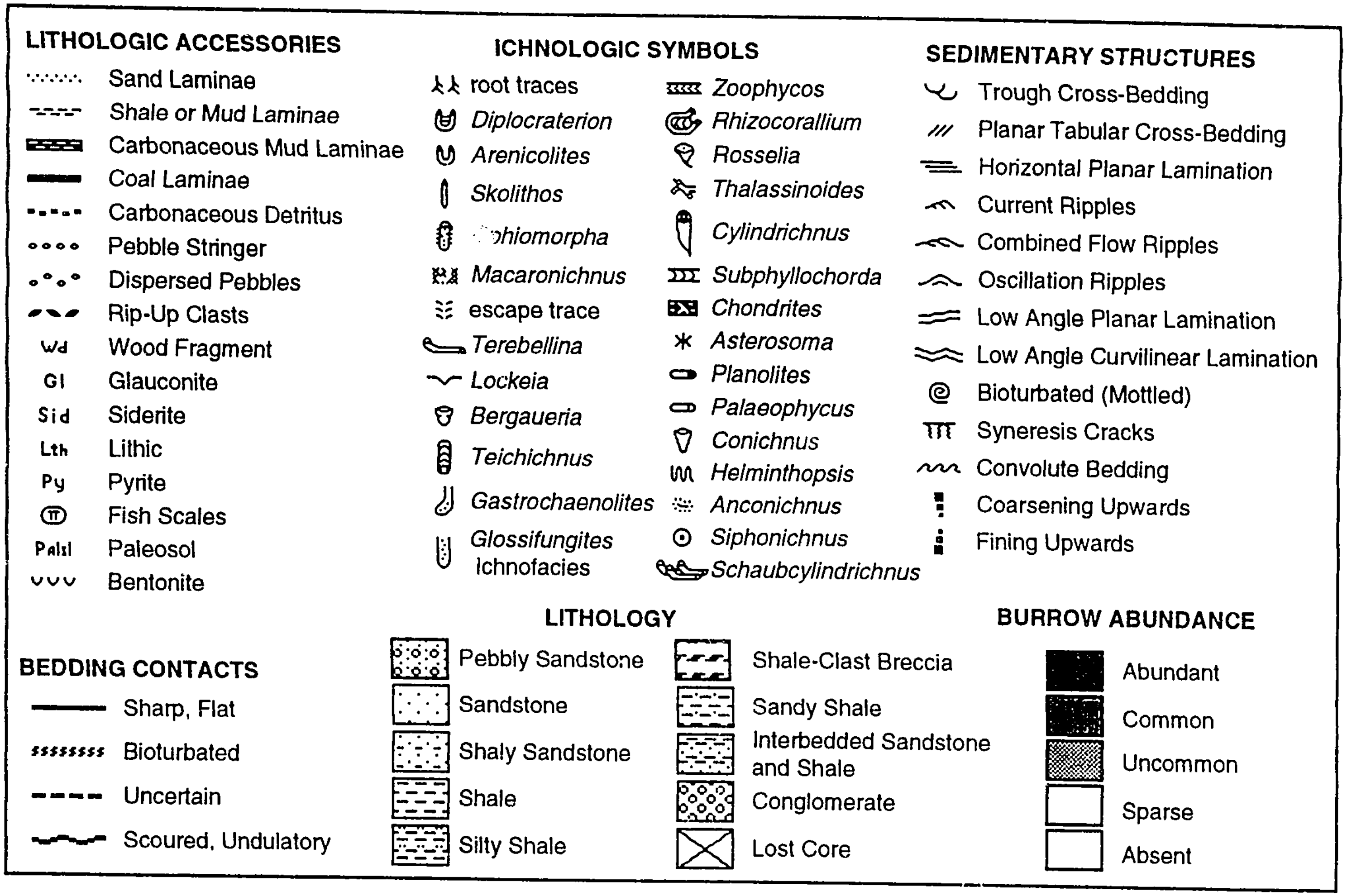


Figure 13.0. Legend of Symbols used in Lithologs.

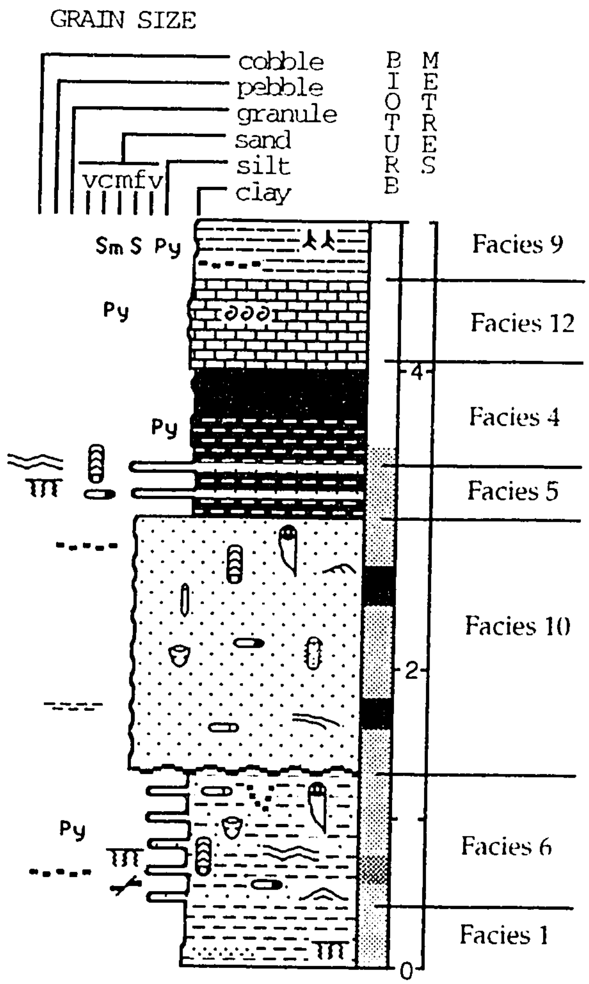


Figure 14 Facies Association 1 idealised succession.

numbers of diminutive *Planolites*. The reduced size and severely limited ichnofaunal diversity support an interpretation of reduced salinities in the bay (Beynon *et al.*, 1988, Wightman *et al.*, 1992). Synaeresis cracks indicate that fluctuations in salinity levels may have occurred (Plummer and Gostin, 1981). Synaeresis cracks are typically associated with sandstone laminations, indicating a genetic link between storm activity and salinity fluctuations. Storm events are generally accompanied by high rates of precipitation. Fresh water, derived from surface run-off from adjacent terrestrial areas, is delivered to the bay *via* the existing drainage patterns. In addition, fresh water is supplied directly to the bay by rainfall. The sudden volumetric increase in fresh water supply to the bay during and immediately after the storm is interpreted to be responsible for the development of synaeresis cracks associated with the sandstone laminations.

Facies 1 grades into 0.5 - 1.0 m of weakly burrowed, interbedded sandstone and shale (Facies 6). Facies 6 is interpreted to represent more proximal brackish bay conditions. Higher numbers of oscillation ripple and wavy parallel laminated sandstone interbeds indicates higher incidence of wave agitation and storm action on the deposits. The increase in the sandstone to shale ratio may be due to increases in storm frequency, and/or a reduction in water depth. Shallower water conditions favour storm wave base contacting the substrate, enhancing the chances for preserving a record of storm activity. The position of Facies 6 within an overall shallowing upward succession suggests that shallowing is the likely mechanism responsible for the increased evidence of storm activity. Synaeresis cracks are interpreted to represent salinity fluctuations associated with concomitant freshwater terrestrial run-off during and immediately succeeding the storm event.

Ichnologically, Facies 6 is characterised by a slightly more diverse ichnofauna (increase to 6 genera) and marginally higher degrees of bioturbation compared with Facies 1. This may reflect a greater lithologic contrast highlighting traces as well as a greater diversity of behaviours associated with the variability in the substrate consistency. The trace fossil assemblage of Facies 6 is, however, considered to be restricted in diversity compared with fully marine deposits (*e.g.* the Viking Formation, Cardium Formation, Wabiska Formation *etc.*), supporting less than fully marine salinity levels (Wightman *et al.*, 1987, Pemberton and Wightman, 1992).

Sharply overlying Facies 6 is 1 - 2 m of low angle parallel laminated fine-grained sandstone (Facies 10). Facies 10 is interpreted to represent storm-influenced bay deposits. Sedimentary structures include hummocky cross stratification (HCS) and swaley cross stratification (SCS). Both structures have been attributed to storm deposition (Duke, 1985; Leckie and Walker, 1982; Walker, 1985). Locally, these laminated successions have erosional bases and biogenically reworked tops. Howard (1972) interpreted such successions as storm-derived. During the storm, laminated bedsets aggrade and are subsequently colonised by benthic trace makers when fairweather conditions return (Pemberton *et al.*, 1992). In Facies 10, bioturbation in the lower portions of the laminated deposit is restricted to rare escape structures (fugichnia) reflecting disruptions caused by organisms entrained in the flow or buried by the bed. The tops of laminated successions are typically thoroughly burrowed by a moderately restricted assemblage of small trace fossils (7 ichnogenera). Waning flow conditions are preserved locally as oscillation ripple laminations below the biogenically-reworked bed tops. Such observations are consistent with the tempestites described by Saunders and Pemberton (1986); Pemberton *et al.* (1992) and Pemberton and MacEachern, (in press). Storm-generated sedimentary structures and a restricted trace fossil assemblage consisting of small forms suggest that Facies 10 was deposited in a storm-influenced brackish bay.

Facies 4 overlies Facies 6 in an idealised succession. This facies is interpreted to represent shallow brackish/stagnant bay margin to coal swamp conditions. The thickness of Facies 4 is variable and ranges from 0.2 - 0.5 m. High carbonaceous content and abundant pyrite support the interpretation of stagnant conditions for the deposition of Facies 4. Biogenic structures in the facies are restricted to rare rootlets and physical structures include rare synaeresis cracks. This suggests both brackish water and fluctuating salinity levels in the environment of deposition. Facies 4 is typically overlain by Facies 5, 12 or 13 described below.

Facies 5 is composed of 0.5 - 1.0 m of interbedded sandstone and black shale. Synaeresis cracks and an impoverished trace fossil assemblage suggest that salinities are typically low and commonly fluctuate in this facies. Fluctuations in salinity may be attributed to increased freshwater runoff associated with storms. The ichnofossil assemblage of Facies 5 is further stressed by low oxygen conditions as indicated by the high organic content preserved in the facies and the abundant pyrite. This facies is interpreted to represent a bay margin environment, possibly intertidal to supratidal.

Facies 12, mottled carbonate mudstone, 0.25 - 1.5 m in thickness may overly Facies 5. Examination of the 5 drill cores through FA1 showed a close association between Facies 12 and 13 and the previously described Facies 4, 5 and 6. Local presence of rip up clasts and shell or bone fragments in Facies 12 is considered evidence for high energy conditions. Rare, thin shell hash laminations and beds having both concave-up and concave-down bivalve shell orientations also occur within Facies 12 and may indicate intermittent storm activity. During the storm, relatively strong wave-forced currents arrange bivalve shells into a stable concave-down orientation. After the storm subsides, debris that was suspended by strong currents falls out of suspension. The hydrodynamically stable orientation for bivalve shells under these conditions is concave-up. Lack of lithologic contrast in Facies 12 obscures identification of trace fossils. Bannerjee and Kidwell (1991) found paleontological, palynological and geochemical evidence for reduced salinities in similar rocks of the Ostracode Zone and Holmden (1994), found geochemical evidence for lacustrine environments of deposition in the carbonates of the Ostracode Zone. Locally, Facies 12 is replaced by argillaceous recrystallized limestone (Facies 13).

Facies 13 is characterized by cone in cone structures which resembles a set of concentric circular cones fitting into one another. Cone in cone structures are considered to be developed in response to pressure aided by crystallisation and weathering (American Geological Institute, 1980). Facies 13 has a genetic link with the waxy mudstone facies described below. Both facies are interpreted to represent extensive periods of subaerial exposure. Differences in the physical characteristics of these two facies are attributed to differences in the host rock. The mottled carbonate mudstone facies is interpreted to represent shallow freshwater lake deposits affected by rare storms. During progradation, the brackish bay is separated from the coast, and becomes lacustrine. Lacustrine carbonates fill the lake and establish terrestrial conditions, resulting in the alteration of Facies 12 into Facies 13 and/or Facies 9.

Facies 9 is composed of a waxy mudstone interpreted as a paleosol developed during extensive periods of subaerial exposure. Facies 9 may be developed at the top of Facies 5, 6 or 13 and represents the final infill of the bay. The degree of paleosol development is variable, but typically ranges from 0.5 - 1.0 m thick. Facies 9 is typically overlain by a flooding surface, locally demonstrating transgressive erosion. Any erosional removal of the paleosol would invalidate an estimation of the duration of the depositional hiatus the deposit represents, based on the relative development of the paleosol. The abundance of pyrite, and carbonaceous [illegible] suggests that reducing conditions prevailed during the development of the paleosol. Facies 9 was likely developed under subaerial but poorly drained conditions (Retallack, 1988). This evidence is consistent with the elevated water tables expected to be present in the environment of deposition of the host rock. Paleosols within FA1, though genetically related to exposure, do not always represent a major lowstand of relative sea level. Careful correlations are required in order to differentiate paleosols associated with lowstand of sea level from those developed on top of bayfill successions.

The regional Ostracode Zone, represented here by FA1, consists of a stacked succession of bay-fill deposits. The regional Ostracode Zone is 20 -30m thick and made up of 4 - 5 bay-fill successions that are individually 2 - 5 m thick. The bay-fill deposits contain abundant evidence to suggest that salinities were typically low and fluctuated markedly. Fluctuating salinities are interpreted to be the result of increased freshwater influx during and immediately following the storm events. Abundant storm-generated sedimentary structures and biogenic fabrics in the deposits are interpreted to represent frequent storm activity affecting the deposits of the regional

Ostracode Zone during fill and shallowing. Late stage fill of the bay reflects a transition from brackish-bay to lacustrine environments of deposition. Prolonged exposure of the bay-fill deposits (FA1) is recorded by the occurrence of paleosols. Careful correlation is required to differentiate bayfill associated paleosol from lowstand related paleosols.

4.3 FACIES ASSOCIATION 2

A relative lowstand of sea level during Ostracode time (Late Albian) resulted in the incision of a valley in the Bellshill Lake - Killam area. Facies Association 2 (FA2) represents the fill of this valley and consists of sandstones and shales with a markedly brackish character (Table 2.0) (Fig. 15). The deposits of FA2 are contained within a 3-5 km wide channel 20 - 50m deep, trending roughly northeast - southwest through the study area (Fig. 4). The valley base typically cuts through the Ostracode Zone and incises into Ellerslie Formation sediments, although locally, it lies directly on Paleozoic carbonates of the Wabamun Formation or Winterburn Group.

Initial deposits of the incised valley in the study area are composed of 15 -20 m of trough cross bedded and current ripple laminated sandstone (Facies 8). This facies is interpreted to be generated by quasi-steady unidirectional currents. Evidence of tidal influence and burrows were not observed in Facies 8 supporting the interpretation of a fresh water fluvial origin for the basal sandstones. Its stratigraphic position at the base of the valley and fluvial origin suggests that Facies 8 in FA2 represents late lowstand to early transgressive fluvial aggradation in the incised valley.

Continued transgression resulted in the deposition of 15 - 20 m of *Cylindrichnus*-dominated inclined heterolithic stratification (IHS) (Facies 11).

Table 2.0 - Facies Association 2

Facies	Name	Pysical Structures	Biogenic Structures	Accessories
1	Weakly Burrowed Silty Shale	synaeresis cracks, rip-up-clasts	*Planolites*	sandstone laminations, carbonaceous detritus, pyrite
2	Weakly Burrowed Contorted Silty Shale	convoluted laminations, micro faults	*Planolites*	pyrite
3	Weakly Burrowed Interlaminated Sandstone and Shale	lenticular to wavy bedded, micro faults, synaeresis cracks	*Planolites*, *Teichichnus* rootlets	carbonaceous detritus, pyrite and smectite
6	Moderately Burrowed Interbedded Sandstone and Shale	lenticular to wavy bedded, oscillation ripple laminations, micro faults, synaeresis cracks	*Planolites*, *Palaeophycus*, *Teichichnus*, *Cylindrichnus*, *Gyrolithes*, *Bergaueria*	pyrite, smectite
8	Unburrowed Trough Cross Stratified Sandstone	trough cross bedding, current ripple laminations, climbing ripple laminations	*Planolites*	carbonaceous detritus, shale laminations
9	Waxy Mudstone	slickensides	rootlets, *Planolites*	carbonaceous detritus, pyrite, smectite, sulfur
11	Inclined Heterolithic Stratification Deposits	trough cross bedding, oscillation ripple laminations, double mud drapes, synaeresis cracks	*Cylindrichnus*, *Gyrolithes*, *Planolites*, *Palaeophycus*, *Teichichnus*, *Skolithos*, *Thalassinoides* and fugichnia	carbonaceous detritus, shale laminae

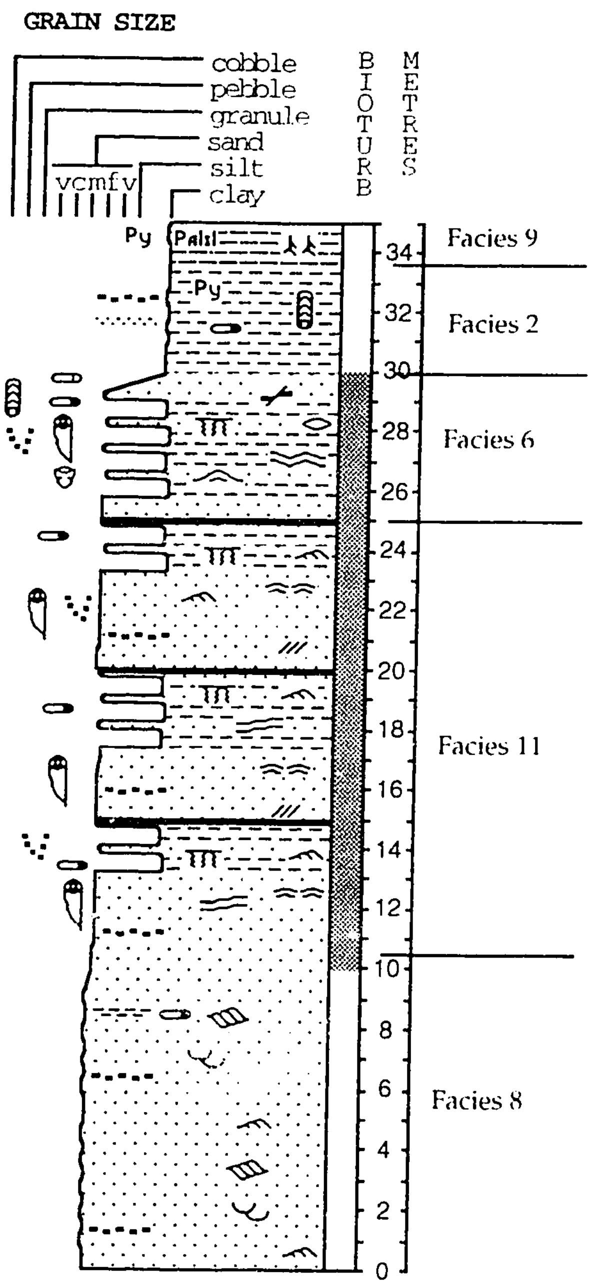


Figure 15 Facies association 2 idealised succession.

IHS is interpreted to represent lateral accretion (point bar) deposits within the valley , and develops in response to the interaction of fluvial and tidal currents in the estuary (Thomas *et al.*, 1987; Beynon *et al.*, 1988; Ranger and Pemberton, 1992). Sand is moved as bedforms (current ripples or trough cross beds) during the ebb tide. At this time, fluvial flow and ebb flow combine to give the highest flow velocities in the channel. During flood tide, however, fluvial out-flow is dammed up by tidal in-flow. This results in standing water to sluggish flow conditions in the channel. Low flow conditions permits muds and silts to fall from suspension and drape the point bar. This daily cycle is one possible mechanism which may produce IHS-type bedding. Another larger scale mechanism involves the variations in spring and neap cycles. Spring cycles are characterised by higher energy and greater flow velocities and therefore results in sandier IHS. As the cycle moves toward neap, flow velocities decline and more mud is deposited, resulting in muddier IHS. On an even larger scale, displacement up and down the estuary of the turbidity maximum zone also controls the proportion of mud and sand in the IHS. The turbidity maximum results from the rapid flocculation of clays due to mixing of fresh and saline waters. As this zone shifts up and down the estuary in response to variations in fluvial discharge, the proportion of mud in the IHS deposits changes since the amount of mud in suspension increases.

The mud beds in IHS deposits drape the point bar and their inclination reflects its slope. Typically, the inclination of the interbeds decreases upward in IHS deposits since the profile of the point bar is steeper towards the thalwag and flatter on top of the point bar. IHS deposits in the Bellshill Lake - Killam area vary from mud-dominated in the west to sand dominated in the east. This is interpreted as evidence for a transition towards progressively more estuarine conditions to the west in the study area. There is also a vertical trend towards progressively more estuarine conditions in the IHS beds, reflected by a decreasing sandstone to shale ratio and an increasing degree of bioturbation upward. This is interpreted to represent a shift in the position of the turbidity maximum zone to the east with time. This may be due either to relative rise in sea level or to changes in the fluvial and tidal flow regime with time. Deposition of the overlying Facies 6 suggests that continued transgression is primarily responsible for this trend. The ichnofossil assemblage in Facies 11 (IHS deposits) is dominated by *Cylindrichnus*, which display a perpendicular orientation to the cross-bed forsets. Bechtel *et al.* (1994), reported a similar relationship developed in IHS deposits of the McMurray Formation, consisting of *Cylindrichnus* and *Gyrolithes*. Ichnologically, Facies 11 is restricted to 3 ichnogenera. Restricted assemblages such as this have been regarded as indicating brackish water conditions (Beynon *et al.*, 1988, Pemberton *et al.* 1992) and demonstrate that the salt wedge was able to penetrate into this portion of the valley.

Weakly to moderately burrowed interbedded sandstones and shales (Facies 6) (2 - 5 m thick) are interpreted as brackish bay deposits developed within the valley in response to continued transgression. Oscillation rippled sandstone interbeds, locally grading into synaeresis-cracked shales are interpreted as evidence of wave agitation and storm activity in the bay. Soft sediment deformation features are considered further evidence of storm influence. Micro-faults and flame structures are the result of rapid, storm-derived sand deposited upon water-saturated, unconsolidated muddy substrates. The trace fossil assemblage of Facies 6 is restricted to small

Planolites, Palaeophycus, Teichichnus and *Cylindrichnus,* indicating brackish-water conditions in the bay (Wightman and Pemberton, 1987, Beynon et al., 1988, Pemberton *et al.*, 1992). This ichnological assemblage represents the resident community of trace makers. In biological terms this community is an r-selected population rather than a K-selected or equilibrium populat[illegible] typical of fully marine asse[illegible]es. The resident suite is r-selected, within the valley, because of the salinity stress (Pemberton *et al.*, 1992). Locally, zones of cryptic bioturbation are present in Facies 3. Cryptic bioturbation refers to zones of thoroughly mottled sediments with indistinct burrows. The size of the indistinct burrows in Facies 6 suggests that some variety of benthic meiofauna is responsible for the cryptic bioturbation (Saunders pers. comm., 1995). Zones of crypto-bioturbation typically occur within the upper portions of sandstone interbeds and the lower portions of the overlying shale interbeds. Cryptic bioturbation in Facies 6 is interpreted as ichnological evidence for storm activity in the bay. In contrast to fairweather deposits, storm-deposited sediments may be well oxygenated throughout their thickness for a period of time after the storm (Saunders *et al.*, 1994) Under oxygenated conditions, organisms which are typically restricted to the thin oxygenated zone near the sediment-water interface, are able to penetrate more deeply into the deposit. This population of trace makers is also termed an r-selected suite, but represents an opportunistic community. This community thrives until food resources are exhausted, the oxygen window is depleted and/or normal (ambient) environmental conditions return (Pemberton *et al.*, 1992).

Weakly burrowed, interlaminated sandstone and shale deposits (Facies 3) range from 0.5 - 2.0 m in thickness, and typically overlie Facies 6. Facies 3 contains synaeresis cracks and is interpreted to represent shallow subtidal to intertidal deposits subject to salinity fluctuation.

Shallowing conditions initiated during the deposition of Facies 3 continued with the deposition of 1 - 2 m of the weakly burrowed, contorted silty shale (Facies 2). Facies 2 is interpreted to represent deposition in an intertidal flat environment. The origin of widespread soft sediment deformation in this facies is problematic. Elliot (1986) outlined two possible mechanisms: rotational slumps on migrating tidal channel point bars and mass movement due to rapid fluctuations in pore water pressure associated with tidal ebb and flood. Mass movement is considered to be a more likely mechanism since there is no evidence for tidal channels (*e.g.* IHS) in Facies 2.

Weakly burrowed silty shales (Facies 1), ranging from 0.5 - 1.0 m in thickness, typically overlie Facies 2. Facies 1 shales are interpreted to be deposited in the lowest energy upper reaches of the tidal flat environment. Rare sandstone laminations indicat that energy levels sufficient to transport sand-sized particles were uncommon. Pyrite is typically present in Facies 1 and is interpreted to represent reducing conditions such as may be found in poorly drained mud flats. This facies typically grades upwards into a waxy mudstone.

Waxy mudstone (Facies 9) with slickensides, abundant smectite and rootlets is interpreted to represent prolonged subaerial exposure and development of a soil. Facies 9 in FA2 is typically 0.5 - 1.0 m thick. The prolonged subaerial exposure needed to generate a soil horizon suggests that Facies 9 developed in response to a relative sea level fall rather than to simple filling and abandonment of a bay. Further evidence for a relative sea level fall is the presence of Facies Association 3 which incises into FA2. FA3 is described in the following section.

In summary, Facies Association 2 represents the infill of the first stage of valley incision. Trace fossil assemblages indicate that the fill of the valley was initially fluvial but but became progressively estuarine in response to transgression. The upper portions of the incised valley fill are characterized by brackish bay-fill and tidal flat deposits. A second fall in relative sea level resulted in the development of a soil horizon represented by a paleosol on the interfluves, and re-incision of these FA2 valley deposits by a second valley complex (FA3).

4.4 FACIES ASSOCIATION 3

Facies Association 3 (FA3) developed in response to a second stage of relative sea level fall during Ostracode (Late Aptian) time, probably related to the same lowstand responsible for the capping paleosols of FA2. FA3 represents a second incised valley complex which cut into the deposits of FA2. The scale of this second incision is significantly reduced compared to that of the first major incision responsible for FA2. The valley generated by this second event is typically 1.5 - 2.0 km wide and 25 - 30 m deep. The relatively small scale of this incision event is interpreted to reflect a shorter duration and/or reduced magnitude of relative sea level lowstand compared to that of the first lowstand during Ostracode time. Late lowstand to early transgressive deposits dominate the fill of this valley, and are grouped as Facies Association 3 (Table 3.0).

FA3 consists of thick (20 - 25 m) sandstones overlain by thin interbedded sandstones and shales (Fig. 16). Most of the valley fill is composed of unburrowed trough cross stratified sandstone (Facies 8).

Table 3.0 - Facies Association 3

Facies	Name	Pysical Structures	Biogenic Structures	Accessories
6	Moderately Burrowed Interbedded Sandstone and Shale	lenticular to wavy bedded, oscillation ripple laminations, micro faults, synaeresis cracks	*Planolites, Palaeophycus, Teichichnus, Cylindrichnus, Gyrolithes, Bergaueria*	pyrite, smectite
8	Unburrowed Trough Cross Stratified Sandstone	trough cross bedding, high angle planar bedding, current ripple laminations, climbing ripple laminations	*Planolites*	carbonaceous detritus, shale laminations

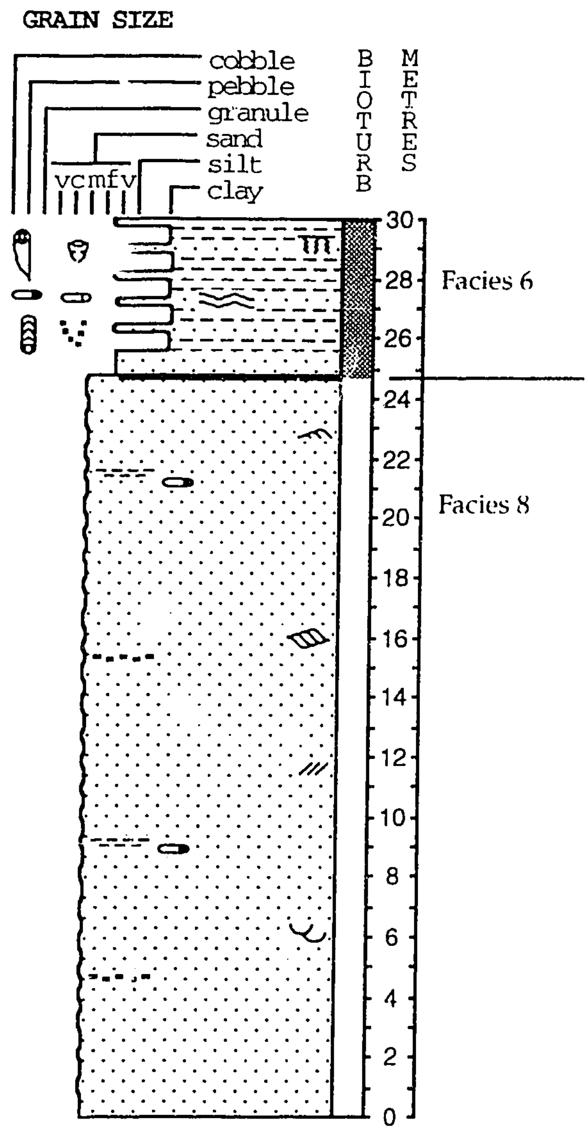


Figure 16 Facies associations 3 and 5 idealised succession.

Abundant trough cross stratified beds, high angle planar stratified beds and current ripple laminated beds indicate deposition by quasi-steady unidirectional currents. The ichnofossil assemblage is composed of a single genus; namely *Planolites*, which is present only in rare numbers within the shale beds. The virtually unburrowed nature of the facies is considered evidence of a fresh to slightly brackish water origin for the facies. Similar monospecific assemblages of *Planolites* have been interpreted to represent such conditions (Beynon *et al.*, 1988, Pemberton and Wightman, 1992). Facies 8 is interpreted to have been deposited as fluvial bedforms and point bars within a channel complex.

Overlying these fluvial deposits is 2 - 5 m of moderately burrowed, interbedded sandstones and shales (Facies 6). This facies is interpreted to represent deposition in standing water periodically affected by periods of higher energy, during which oscillation ripples were generated. This facies also represents the cessation of freshwater conditions and a return to more estuarine conditions, associated with renewed transgression. Facies 6 is typically not more than 5 m thick and represents the filling of the narrow incision of this Ostracode-aged valley. A relative stillstand in transgression resulted in the establishment of a regionally extensive brackish bay above Facies 3, constituting Facies Association 4.

In summary, Facies Association 3 represents the fill of an incised valley that developed in response to a second relative sea level fall during Ostracode time (Late Aptian). Fill of this valley was dominated by fluvial sandstones with only minor brackish bay-fill deposits capping the succession, related to the onset of transgression. FA3 forms the main reservoir sandstone in the Thomson Lake, Bellshill Lake and Forrestburg oilfields.

4.5 FACIES ASSOCIATION 4

Facies Association 4 (FA4) was deposited in response to a relative stillstand of sea level. The sediments comprising FA4 typically consist of coal, and carbonaceous shales interbedded with a number of other facies (Table 4.0) (Fig. 17). These deposits are interpreted to represent shallow brackish bays and coal swamps. FA4 is typically 5 - 8 m thick, and is regionally extensive across the study area, except where cut by early Glauconitic-aged (Early Albian) valleys.

The FA4 succession is highly variable locally, though it is dominantly composed of carbonaceous shale and coal (Facies 4), with 0.3 - 1.0 m interbeds of weakly burrowed silty shale (Facies 1), interbedded sandstone and black shale (Facies 5), *Teichichnus*-dominated sandy shale (Facies 7), unburrowed trough cross stratified sandstone (Facies 8) and mottled carbonate (Facies 12). Carbonaceous shale and coal are interpreted to be deposited in a swamp environment where the water table was relatively high and reducing conditions prevail. Evidence for reducing conditions includes abundant pyrite and unoxidised carbonaceous material. Each of the other 5 facies that interfinger with the carbonaceous shale and coal are interpreted to represent relatively short lived deeper water conditions. Oscillation ripple laminated interbeds, rare shell hashes and coquinas testify to the existence of wave agitation and storm activity on standing bodies of water. Physical structures in the interfingering units include abundant convoluted bedding and microfaults at the base of units suggesting rapid deposition associated with storm activity. The ichnofossil assemblage in FA4 is typically restricted in diversity (6 genera), size and abundance of individual forms. Locally, horizons are thoroughly burrowed by a single genus (*i.e. Teichichnus*-

Table 4.0 - Facies Association 4

Facies	Name	Pysical Structures	Biogenic Structures	Accessories
1	Weakly Burrowed Silty Shale	synaeresis cracks, rip-up-clasts	*Planolites*	sandstone laminations, carbonaceous detritus, pyrite
4	Carbonaceous Shale and Coal	synaeresis cracks	rootlets	pyrite, smectite
5	Interbedded Sandstone and Black Shale	lenticular to wavy bedded, oscillation ripple laminations, synaeresis cracks	*Planolites*, *Teichichnus*	carbonaceous detritus, pyrite, smectite
7	*Teichichnus*-Dominated Sandy Shale	biogenically homogenised	*Teichichnus*, rare *Planolites*	carbonaceous detritus, pyrite
9	Waxy Mudstone	slickensides	rootlets, *Planolites*	carbonaceous detritus, pyrite, smectite, sulphur
12	Mottled Carbonate Mudstone	N/A	Not discernible	shell material, bone fragments, pyrite, smectite
13	Recrystallised Argillaceous Limestone	sedimentary cone-in-cone structures	Not discernible	N/A

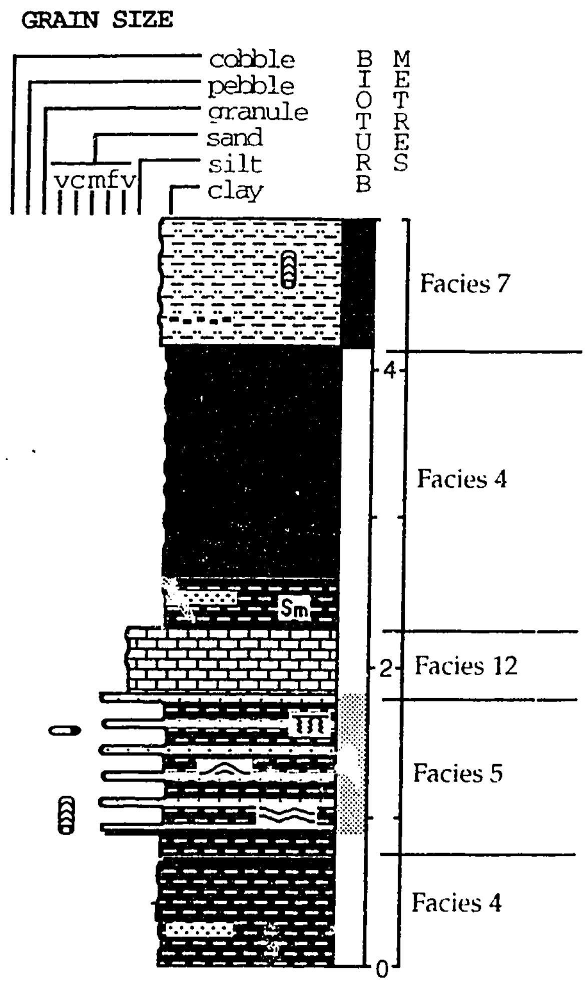


Figure 17 Facies Association 4 idealised succession.

dominated sandy shale). Wightman *et al.* (1987), Beynon et al. (1988) and Pemberton and Wightman (1992), attributed such monospecific assemblages to brackish water conditions. Based on the above criteria, FA4 is interpreted to represent a swamp to storm-influenced brackish bay environment. Where preserved, the top of FA4 consists of paleosol or limestone with sedimentary cone-in-cone structure directly overlain by a scour surface. Associated with this exposure surface and paleosol development is a third stage of relative fall in sea level which was responsible for fluvial incision into FA4 deposits. These fluvial deposits constitute Facies Association 5 described in the following section.

4.6 FACIES ASSOCIATION 5

Facies Association 5 (FA5) developed in response to a third period of relative sea level fall during late Ostracode time (Late Aptian). Relative sea level fall initiated fluvial valley incision into FA4 and was probably responsible for the development of the paleosol and sedimentary cone-in-cone structure within the carbonates capping FA4. Based on its narrow width and sporadic distribution in the study area, the scale of the incision is interpreted to be significantly reduced compared to the first and second major incisions. The relatively small scale of this incision event likely indicates that relative sea level lowstand was of short duration and/or that total base level fall was much less than that of either of the two previous events.

In the study area, the preserved record of FA5 consists exclusively of unburrowed trough cross stratified sandstone (Facies 8), 5 - 10 m thick (Table 5.0) (Fig. 16). FA5 is interpreted to represent fluvial channel deposition similar to FA2 and FA3, and therefore should have the same succession of

Table 5.0 - Facies Association 5

Facies	Name	Pysical Structures	Biogenic Structures	Accessories
8	Unburrowed Trough Cross Stratified Sandstone	trough cross bedding, high angle planar bedding, current ripple laminations, climbing ripple laminations	*Planolites*	carbonaceous detritus, shale laminations

facies. However, the upper portion of FA5 has been removed by widespread wave ravinement associated with the transgression of the Moosebar Sea. The scour surface is directly overlain by deposits with a significantly more marine trace fossil assemblage than encountered within the Ostracode Zone. The sandy shales of the overlying Glauconitic Member display a diverse trace fossil assemblage consisting of *Helminthopsis, Chondrites, Planolites, Palaeophycus, Teichichnus, Terebellina, Zoophycos, Asterosoma,* and *Diplocraterion*.

CHAPTER 5

ESTUARINE MODELS

5.1 INTRODUCTION

Recently, increased interest has been shown in estuarine depositional systems, due largely to the exploration for hydrocarbons in clastic reservoirs deposited within estuarine environments. The term estuarine can mean different things to different people. Hydrologists consider estuarine to mean less than marine salinities. Oceanographers typically define an estuary as body of water were marine and fluvial water mix. Sedimentologists and stratigraphers such as Dalrymple *et al.*, (1992), define an estuary as a site of rapid sedimentation, due to the input of material from both fluvial and marine sources, that forms within an incised valley during a transgression. This study follows the later definition of the term estuary. This section discusses the types of estuarine depositional models in existence and applies those models to the Ostracode Zone in the Bellshill Lake - Killam area.

5.2 ESTUARINE MODELS

The 'tripartite' zonation of facies within estuaries, was first described by Van Veen (1936). He recognised the three part sand-mud-sand zonation of facies in the tidally modified Haringvliet Estuary in The Netherlands. This work was largely ignored, however, until Oomkins and Terwindt (1960), Allen (1971) and Dorjes and Howard (1975). Allen (1971), and Dorjes and Howard (1975) recognised the textural variations and attributed the variations to the interactions of fluvial and marine processes. Roy *et al.*(1980), established the wave dominated estuarine model in their work on modern intervals [illegible] coast of New South Wales, Australia. Dalrymple *et al.* (1992) used these works as the basis for their summary of estuarine models. They define two end members of continuum from wave to tidal dominated estuaries. Fluvial processes are an important part of the estuarine system from a sediment supply perspective, but have little effect upon the classification of the estuary (MacE[illegible] and Pemberton, 1994). In a wave dominated estuary, there is a three [illegible] ivision in the distribution of energy (Fig. 18a). Wave energy is high at the mouth of the estuary but dissipates rapidly as it contacts the barrier bar. Energy is also high at the mouth of the river that feeds the estuary. This energy level distribution through the estuary, results in a tripartite zonation of facies, sand-mud-sand, along the length of the estuary (Dalrymple *et al.*, 1992). Tide dominated estuaries are similar in that energy levels are high at the inlet and outlet of the estuary but, because there is no barrier bar, tidal energy is permitted to enter the central portion of the estuary (Fig. 18b). As well, the shape of the estuary (typically funnel shaped), acts to focus and increase tidal energy through the middle portion of the estuary. The overall pattern of energy levels in a tide dominated estuary is therefore, high at both ends and somewhat reduced in the central section. Energy levels in the central portion of a tide dominated estuary, however, is not nearly as reduced as is typically found in the central portion of a wave dominated estuary (Dalrymple *et al.*, 1992). The overall pattern of sedimentation within the estuary is controlled by these energy distributions in the tide dominated case as well. This results in a sediment distribution pattern where the middle fraction is more coarse than would be found in the central portion of a wave dominated system (Dalrymple *et al.*, 1992).

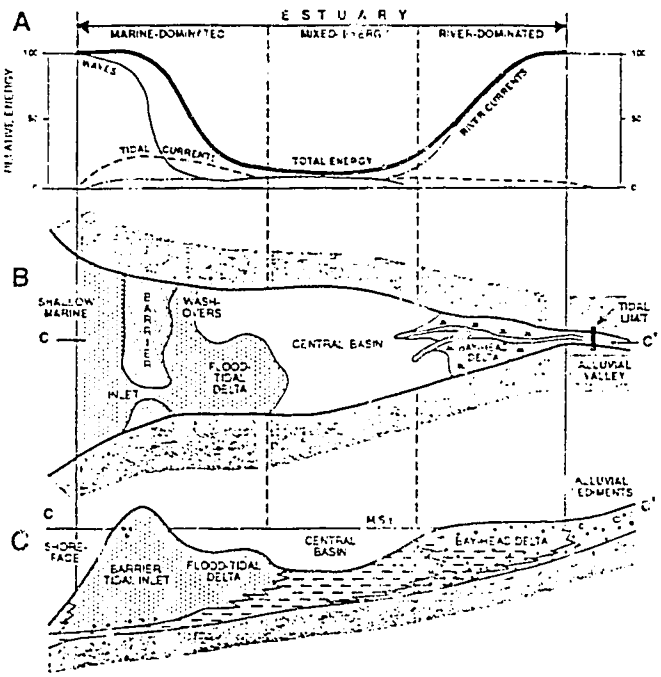


Figure 18 a Distribution of A) energy types, B) morphological elements in plan view, and C) sedimentary facies in cross section within an idealized wave dominated estuary (from Dalrymple *et al.*, 1992). M.S.L. = mean sea level.

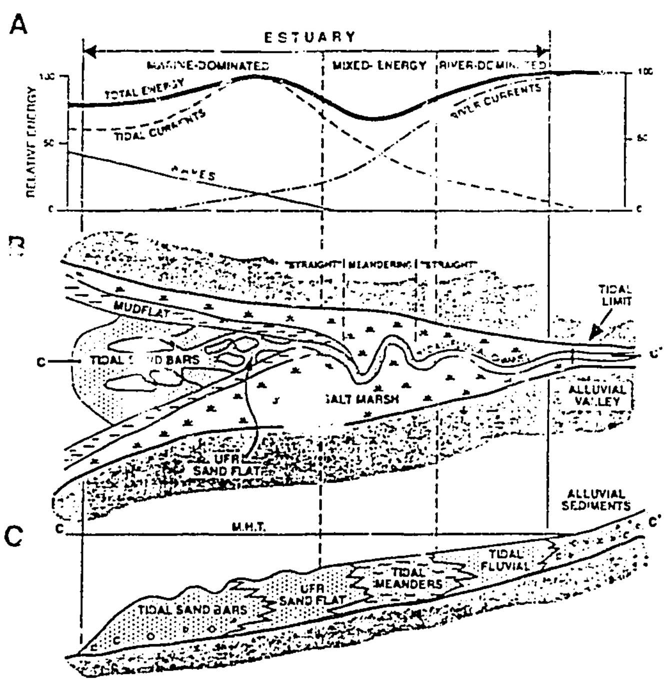


Figure 18 b Distribution of A) energy types, B) morphological elements in plan view, and C) sedimentary facies in cross section within an idealized tide dominated estuary (from Dalrymple *et al.*, 1992). M.S.L. = mean sea level; UFR = upper flow regime.

Fundamental in the definition of estuaries by Dalrymple et al. (1992), is the recognition that estuaries form within incised valleys and that the valleys are filled during transgression. Stewart (1963), was first to recognise the marine influence on an incised valley fill in the W.C.S.B. Stewart (1963) noted the tidal influence on the McMurray Formation in the Cold Lake Alberta area. Since that time several workers such as Rahmani (1988), Beynon *et al.* (1988) and Ranger and Pemberton (1992) have recognised the tidal influence on estuarine deposits in the W.C.S.B. Rahmani (1988) invoked a tidally dominated estuary for the Upper Cretaceous Horseshoe Canyon Formation in the Drummheller Alberta area. Beynon *et al.* (1988) recognised tidal influences on the Lower Cretaceous Grand Rapids Formation in the Cold Lake, Alberta area. Ranger and Pemberton (1992) noted the tidal influence on estuarine point bars in the Lower Cretaceous McMurray Formation in the Athabasca Oil Sands, AB. Wave dominated systems, originally defined by Roy *et al.* (1980), have also been documented in the W.C.S.B. Workers including Pattison (1991) and Reinson *et al* (1988) noted the correlation between the wave dominated model and the facies relationships in the Crystal, Sundance-Edson and Cyn-Pem valley systems. MacEachern and Pemberton (1994) agreed with this correlation and applied ichnology to reinforce the wave dominated interpretation for those valley systems.

The ichnology and sedimentology of the incised valley fill deposits in the Bellshill Lake - Killam area was examined to determine which estuarine model best fit the facies associations present. Facies Associations 2, 3 and 5 (summarised in Tables 2.0, 3.0, and 5.0) are interpreted to be incised valley deposits. FA2 preserves a fairly well developed succession of estuarine environments including fluvial channel, estuarine channel, bayfill and tidal flat deposits. The absence of muddy central basin deposits from FA2 and the predominance of sandy bayfill deposits (Facies 6) as well as tidally generated facies such as the IHS deposits (Facies 11) and tidal flat deposits (Facies 1, 2, 3), strongly suggest that FA2 fits the tide dominated estuary model. FA3 and 5 are dominated by fluvial sandstones with thin tidally generated facies capping them. This suggests that these facies associations also fit in the tidally dominated estuary model. Absence of thicker deposits from the central part of the estuary is likely due to the relatively small scale of the incision event responsible for the existence of FA3 and FA5. The small scale of these deposits reduces both the preservation potential and the possibility of a cored interval through the key deposits in the centre of the estuary, on which the classification is partly hinged. The following chapter places the regional deposits and the incised valley estuarine deposits of the Bellshill Lake - Killam area in a sequence stratigraphic framework and based on this framework, the stratigraphy of the study area is assembled.

CHAPTER 6

STRATIGRAPHY

6.1 INTRODUCTION

The stratigraphy of much of the W.C.S.B., particularly during the Mesozoic Era, has been complicated by episodic fluvial incision. These incision events are interpreted to be due to relative lowstands of sea level and corresponding fluvial down-cutting in response to base level fall. The geomorphic feature resulting from this fluvial incision is called an incised valley (Van Wagoner *et al.*, 1990; Zaitlin *et al.*, 1994). Zaitlin *et al.*, (1994) define an incised valley system as a "fluvially - eroded, elongate topographic low that is typically larger than a single channel form and is characterized by an abrupt seaward shift in depositional facies across a sequence boundary at its base, which is in turn mappable regionally onto the interfluve. The fill typically begins to accumulate during the next base level rise and may contain deposits of the following highstand and subsequent sea level change cycles". Zaitlin *et al.* (1994) outline four criteria for the recognition of incised valleys: i) erosional truncation of underlying strata, ii) the erosion surface at the base of the incised valley is correlateable with the erosion surface on top of the interfluve, iii) there is a basinward shift of depositional facies across the erosion surface at the base of the incised valley, and iv) marker beds within the incised valley onlap the valley walls.

The processes controlling and promoting incision include changes in: i) fluvial base level, ii) increased fluvial discharge and iii) sediment supply (Zaitlin *et al.* , 1994). Lowering of fluvial base level increases the potential energy of the system and promotes fluvial down cutting in order to reestablish equilibrium (Zaitlin *et al.*, 1994).

Base level changes may arise from changes in the volume of water in the basin or changes in the volume of the basin itself (Plint *et al.*, 1992). Revelle (1990) listed the following mechanisms of sea level change: i) ocean steric (thermohaline) volume changes, ii) glacial accretion or wastage iii) liquid water on land (changes in the water budget, and iv) crustal deformation (including lithosphere formation and subduction, glacioisostatic rebound, continental epeirogeny and sedimentation. These mechanisms operate on different scales of time and the relative amount of sea level change that may be initiated by each mechanism. In addition, several of the above mechanisms may operate in concert, obscuring the cause of a particular sea level fluctuation (Zaitlin *et al.* , 1994). In a manner analogous to constructi[illegible]uctive interference of acoustic waves, differing orders of magnitu[illegible] level rise and fall may combine to produce relative lowering of sea level during an overall rise of sea level. Due to these factors, sea level fluctuations are typically described as relative rises or relative falls .

Valley incision may also be initiated by an increase in fluvial discharge. Increased discharge may result from stream capture or climatic change. Either mechanism increases the erosive power of the fluvial system (Zaitlin *et al.*, 1994). Erosive power may also be increased by decreasing the volume of sediment being transported by the fluvial system. Decreased sediment load increases the total energy available for fluvial erosion of the substrate (Zaitlin *et al.*, 1994).

The nature of the substrate also controls valley incision. Substrate coherence and structural trends exert a control on the depth, morphology and location of the incised valley. Unconsolidated to semi-consolidated strata are relatively easily eroded so that valleys incised in these deposits may be deeper than valleys incised into resistant strata (Zaitlin *et al.*, 1994). Semi-consolidated to unconsolidated strata are typically found in exposed shelfal and coastal plain deposits. It should be noted that carbonaceous deposits such as coal are typically present in coastal environments and that these deposits resist fluvial erosion (Zaitlin *et al.*, 1994).

Although all of the factors mentioned above may exert a control on valley incision, lowering of relative sea level is thought to be the dominant force controlling the incision of valleys, particularly in the W.C.S.B. (Zaitlin *et al.* , 1994) In sequence stratigraphic terms, the incised valleys are cut during the lowstand systems tract and filled during the ensuing late lowstand, transgressive and highstand systems tract (Van Wagoner *et al.*, 1990; Zaitlin *et al.* , 1994). The sequence stratigraphic organisation of incised valleys is described in the following section.

6.2 SEQUENCE STRATIGRAPHIC ORGANIZATION OF INCISED VALLEY FILLS

Valley incision and the subsequent fill occurs in response to relative falls and rises of sea level. While this concept is relatively straightforward, complex terminology has developed in order to relate different stages of cut and fill to specific periods of relative sea level rise or fall. This section places incised valleys and their subsequent fill into sequence stratigraphic terms.

Incised valleys develop in response to relative lowering of sea level. Figure 19 i) shows the relative position of the lowstand systems tract (LST) on an idealised sea level curve. In the context of incised valleys, the LST is characterized by valley incision where falling base level results in valley

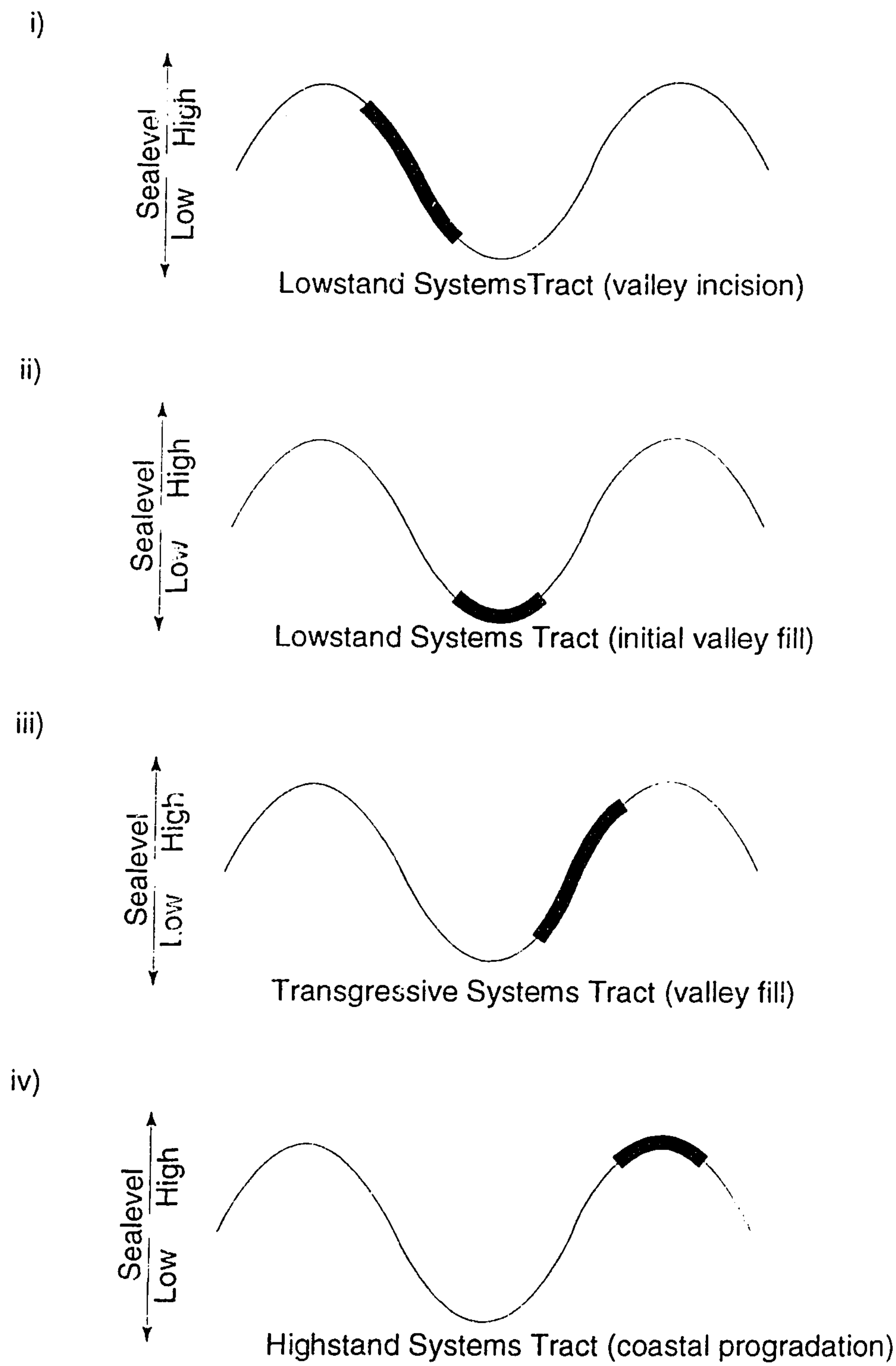


Figure 19.0 Relative sea-level curves with corresponding stages of valley development. After Van Wagoner *et al.*, 1990.

incision and sediment bypass (Van Wagoner *et al.*, 1990; Zaitlin *et al.* 1994). As the rate of relative sea level fall slows and fluvial base level begins to rise (Fig. 19 ii), fluvial deposits begin to aggrade in the valley. These deposits accumulate in the late LST to early transgressive systems tract (TST) (Van Wagoner *et al.*, 1990; Zaitlin *et al.*, 1994). The TST, Figure 19 iii) typically makes up the greater volume of valley fill. Deposits of the TST are typically estuarine in nature, reflecting the interaction of fluvial and marine processes within the incised valley (Zaitlin *et al.*, 1994). As the rate of transgression slows (Fig. 19 iv), a point of maximum transgression is reached and coastal progradation is initiated, filling any remaining accommodation space in the incised valley (Zaitlin *et al.*, 1994). This model suggests that elements of each systems tract (*sensu* Van Wagoner *et al.*, 1990) may be found within the incised valley (Zaitlin *et al.*, 1994).

Compound incised valley fills are also found in the rock record. Compound fills record two or more episodes of valley incision and fill. Such compound valley fills are complex since erosion, associated with later sequence boundary development, may remove all or part of the preceding sequence. Multiple incised valleys commonly result in the juxtaposition of genetically unrelated incised valley facies associations. The Ostracode aged (late Aptian) incised valley in the Bellshill Lake - Killam area is an example of a compound incised valley fill. The following section describes the stratigraphy of the Bellshill Lake - Killam area.

6.3 PROPOSED STRATIGRAPHIC ORGANIZATION

The stratigraphy of the Ostracode Zone in the Bellshill Lake - Killam area is complicated by multiple episodes of valley incision and fill. This section outlines the regional stratigraphy of the Ostracode Zone, the anomalous compound incised valley fill, and the initial deposits of the Glauconitic Member.

The regional Ostracode Zone in the study area represents storm influenced brackish bay and lacustrine deposits (see chapter 4). These rocks were deposited in response to rising base level and concomitant lowering of the coastal gradient associated with the transgression of the Moosebar Sea. In sequence stratigraphic terms, the regional Ostracode Zone was deposited during a second order transgressive systems tract (TST). Maximum extent of the Moosebar Sea was reached during Glauconitic time (early Albian) (Williams and Stelck, 1975; Caldwell, 1984). During this major transgression, however, smaller scale fluctuations in relative sea level resulted in periods of relative sea level lowstand and subsequent erosion. During Ostracode time (late Aptian) there is evidence for at least three relative lowstands of sea level in the study area. The first relative lowstand of sea level resulted in the incision of a 3 - 5 km wide valley through the Bellshill Lake - Killam area. The valley cuts regional Ostracode Zone bay deposits and Ellerslie Formation channel sands and locally rests directly on Paleozoic carbonates. Figure 20 is an isopach map of the interval between a Glauconitic Member flooding surface and the base of the Ostracode Zone. The Glauconitic marine flooding surface is generally regarded to be flat. The isopach map, therefore, can be interpreted to reflect the paleogeography of the base of the Ostracode Zone. Thick values correspond to lows while thin values correspond to topographic highs. Regionally, the Ostracode bayfill deposits are 10 - 20 m thick. Anomalously thick isopachs outline the area where valleys were incised during Ostracode time. Isopach values suggest

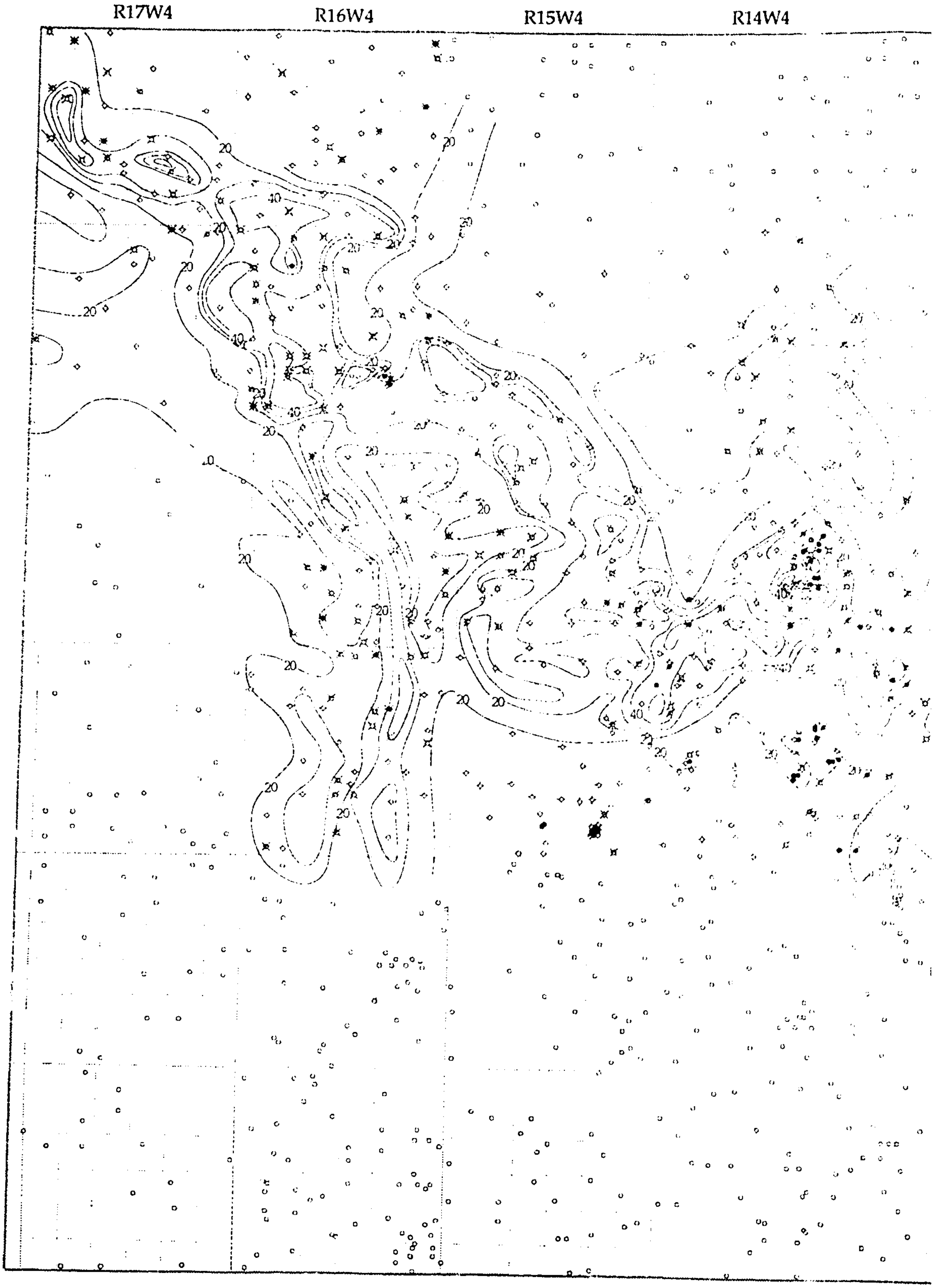
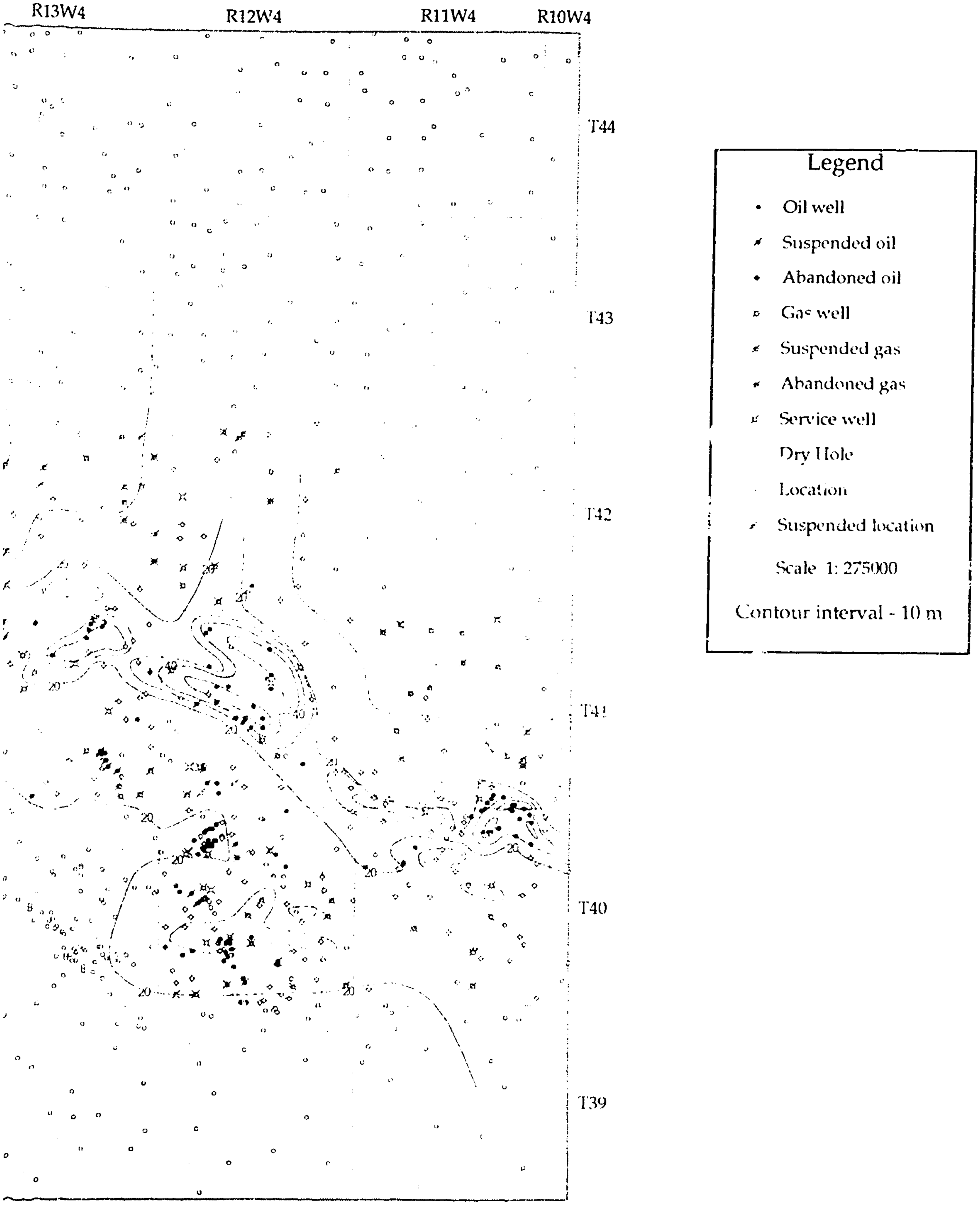


Figure 20.0 Isopach map of the Ostracode Zone along the trend of the valley. Regionally the Ostrac
increaces to 30 - 50 m. Note the pronounced thining of the Ostracode Zone in Range 1



:acode Zone is 10 - 20 m thick . In the valley, the isopach
;e 16 due to Glauconitic aged valley incision.

that the valley is typically 30 - 40 m deep and locally up to 50 m deep. Careful correlation of electric well logs and core lithologs demonstrates that the sequence boundary at the base of the channel correlates to a regional exposure surface represented by a paleosol. Although this sequence boundary was not cored at the base of the channel, the presence of fluvial sandstone overlying Paleozoic carbonates attests to a major unconformity and basinward shift of facies across the boundary. Marker beds within the valley onlap the sides of the valley. The preceding observations fulfil all the necessary criteria for the recognition of incised valley fills, as outlined in section 5.1.

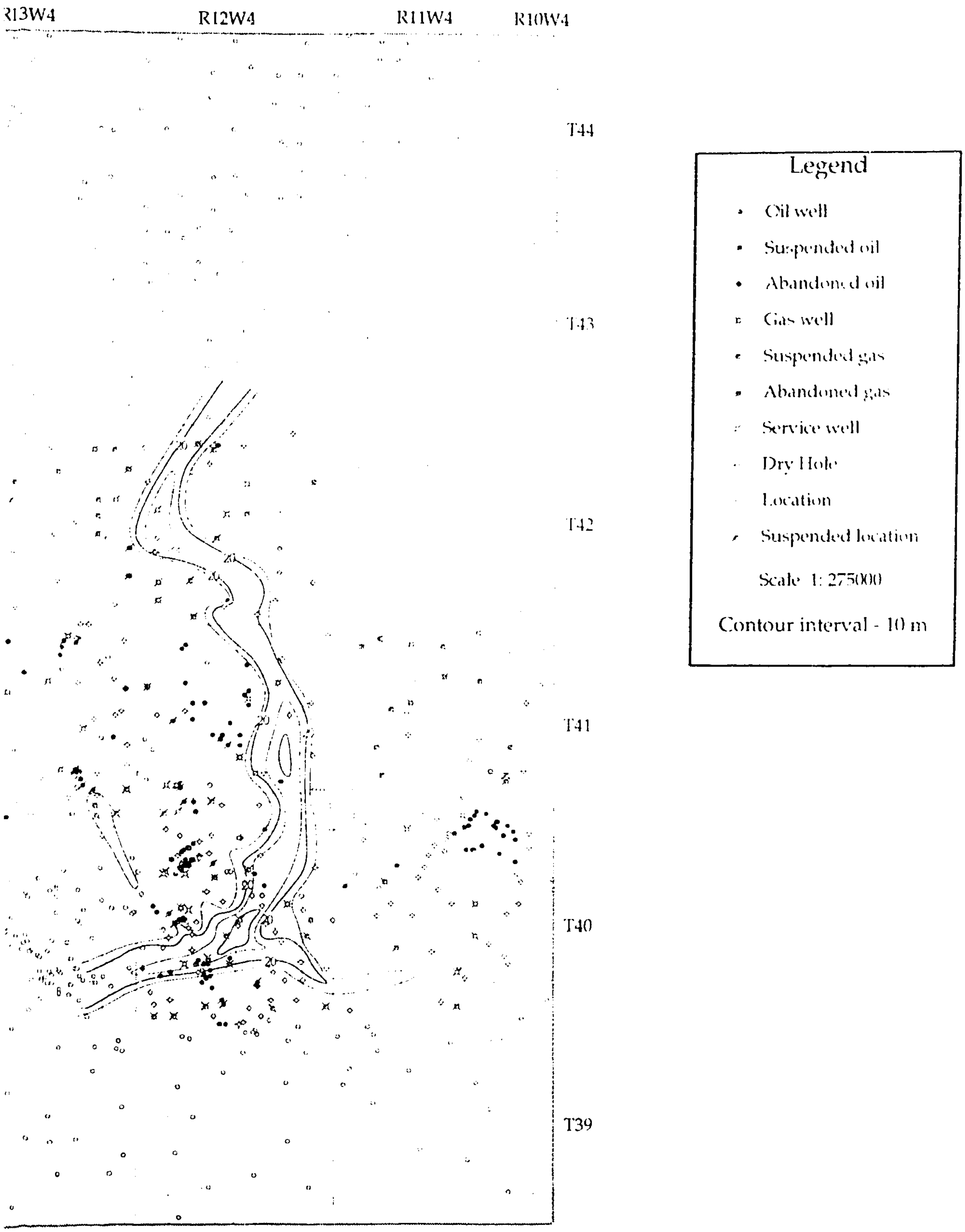
During the ensuing late lowstand and early transgressive systems tract, the initial Ostracode incised valley was partially filled with brackish to fluvial point bar, brackish bayfill and tidal flat deposits. A fully developed and preserved valley fill succession should record elements from each systems tract (Zaitlin *et al.*, 1994). The absence of late transgressive and highstand systems tract deposits from the first incised valley fill suggests that relative sea level did not rise sufficiently to inundate the area and establish barrier bar or shoreface deposits in the study area. Tidal flat deposits in the valley indicate that no additional accommodation space was being created and that the embayed valley was filling. These deposits are therefore interpreted to herald the onset of lowstand conditions.

The second relative lowstand of sea level is represented by the paleosol developed on top of the tidal flat deposits. This paleosol correlates with the base of the second valley incision during Ostracode time (late Aptian). This second episode of relative lowstand incised a sequence boundary into estuarine point bar, bayfill and tidal flat deposits of the previous valley fill succession (FA2). During late lowstand and early transgression, all of the accommodation space created by the second incision was filled by freshwater fluvial sandstone. Continued transgression resulted in the filling of the remaining accommodation space in the main valley and deposition on the interfluve. This fill consists of strata deposited in brackish bay and coal swamp environments. These deposits have a distinctive electric log signature that may be correlated through the study area except where cut out by Glauconitic-aged (early Albian) or later incisions.

Locally, these late stage bayfill and swamp deposits are erosionaly thinned by a third relative lowstand of sea level during Ostracode time (late Aptian). Channels developed during this third lowstand are much smaller (typically 5 - 10 m deep) than the previous two incision events. This may indicate that the lowstand was of shorter duration or it may reflect the competence of the deposits being incised. As mentioned previously, coals and fine-grained deposits are more difficult to erode than coarse-grained deposits. In this case, there is evidence for both controls. The trend in valley size and channel thickness, from the first to last incisions, is towards smaller and narrower valleys and channels. It is likely that both substrate competence and duration of lowstand limited the development of the third incision event. This incision is filled by fresh water fluvial sandstones that aggraded during the late lowstand to early transgressive systems tract. The top of the these fluvial sandstones is typically removed by Glauconitic-aged erosion. Where preserved, these late-stage deposits consist of thin (0.5m) interbedded bayfill deposits. In spite of the relatively small scale of this incision, it fulfils several of the criteria for recognition of incised valleys. These criteria include: i) erosional truncation of underlying strata, ii) the erosion surface at the base of the incised valley is correlateable with the erosion surface on top of the interfluve, iii) there is a basinward shift of depositional facies across the erosion surface at the base of the incised valley and iv) marker beds within the incised valley onlap the valley walls Regional correlation of electric logs and core lithologs suggests that these sandstones represent the last preserved deposits of the Ostracode zone and that the rocks deposited above were laid down after the Moosebar Sea had transgressed the area.

The first preserved deposits of the Glauconitic Member in the study area consist of mud-dominated incised valley deposits. Evidence for a Glauconitic-age (early Albian) for these deposits includes a 90° change in orientation of the drainage pattern compared with Ostracode-aged channels and, where channels are present, they cut the entire Ostracode Zone including the upper channel sandstone described above. Figure 21 is an isopach map of the interval between the first preserved Glauconitic flooding surface and the base of the Glauconitic-aged incised valleys. This map shows the change in orientation of the drainage system that occurred in Glauconitic time, when compared with Figure 20. The sequence boundary at the base of these channels correlates to a paleosol that is developed on the interfluve which includes exposed parts of FA4 and FA5. The first preserved record of fully marine deposits of the Glauconitic Member overly these mud-filled, north-south trending valley complexes and are composed of shaly sandstone with a robust, diverse trace fauna including *Diplocraterion, Cylindrichnus, Teichichnus, Palaeophycus, Planolites,Thalassinoides* and *Ophiomorpha*. Burrowed shaly sandstones overlie a variety of deposits in the study area, as a result of erosion during lowstand and transgression. Shaly sandstones unconformably overlie deposits from FA4 and FA5 of the Ostracode Zone (see Chapter 4) as well as early Glauconitic-aged incised valleys.

Figure 21.0 Isopach map of the initial deposits of the Glauconitic Member. Deposits range in thicknes
deposits.



:ness from 10 - 40 m. Note the north - south orientation of the

The contact between the shaly sandstone and the underlying deposit is demarcated by the development of two styles of penetrative burrows. Development of these two different styles is controlled by the nature of the underlying substrate. Where the shaly sandstone facies overlies exhumed mudstones or interfluve related paleosols, the surface is marked by the development of the *Glossifungites* ichnofacies. Where this surface was developed on sandstones it is recognised by a palimpsest assemblage of trace fossils. The *Glossifungites* ichnofacies is a substrate controlled ichnofacies typically consisting of sharp-walled, unlined burrows that are excavated in a firm, dewatered or exposed substrate (Pemberton and Frey, 1984). In the case of interfluve paleosols the substrate becomes firm during relative sea level lowstand and subaerial exposure, and thus represents a sequence boundary. Burrows excavated in firm substrates maintain their integrity after the burrow is vacated and are subsequently passively infilled by overlying deposits (MacEachern *et al.*, 1992) (Fig. 22 a). Where the shaly sandstones overlie sandy deposits, the hiatus is recognised by a palimpsest suite of traces fossils (Fig. 22 b, c).

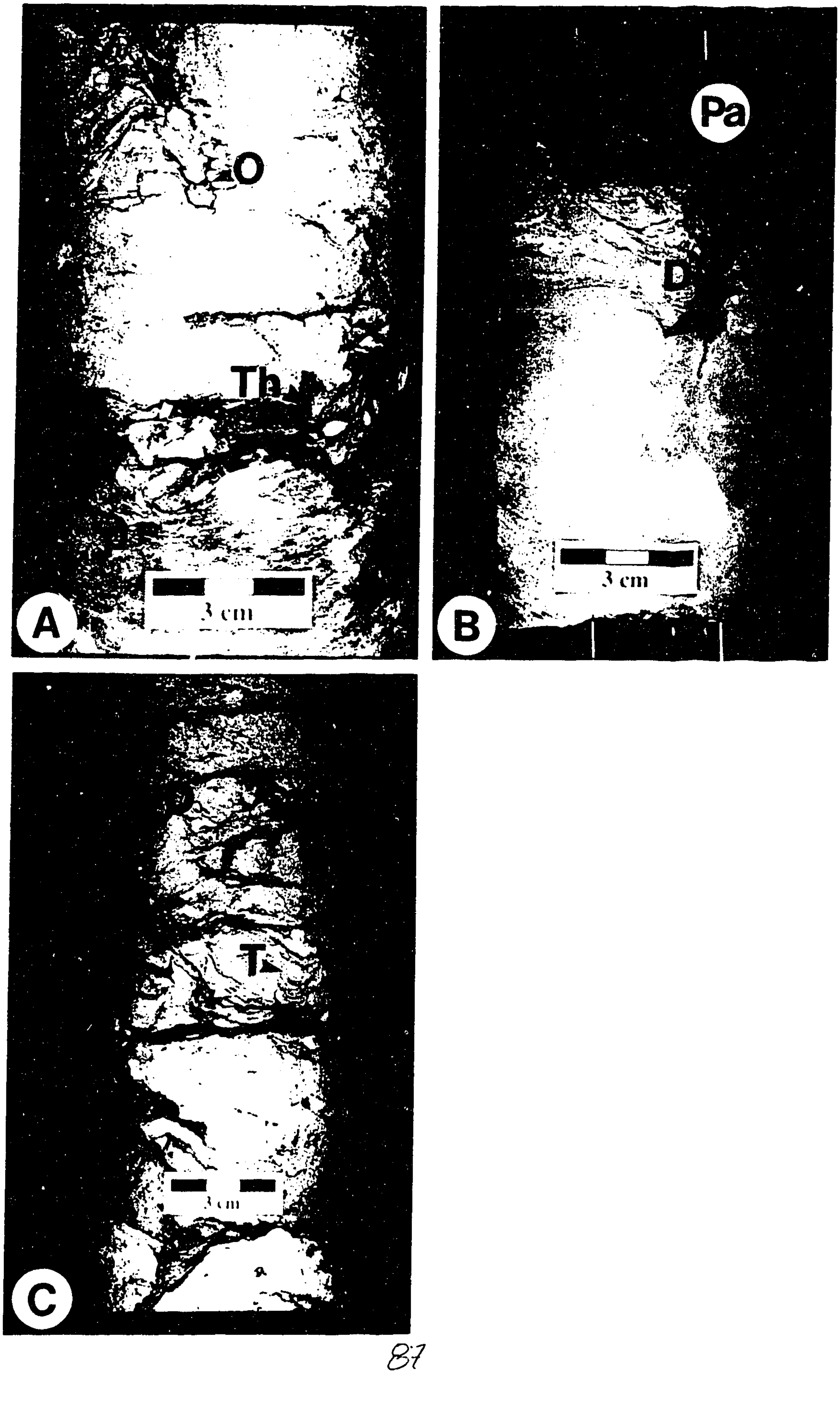
In contrast to mud dominated deposits, sandy substrates are not typically consolidated by simple dewatering associated with lowstand of relative sea level. In order for sandy deposits to become stiff they must typically be cemented by some agent such as calcite or siderite. In the study area, sandstones underlying sandy shale deposits were not cemented prior to exposure. Instead, the hiatus between deposition of the burrowed sandy shale and underlying sandstone is marked by a palimpsest assemblage of trace fossils which are not substrate-controlled. The assemblage cross cuts ubiquitously the underlying, soft ground, burrow suite. Burrow fill is clearly

Figure 21 Ostracode Zone/Glauconitic Member contact.

(A) *Glossifungites* ichofacies at the Ostracode/Glauconitic contact. Ichnofacies consists of *Thalassinoides* burrows subtending into a paleosol mudstone (p) that was firmed by subaerial exposure due to a relative lowstand of sea level. *Ophiomorpha* (O) in the overlying sandstone may be related to the *Thalassinoides* burrows colonising the omission surface. The difference in burrow morphology may reflect a change in behaviour (ie, lining the burrow with mud) to accomodate the shifting, unconsolidated substrate of the sandstone at the top of the photo. From 11-33-41-14W4 depth 948.1m.

(B) Palimpsest trace fossil assemblage at the Ostracode/Glauconitic contact. In this photo, the omission surfaces is developed on a sandy substrate that was not lithified prior to exposure. the hiatus between the sandstone and the overlying shaley sandstone is marked by a palimpsest assemblage of trace fossils (*Diplocraterion* (D) and *Palaeophycus* (Pa)) which are not substrate controlled. This assemblage cross cuts the underlying soft ground suites. The burrow fill is clearly related to the overlying shaley sandstone, highlighting the discontinuity since the palimpsest assemblage is penecontemporaneous with the discontinuity. From 6-27-41-13W4 depth 3013 ft. (918.4m).

(C) This photo is of the same omission surface in a different location. The palimpsest assemblage in this photo consists of *Diplocraterion* (D) and *Teichichnus* (T). From 10-21-42-14W4 depth 3135.5 ft. (955.7m).


O
Th
3 cm
A
Pa
D
3 cm
B
T
3 cm
C

related to the overlying deposit, highlighting the discontinuity (Bromley, 1975) since the palimpsest assemblage is penecontemporaneous with the discontinuity. These surfaces accentuate the stratigraphic complexity of the of the initial deposits of the Glauconitic Member in the Bellshill Lake - Killam area.

CHAPTER 7
SUMMARY

7.1 SUMMARY

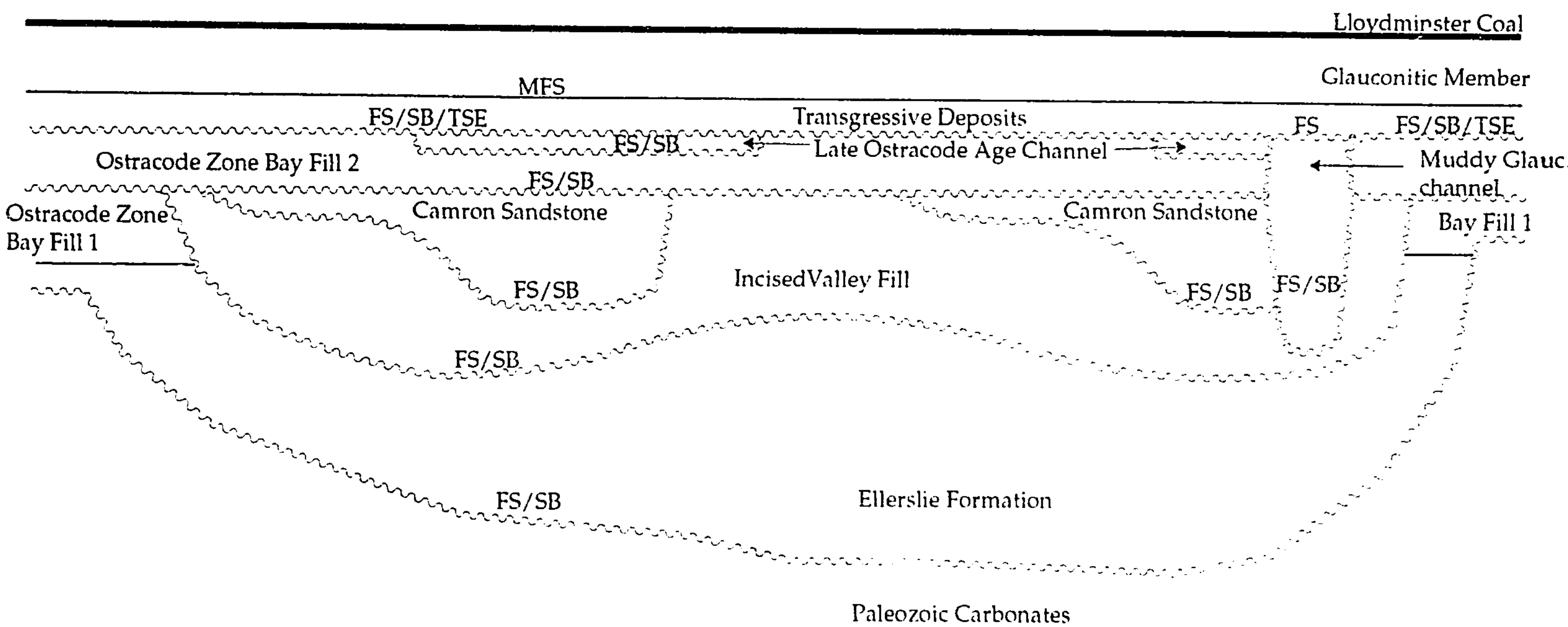
The study area is located in the Bellshill Lake - Killam area of east - central Alberta (TWP 39 - 44 Rng 11-17). The interval of interest is the Lower Cretaceous Ostracode Zone. The database used in this study consists of geologic tops information from 1640 geophysical well logs and detailed sedimentologic and ichnologic descriptions of 45 drill core through the zone of interest. Application of ichnology in conjunction with conventional sedimentologic analysis has proven to be a powerful tool for reconstructing paleoenvironments. An integrated approach combining ichnology, sedimentology and stratigraphy was employed in this study.

The Ostracode Zone and its equivalents represent the last stages of Lower Mannville Group deposition. Regionally, the zone was deposited in response to lowering of coastal gradient and the development brackish bays associated with the transgression of the Moosebar Sea. Locally, however, the Ostracode Zone contains thick sandstone deposits which developed in response to fluvial incision initiated by relative sealevel lowstand. Placement of these sandbodies was controlled and localised by lows on the paleotopography of the sub-Cretaceous unconformity.

A total of 13 facies were described in the Ostracode Zone in the Bellshill Lake - Killam area. These facies are dominated by interbedded sandstones and shales, sandstones, coals, limestones and paleosols with a restricted ichnofossil assemblage. These facies were group into five associations of genetically-related facies. Facies association 1 (FA1) comprised the initial bayfill succession of the regional Ostracode Zone. FA1 is interpreted to be deposited as a series of stacked bayfill and abandonment deposits. FA2 comprises the fill of the first incised valley. FA2 consists of fluvial pointbar, estuarine pointbar (IHS), bayfill, tidal flat and abandonment deposits. FA3 represents the fill of the second incised valley, cut during a second relative lowstand sealevel and consists of fluvial sandstones and minor bayfill deposits. FA4 represents the second succession of regional Ostracode Zone bayfill deposits and is dominated by coal swamp, and lacustrine deposits. FA5 comprises the fill of the third and last incised valley that is cut during Ostracode time and consists of fluvial sandstone.

Classification of estuarine deposits into tidal or wave dominated can be made based on the elements present in FA2, 3, and 5. Absence of typical wave dominated facies, such as muddy central basin mudstones, from these facies associations, and the predominance of sandy bayfill deposits (Facies 6) as well as the presence of tidally generated IHS deposits (Facies 11) indicate that these estuaries are tidally dominated.

The depositional history of the Ostracode Zone in the study area begins with the deposition of regionally extensive bayfill and abandonment deposits (FA1), in response to the transgression of the Moosebar Sea. During Late Aptian time, a fall in relative sea level resulted in the incision of a fluvial valley through the study area. This incised valley removed the regional succession and rests on the Ellerslie Formation. Locally, the base of the valley rests directly on Paleozoic carbonates. This north-west - south-east trending valley was subsequently filled during the next relative rise in sea level by FA2. This incised valley fill was, inturn, incised by the next relative lowstand valley incision. FA3 fills the second valley incision event during



FS - Flooding Surface
SB - Sequence Boundary
TSE - Transgressive Surface of Erosion
MFS - Maximum Flooding Surface

Figure 23.0 Idealised cross section showing the stratigraphic organisation of the Ostracode Zone and the initial deposits of the Glauconitic Member.

the next episode of relative sea level rise. Continued transgression results in the deposition of FA4, a second regional bayfill succession. This regional succession was cut by the last episode of lowstand fluvial incision to be preserved in the Ostracode Formation. Renewed transgression resulted in the deposition of FA5. The stratigraphy of the Ostracode Zone in the study area is summarised in a generalised cross section showing the relative stratigraphic positions of these facies associations (Fig. 23).

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