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SEDIMENTOLOGY AND ICHNOLOGY OF BRACKISH WATER DEPOSITS IN THE BLUESKY FORMATION AND OSTRACODE ZONE, PEACE RIVER OIL SANDS, ALBERTA

BY
STEPHEN MICHIAL HUBBARD ©

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

DEPARTMENT OF EARTH AND ATMOSPHERIC SCIENCES

EDMONTON, ALBERTA

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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 **SEDIMENTOLOGY AND ICHNOLOGY OF BRACKISH WATER DEPOSITS IN THE BLUESKY FORMATION AND OSTRACODE ZONE, PEACE RIVER OIL SANDS, ALBERTA**, SUBMITTED BY STEPHEN MICHIAL HUBBARD IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Dr. S. George Pemberton – Supervisor

Dr. Charles R. Stelck

Dr. H. Edward Clifton

Dr. W. G. Evans

Date: Sept. 27, 1999

ABSTRACT

The Peace River Oil Sands deposit was studied in order to gain an understanding of facies relationships and reservoir distribution in the area of highest bitumen saturation. The deposit, as a whole, is economically significant as it contains greater than 100 billion barrels of heavy oil in place. A detailed facies study focused on the Bluesky Formation and Ostracode Zone as exploitable bitumen reserves at Peace River are contained predominantly within these units. The interpreted depositional framework shows a transgressive evolution from a brackish bay system (Ostracode Zone) into a marginal marine, wave-dominated estuarine complex (Bluesky Formation).

Estuarine facies models have evolved significantly over the past decade, proving to be helpful in identifying numerous ancient deposits. The Bluesky Formation in the Peace River area, and modern and Pleistocene deposits from Willapa Bay, Washington were compared in order to demonstrate similarities common amongst various estuarine deposits.

ACKNOWLEDGEMENTS

This thesis could not have been completed without the support of numerous people and organizations. First of all, I'd like to thank George Pemberton for his guidance and friendship over the past few years; he always went above and beyond providing everything I ever needed to get my work finished. As well, his Ichnology Research Group provided an excellent place to learn, discuss ideas and have fun. I'm thankful to all the members of the group for their support, especially Murray Gingras who was a constant help in the preparation of this thesis, and John-Paul Zonneveld for getting me involved as an undergraduate student. Jason Lavigne was especially helpful during the final preparation of the thesis when we were just trying to figure out how to put it all together!

Financial and technical support for the thesis was provided by Shell Canada Limited. I am thankful to Lorie Cooper, Larry Marks and Felix Frey for helping to get the project started. Summer work in 1998 with the Peace River team greatly enhanced the results of the thesis; in particular, Mark Thomas and Sheri Bechtel are recognized, as is Ed Howard (R.N. Dell Energy, Calgary) who was a contract geologist with Shell during that time. I am grateful of all their efforts on my behalf. Personal funding was graciously provided by the University of Alberta, the Department of Earth and Atmospheric Sciences at the U of A, and the Natural Sciences and Engineering Research Council of Alberta.

Dr. Charles R. Stelck was an invaluable source of knowledge, especially in the initial stages of the project while I was getting familiar with Lower Cretaceous litho- and bio- stratigraphy. Dr. Brian Jones contributed significantly in the direction and preparation of the Appendix of the thesis. I'm also thankful to the members of my thesis defense committee for reviewing my work, including George, Dr. Stelck, Dr. Ed Clifton and Dr. George Evans.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 - INTRODUCTION

Major oil sand deposits, including Athabasca, Cold Lake and Peace River, are found in Lower Cretaceous strata of northern Alberta (Fig. 1.1). The Peace River deposit comprises bitumen-rich sands from the Aptian/Albian Gething Formation, Ostracode Zone, and Bluesky Formation, which overlay Paleozoic and older Mesozoic strata. As the deepest of Alberta's economically significant heavy oil deposits, the Peace River deposit is also the most understudied. Unlike the giant Athabasca Oil Sand Deposit of eastern Alberta, the Peace River Oil Sands are restricted to the subsurface and in-situ production is the only means of recovering the massive amount of bitumen. Lower Cretaceous sediments of the Ostracode Zone and Bluesky Formation contain the majority of economically important bitumen reserves (Hubbard *et al.*, 1999). These units, along with those of the underlying Gething Formation, contain approximately 88 billion barrels of heavy oil (Alberta Energy and Utilities Board, 1997). Lithostratigraphically equivalent units from across Western Canada are commonly tar-bearing (Fig. 1.2).

The study was initiated in order to attain a thorough understanding of depositional environments associated with the deposits of the stratigraphic interval of interest at Peace River. Although current bitumen production and industry research focuses within a localized region of the deposit (Township 85-18W5), the depositional history of the lowermost Cretaceous study interval could not be resolved on this scale. A more regional study area was necessary to discern the complex depositional history. The understanding of facies distribution and thicknesses has direct implications on the understanding of reservoir geometry across the study area.

The overall Lower Cretaceous depositional framework in the Peace River area shows a transgressive sedimentologic evolution beginning with the Gething Formation which consists predominantly of fluvial/non-marine deposits. As fluvial deposition waned, a large brackish-water basin formed over the region during which time deposits of the

Fig. 1.1. The distribution of major Lower Cretaceous oil sand deposits in Alberta.

Ostracode Zone accumulated. Finally, as the Boreal Sea inundated the region from the north, marginal marine, wave-dominated estuary/barrier-bar sediments of the Bluesky Formation were deposited (Hubbard and Pemberton, 1999). The Lower Cretaceous sedimentary package was deposited on the sub-Cretaceous unconformity in the study area. Jurassic, Triassic, Permian and Mississippian strata subcrop beneath Lower Cretaceous deposits in the Peace River region. Depocenters where the thickest Lower Cretaceous sediments are located coincide with lows on the underlying unconformity surface. In some cases, lows in the unconformity surface appear to be related to faults associated with the Peace River Arch (Hubbard *et al.*, 1999). Subsequent to deposition,

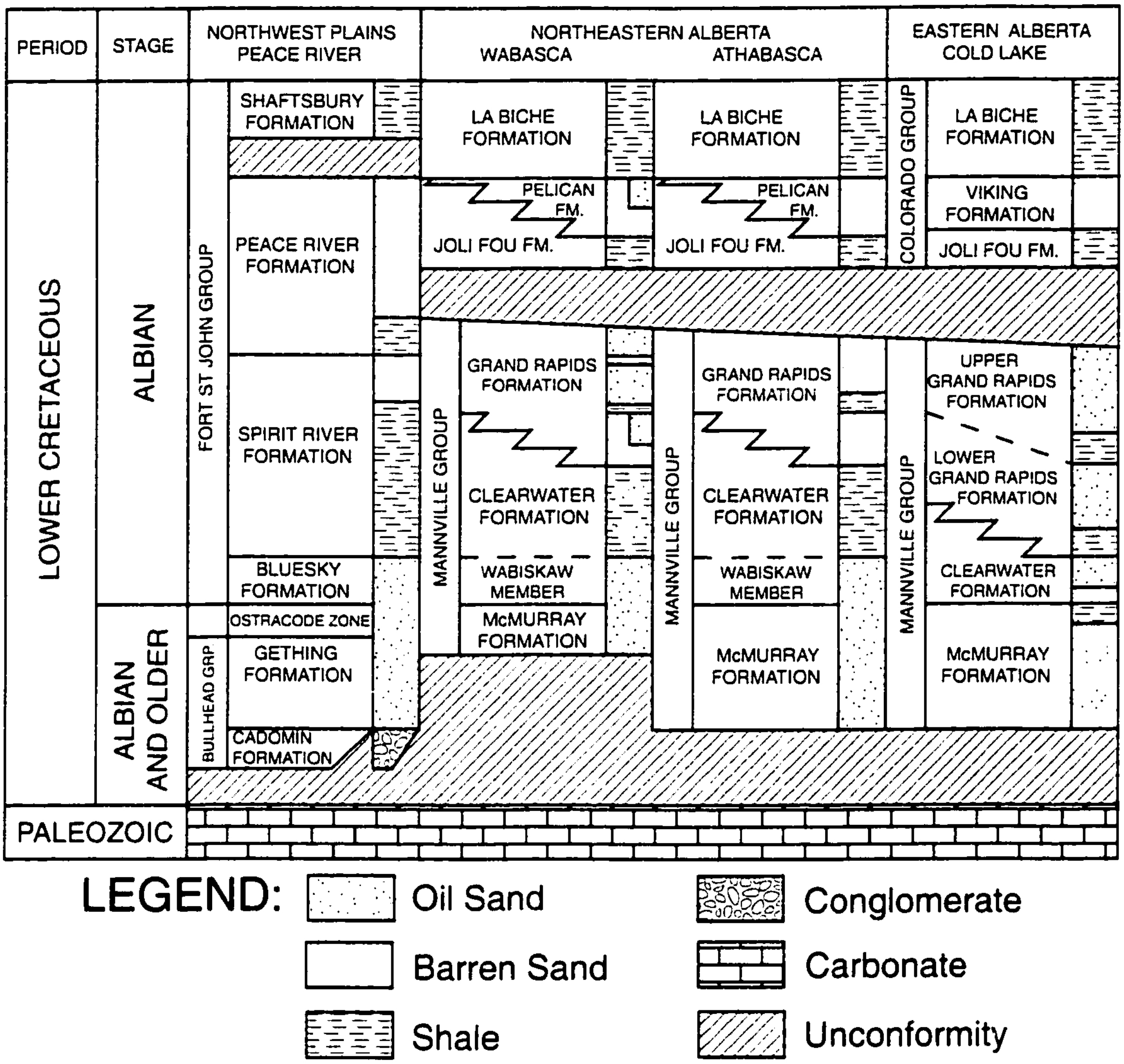

Fig. 1.2. Lower Cretaceous correlative stratigraphy and distribution of oil sand bearing intervals: Western Canada Sedimentary basin. Not to scale (modified from Mossop *et al.*, 1980).

faulting has also been shown to affect reservoir distribution and configuration.

During the past two decades, numerous workers have developed facies models for various types of estuarine environments (Roy *et al.*, 1980; Clifton, 1982; Reinson, 1992; Dalrymple *et al.*, 1992). These models have evolved significantly over the past decade, proving to be helpful in identifying numerous ancient estuarine deposits (Zaitlin and Shultz, 1990; Pattison, 1992; MacEachern and Pemberton, 1994; Broger *et al.*, 1997; Lessa *et al.*, 1998; Hubbard *et al.*, 1999). Idealized facies models are broad in definition and often recognizing variations on the idealized situations can be difficult. Estuarine deposits are highly variable and in core-based studies they are often overlooked or misinterpreted as a result.

The Bluesky Formation in the Peace River area, and modern and Pleistocene deposits from Willapa Bay, Washington were compared and contrasted in order to show similarities common amongst estuarine deposits. Despite fundamental differences between the deposits such as tectonic setting and tidal influence, sedimentological similarities are often apparent. From an ichnological perspective, the diversity, size and abundance of trace fossils typically decreases with increasing brackish water towards the upper estuary. The effect of brackish water on benthic organisms in estuaries and the subsequent signature in deposits throughout the rock record is understood and applicable to many estuarine deposits (Dorjes and Howard, 1975; Wightman *et al.*, 1987; Pemberton and Wightman, 1992; Gingras *et al.*, 1999).

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CHAPTER 2 – REGIONAL GEOLOGY AND SEDIMENTOLOGY OF THE BASAL CRETACEOUS PEACE RIVER OIL SANDS DEPOSIT, NORTH-CENTRAL ALBERTA[1]

INTRODUCTION

Eighty-eight billion barrels (14,040 x 10^6 m^3) of heavy oil (<10 API) are contained within the basal Cretaceous section at Peace River, Alberta (Alberta Energy and Utilities Board, 1997). Despite the massive size of this reserve, the Peace River deposit is the least studied of Alberta's giant oil sand deposits (Table 2.1; Fig. 2.1). The Gething Formation, Ostracode Zone and Bluesky Formation, latest Aptian to early Albian in age, consist of siliciclastic sediments deposited unconformably on Paleozoic and, locally, older Mesozoic strata as the Boreal Sea inundated the region from the north. Lithologically equivalent units are correlatable across the Western Canada Sedimentary Basin (Fig. 2.2).

The main objectives of this paper are to document the geology of the Peace River Oil Sands, and to establish a depositional model that explains reservoir distribution in the area of richest bitumen saturation (Fig. 2.1). Other objectives include an understanding of the effects of tectonics and basin paleotopography on lowermost Cretaceous sedimentation and reservoir distribution.

Sedimentological analyses reveal a three-stage depositional history throughout the study interval (Hubbard and Pemberton, 1999). From a lithostratigraphic perspective, the Gething Formation was deposited within a fluvial/non-marine system, the Ostracode Zone within a brackish bay and associated sub-environments, and the Bluesky Formation within a complex estuarine environment. The Bluesky Formation is overlain by marine mudstones of the Wilrich Member (Spirit River Formation), which

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[1] A version of this chapter has been published. Hubbard, S.M., Pemberton, S.G., and Howard, E.A. 1999. Regional geology and sedimentology of the basal Cretaceous Peace River Oil Sands deposit, north-central Alberta. Bulletin of Canadian Petroleum Geology, v. 47, p.270-297.

Deposit	Areal Extent (10^3 Ha)	Bitumen In Place ($10^9 m^3$)	(10^9bbls)
Bluesky/Gething (L. Cretaceous)	1153	14	88
Belloy (Permian)	26	0.3	1.8
Debolt (Mississippian)	302	7.8	49
Shunda (Mississippian)	143	2.5	15.8
	Total:	**24.6**	**154.6**

Table 2.1. Bitumen reserves of the Peace River Oil Sands deposit.

represent the maximum transgression of the Boreal Sea in the basal Cretaceous sequence at Peace River (Cant and Abrahamson, 1996). The lowermost Cretaceous sedimentary package pinches-out to the north on Mississippian carbonates (Fig. 2.3).

The Peace River Oil Sand deposit is positioned in proximity to the axis of the Peace River Arch (Fig. 2.4), which is a well-documented basement structural feature that has significantly influenced the structure and deposition of overlying Paleozoic and Mesozoic rocks (Williams, 1958; Stelck, 1975; Cant, 1988; Hart and Plint, 1990; Donaldson *et al.*, 1998). Detailed analysis of the basal Cretaceous section at Peace River shows that sedimentation was, and subsequently reservoir distribution has been, locally influenced by faults associated with this feature.

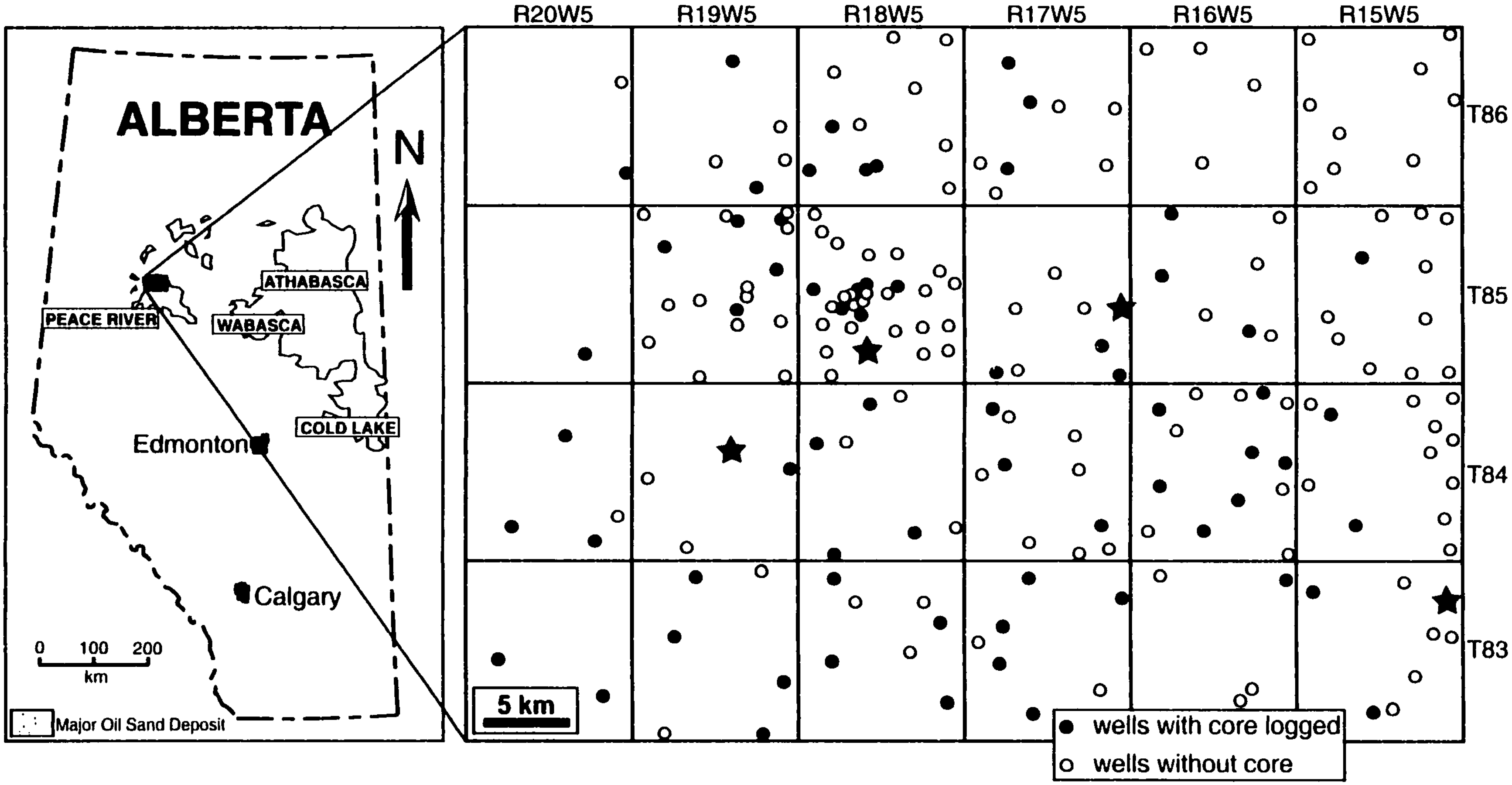


Fig. 2.1. The heavy oil deposits of Alberta including the Peace River Oil Sands study area. Wells utilized in the study are indicated; stars represent the location of wells with cores described in this paper (Figs. 2.5,2.12-2.14).

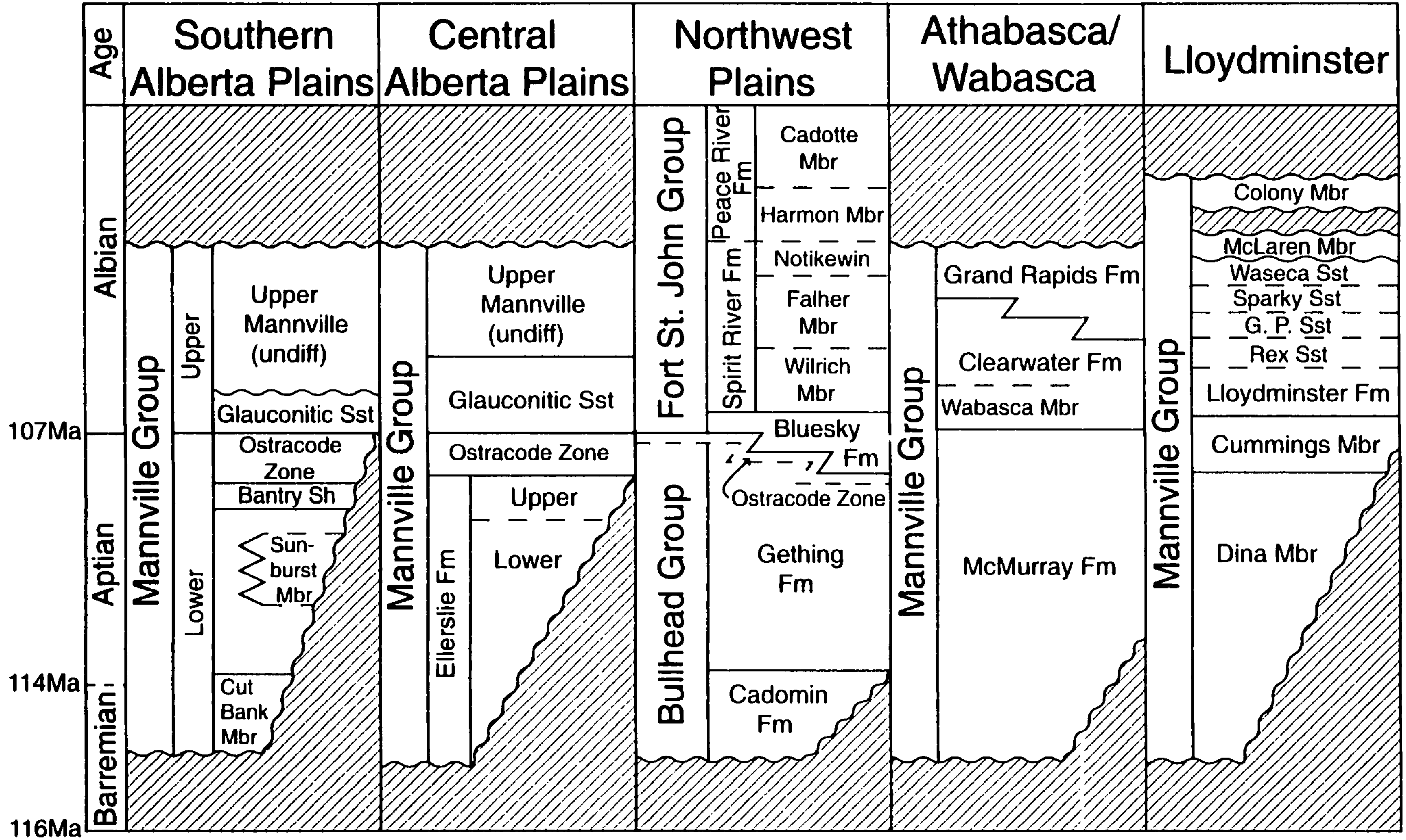


Fig. 2.2. Subsurface Lower Cretaceous correlative stratigraphy of the Western Canada Sedimentary Basin (modified from Smith, 1994).

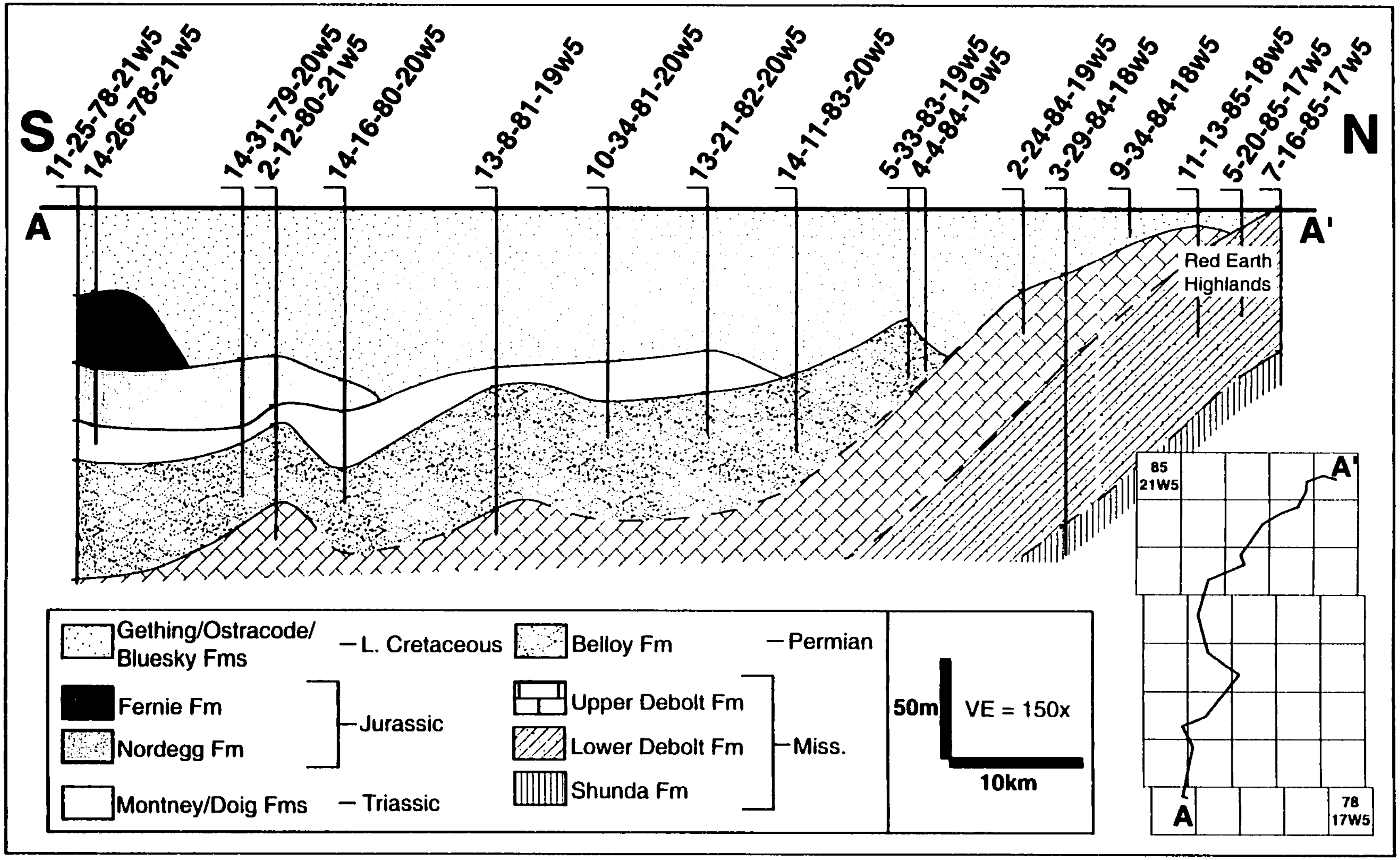


Fig. 2.3. Regional cross-section showing the unconformable relationship between Lower Cretaceous deposits, and underlying Paleozoic and early Mesozoic strata.

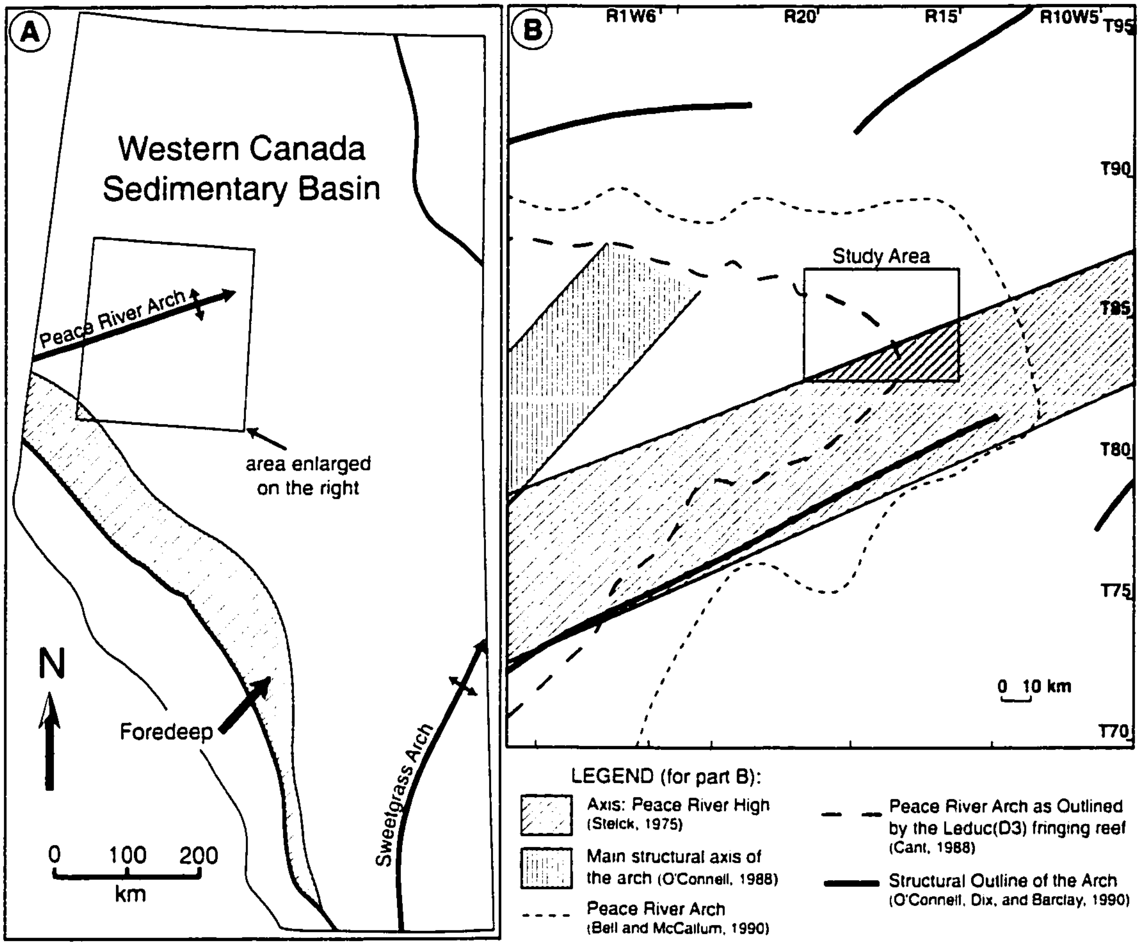


Fig. 2.4. a) Major tectonic elements of Alberta during Mannville time (modified from Hayes *et al.*, 1992). **b)** Location of various features associated with the Peace River Arch as documented in recent literature.

PEACE RIVER OIL SANDS RESERVOIR

HISTORY AND RESERVOIR CHARACTERISTICS

Discovered in the 1950's, the Peace River Oil Sand deposit is located exclusively within the subsurface, averaging 550m in depth. The total area of the deposit spans greater than 6200km^2, containing >150 billion barrels of bitumen in place (Table 2.1). Although Permian sandstones and Mississippian carbonates contain significant reserves, at this time recoverable bitumen is restricted to Lower Cretaceous sediments and thus this paper only considers these deposits. Pilot projects initiated by Shell Canada in the

1970's and early 1980's led to commercial production of bitumen in 1986. Production of the <10 API gravity bitumen has relied on constantly evolving steaming techniques such as Steam Assisted Gravity Drainage (SAGD) and cyclic steam injection.

Research and development of the deposit over the last twenty years has been focused within Township eighty-five West of the Fifth Meridian. In the development area, net pay averages 20 to 30m in thickness, with sandstone porosity averaging 28 % and gas permeabilities (after bitumen extraction) ranging from 1 to 4 darcies. Bitumen saturation averages 77% and can reach up to 88%.

RESERVOIR GEOLOGY

A typical well from the development area at Peace River is depicted in Figure 2.5. Exploitable bitumen reserves at Peace River are contained predominantly in estuarine (tidal deltaic) sands of the Bluesky Formation. Although the Ostracode Zone at Peace River is a mud-dominated interval, localized fluvio-deltaic sandstones may be critical to the future development of the deposit. Often these sandstones are of excellent reservoir quality. When overlain by estuarine sandstones of the Bluesky Formation, net sand can reach up to >30m in thickness (Fig. 2.6). Depocenters where the thickest Lower Cretaceous sediments are located coincide with paleo-lows on the underlying Mississippian surface (Fig. 2.7).

The reservoir at Peace River represents a large stratigraphic trap enhanced by a regional structural dip of strata to the southwest created by orogenic accretionary events. It is encased by: (1) an up-dip seal created by the pinch-out of onlapping sandstones onto low-permeability carbonates of the Mississippian Highlands to the north and east; (2) a top-seal due to deposition of basinal shales of the Wilrich Member overtop of the Bluesky Formation; and (3) a lateral seal to the east-southeast consisting of estuarine mudstones. It should be noted that in places, underlying carbonates contain vast amounts of bitumen (Table 2.1). They are not a true bottom-seal to the reservoir,

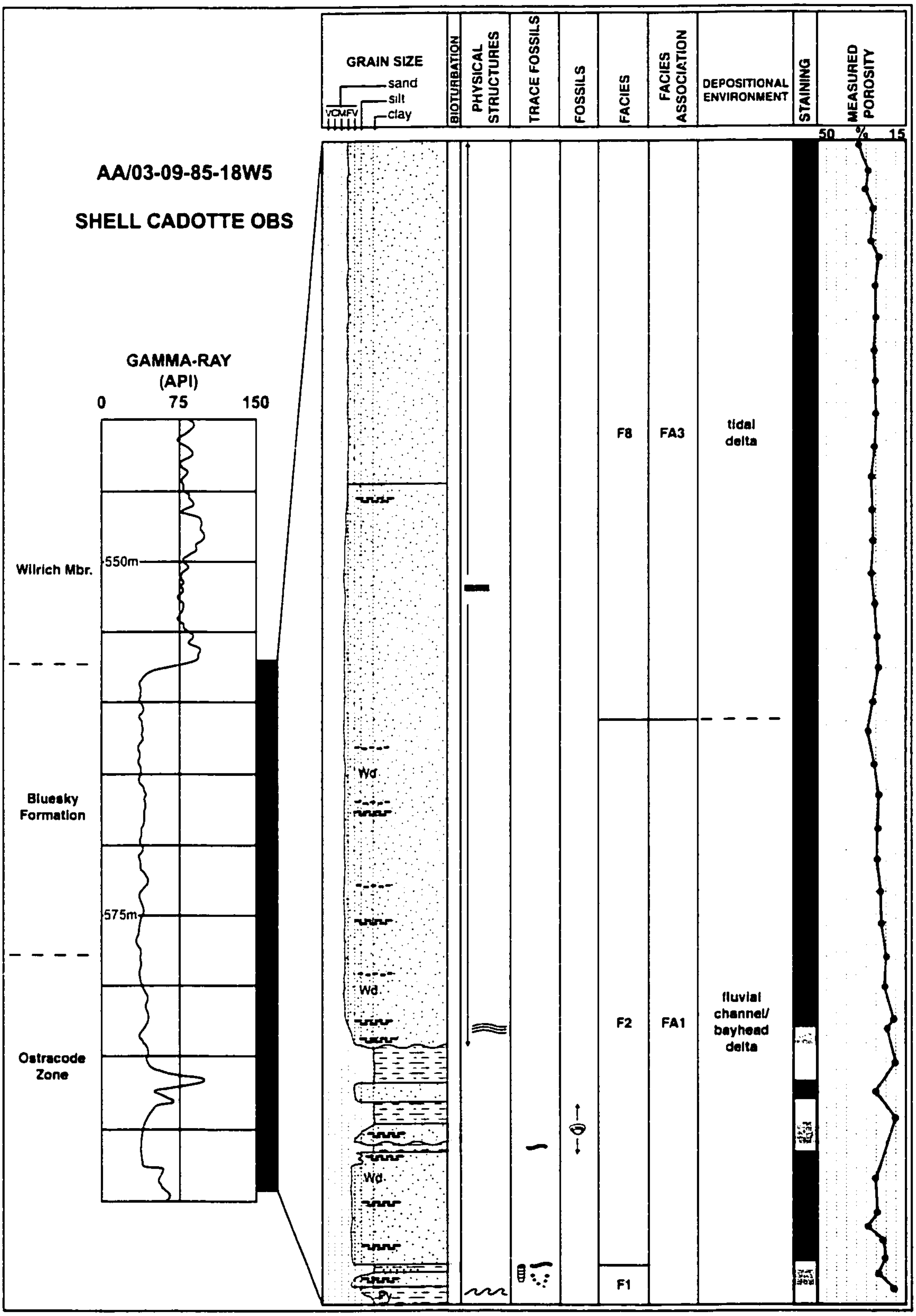


Fig. 2.5. A characteristic well (03-09-85-18W5) from the development area at Peace River. See Table 2.3 for a legend to the symbols used. Well-location is shown on Figure 2.1.

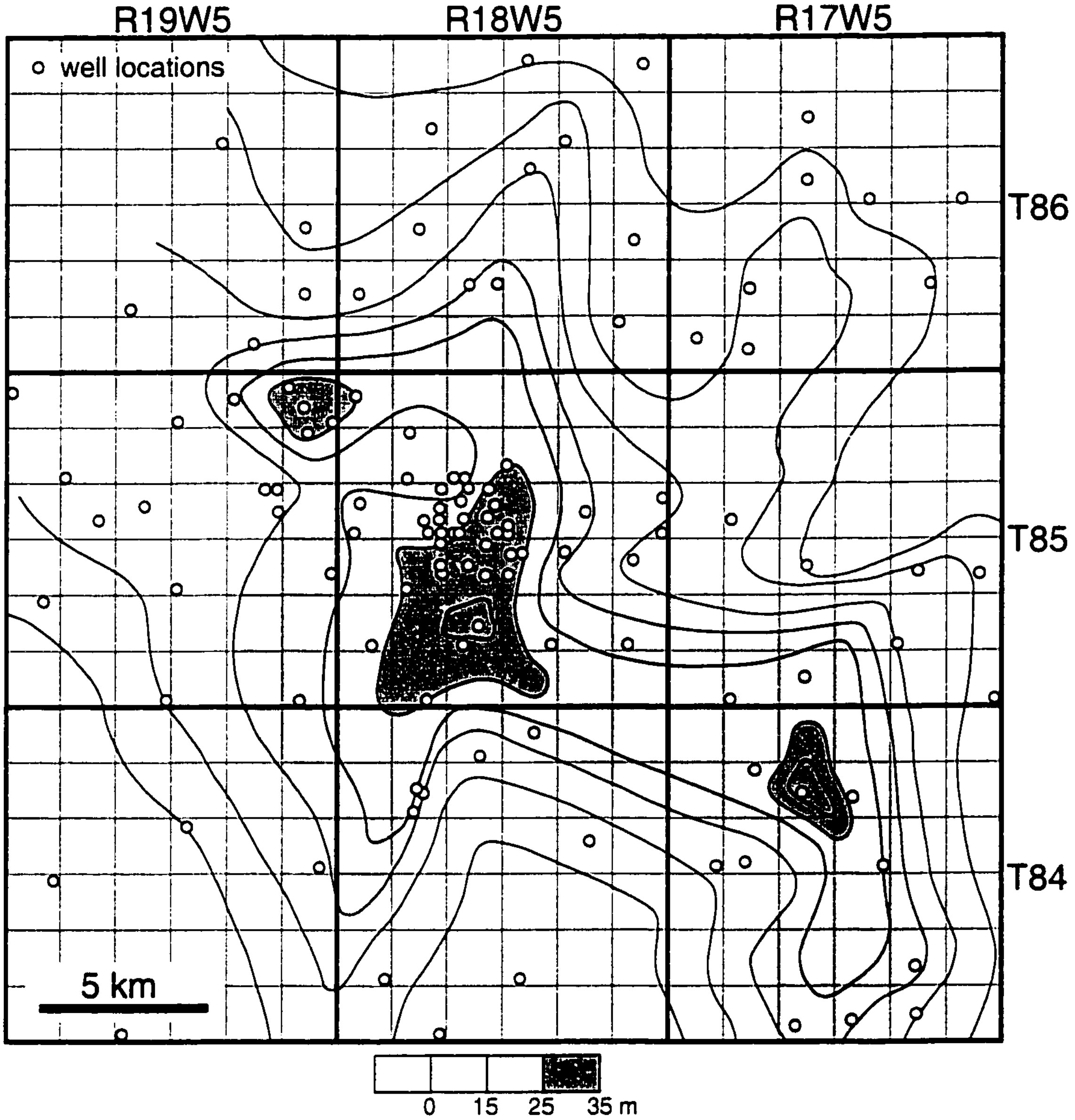


Fig. 2.6. Combined net (continuous) sand map of the Bluesky Formation and Ostracode Zone in the Peace River Oil Sands area. Wells utilized in constructing the map are delineated by the white circles. Contour interval = 5m.

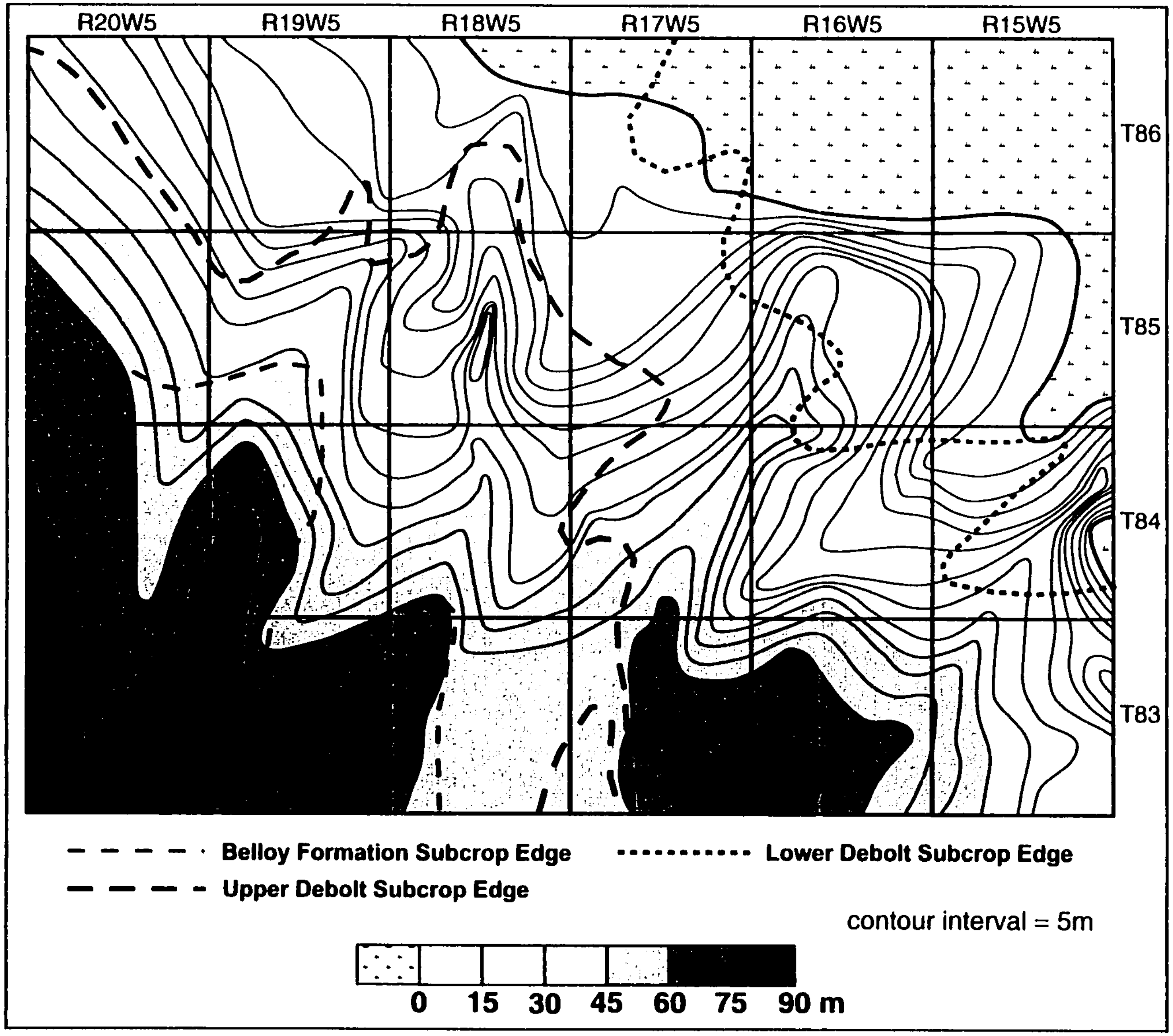


Fig. 2.7. Isopach map of the Lower Cretaceous Gething Formation, Ostracode Zone and Bluesky Formation, demonstrating the paleotopography on the sub-Cretaceous unconformity. Location of the sub-crop edges of underlying strata are delineated.

however as saturated units they have a similar effect on the oil sand reservoir.

The source of the massive amounts of bitumen present in Alberta is debatable (Creaney and Allen, 1990,1992; Brooks *et al.*, 1988; Riediger *et al.*, 1990). Bitumen at Peace River likely originated in the deep basin to the southwest, migrating up-dip to its present location through the Late Cretaceous and Tertiary

DATABASE AND METHODOLOGY

The study area encompasses Townships 83-86, and Ranges 15-20W5 (Fig. 2.1). The sedimentologic study includes a database of approximately 220 wells, over 70 of which were cored through the Lower Cretaceous study interval. Depositional environments within the Bluesky Formation and Ostracode Zone were the focus as exploitable bitumen at Peace River is considered by the authors to be exclusively within deposits of these lithostratigraphic units (previous studies have delineated the reservoir sands as part of the Gething Formation: Rottenfusser, 1982; 1984). Sedimentological characteristics analyzed included grain-size, grain-sorting, unit contacts and thicknesses, physical and biogenic sedimentary structures, macro-fossils and lithologic constituents.

A series of eight facies maps were constructed through the study interval in order to aid interpretations by revealing sediment distribution and sand-body geometries (Fig. 2.8). Each of the maps produced represents a 4m slice through the study interval (measured from the top of the Bluesky Formation). A dominant facies was assigned within each "slice" at each well location across the study area. This methodology helps to visualize sediment (and subsequently reservoir) distribution in three dimensions. Utilizing this data in interpreting the depositional history of the units relies on the assumption that the top of the Bluesky Formation was preserved as a flat surface after deposition. This assumption is valid as the top of the Bluesky Formation roughly parallels various marker horizons within the overlying Wilrich Member. This is due to the fact that the Bluesky Formation is sharply overlain by transgressive units that were

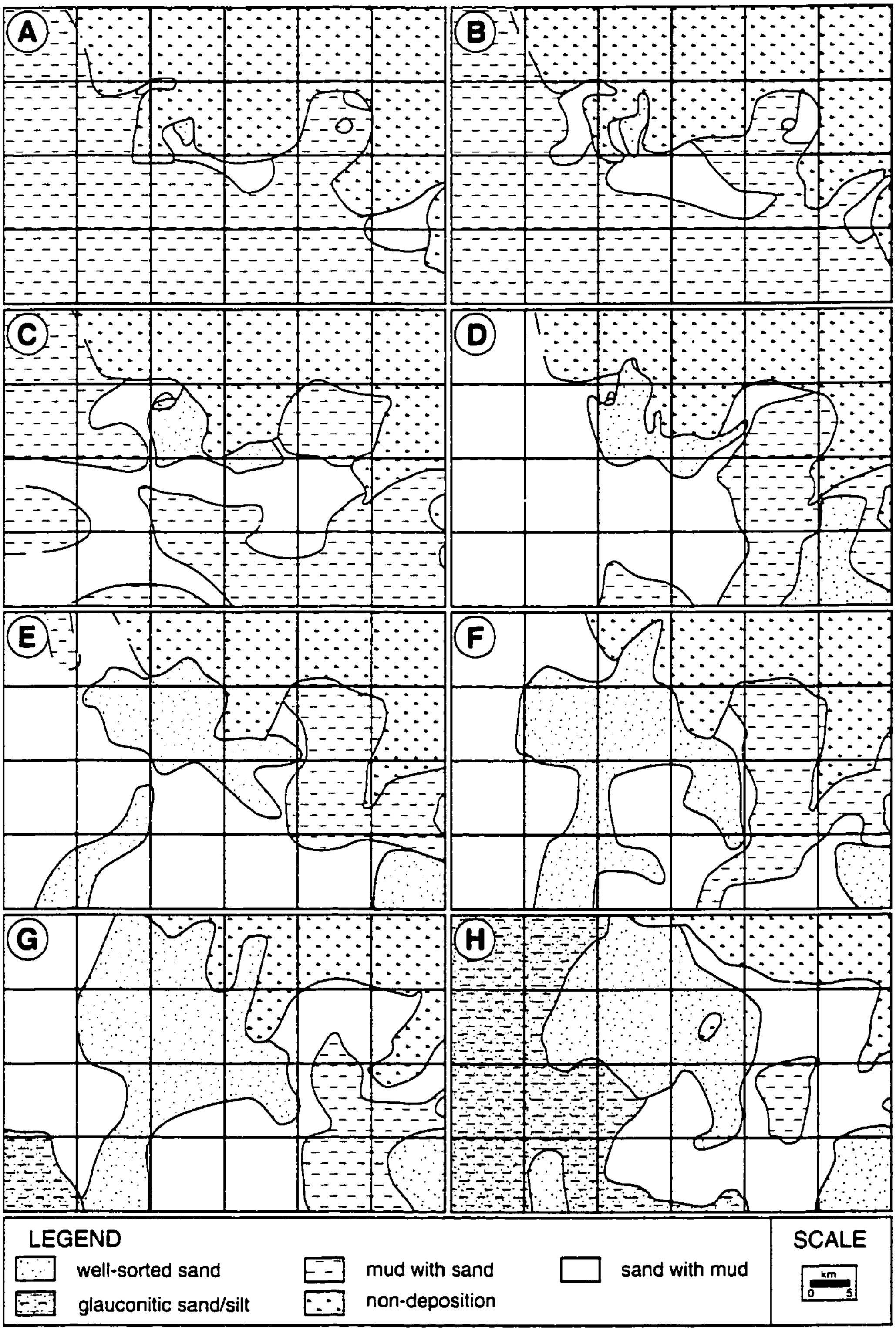


Fig. 2.8. Facies maps through the Ostracode Zone and Bluesky Formation. Each map represents a four meter "slice" through the study interval (measured from the top of the Bluesky Formation). **a)** 32 - 28m below the top of the Bluesky Formation; **b)** 28 – 24m; **c)** 24 – 20m; **d)** 20 – 16m; **e)** 16 – 12m; **f)** 12 – 8m; **g)** 8 – 4m; **h)** 4 – 0m.

deposited during an event that eroded topographical highs following the final stages of Bluesky Formation deposition.

An understanding of Lower Cretaceous paleotopography and sedimentation in the Peace River study area was attained by isopaching the Gething Formation, Ostracode Zone and Bluesky Formation (Fig. 2.7). Again, by assuming that the top of the Bluesky Formation approximates a regionally "flat" surface after transgression of the Boreal Sea over the study area, the isopach map of the interval between this surface and the sub-Cretaceous unconformity forms a mould of the unconformity surface. Ranger and Pemberton (1997) demonstrated the effectiveness of this methodology in their analysis of the south Athabasca oil sands. Thins represent highs on the unconformity surface and thicks define the lows.

The delineation of faults within the study area was mainly established through: 1) trends observed in the isopach map of the basal Cretaceous interval, 2) corresponding locations of sub-crop edges of underlying formations, and 3) cross-section analyses. Unfortunately, this particular study was limited by the density of well penetrations in the study area and a paucity of useful seismic data. Therefore, exact fault orientations were not able to be ascertained.

BASIN PALEOTOPOGRAPHY AND TECTONICS

Basal Cretaceous deposits of the Gething Formation, Ostracode Zone and Bluesky Formation lie directly on the sub-Cretaceous (angular) unconformity. In the study area Cretaceous sediments overlay Mississippian, Permian, Triassic and Jurassic deposits (Fig. 2.3). Basin paleotopography undoubtedly exerted a strong control on Lower Cretaceous sedimentation. Large-scale features influencing basin -configuration and -topography included the Peace River Arch and the Aptian Archipelago.

The Peace River Oil Sands deposit lies proximal to the axis of the Peace River Arch which is thought to have been a low during Gething-Bluesky deposition (Fig. 2.4;

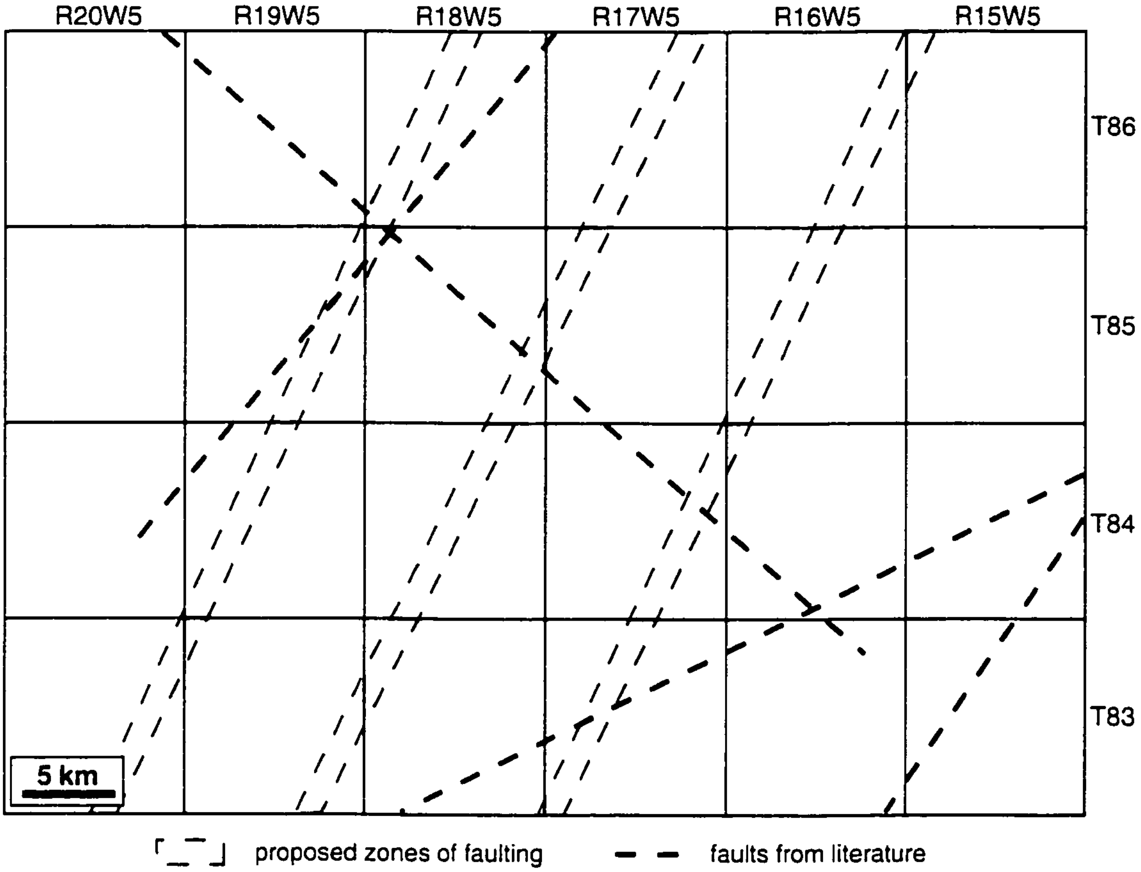


Fig. 2.9. Map showing position of numerous fault zones interpreted in the study area. Shaded areas represent proposed zones of faulting which show effects on Lower Cretaceous sediments. Dashed lines represent faults interpreted by previous workers (Dix, 1990; Sikabonyi and Rodgers, 1959; Cant, 1988).

Williams, 1958; Jackson, 1984; Cant, 1988). Numerous authors have demonstrated that the Peace River Arch and deep-seated faults associated with the feature have influenced basal Cretaceous facies distribution and thicknesses across the basin (Williams, 1958; Stott, 1973; O'Connell, 1988, 1990; Gibson, 1992). Regional scale fault zones associated with the Peace River Arch have been interpreted across the study area (Fig. 2.9), and although the scope of this study did not allow for the exact delineation of fault orientations, displacement on syn- and post- Bluesky Formation faults was often apparent (Fig. 2.10). The effects of these faults in the development area can be significant as facies distribution trends are altered. Thick reservoir quality sands are sometimes positioned structurally higher than mapping would suggest, thus complicating locations

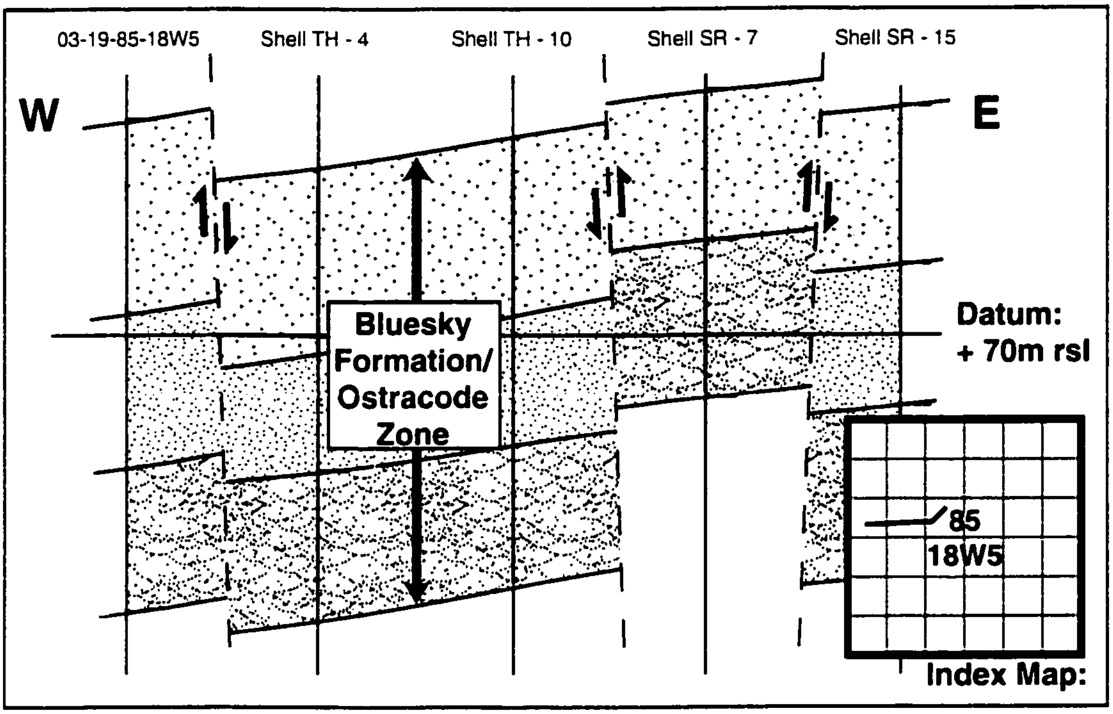


Fig. 2.10. Schematic structural cross-section through Township 85-18W5 showing evidence of syn- and post- Bluesky deposition faulting (not to scale).

of prospective development areas in some instances. Development of effective steam chambers during the production of bitumen can also be severely impeded.

As discussed, mapping of fault zones within the study area relied on trends observed on the Lower Cretaceous isopach map and their correlation with trends observed in underlying subcrop edges of the Paleozoic and older Mesozoic strata (Fig. 2.7). In many cases it appears that paleotopographic lows were controlled by fault orientations associated with activations/reactivations of the Peace River Arch (Fig. 2.4). A similar effect has been observed in the McMurray sub-basin to the east where workers have demonstrated the effect underlying salt solution has had on Lower Cretaceous facies distribution within the McMurray Formation (Stewart, 1963, Ranger and Pemberton, 1997).

In the northernmost part of the study area basal Cretaceous sediments pinch-out onto Mississippian carbonates of the Red Earth Highlands (Fig. 2.3). The Red Earth

Highlands were part of a chain of Paleozoic islands (the Aptian Archipelago; Rudkin, 1964) which extended from southern Saskatchewan to northeastern British Columbia during Barremian through to early Albian time (Christopher, 1974; Fig. 2.11). Several sub-basins were created as a result of these paleotopographic highs. The Red Earth Highlands effectively separates the Peace River and Wabasca oil sand deposits. Ranger and Pemberton (1997) observed this same effect further eastward where the Grosmont High provides the boundary between the Athabasca and Wabasca oil sand deposits.

Differential erosion of westward dipping Paleozoic and early Mesozoic strata uplifted during the Columbian Orogeny, created the northwest–southeast trending paleotopographic highs of the Aptian Archipelago (Cant and Stockmal, 1989). Stockmal *et al.* (1992) suggested that this feature could be, in effect, the peripheral bulge associated with the formation of the Alberta Foreland Basin. Although peripheral bulges typically subside soon after formation, conducive conditions could theoretically preserve associated remnant structural highs (Octavian Catuneanu, pers com, 1998). The orientation of the chain of highlands parallel to the deformational edge of the Rocky Mountains infers their origin is somehow linked to the Columbian Orogeny (Fig. 2.11).

REGIONAL DEPOSITIONAL SETTING

Lower Cretaceous paleogeography of the Western Canada Sedimentary Basin has been extensively documented in the literature (Rudkin, 1964; Williams and Stelck, 1975; McLean and Wall, 1981; Jackson, 1984; Smith, 1994). During Gething Formation through to Bluesky Formation time, sedimentation occurred during an overall transgression of the Boreal Sea from the north. Deposits of the Gething Formation were laid down in a fluvial/non-marine depositional setting, directly on the sub-Cretaceous unconformity in the structurally lowest areas of the study area. A series of north-south trending channel systems drained the basin northward to the Boreal Sea during Gething time (Fig. 2.11). Gething Formation deposits at Peace River were deposited in the Edmonton Channel

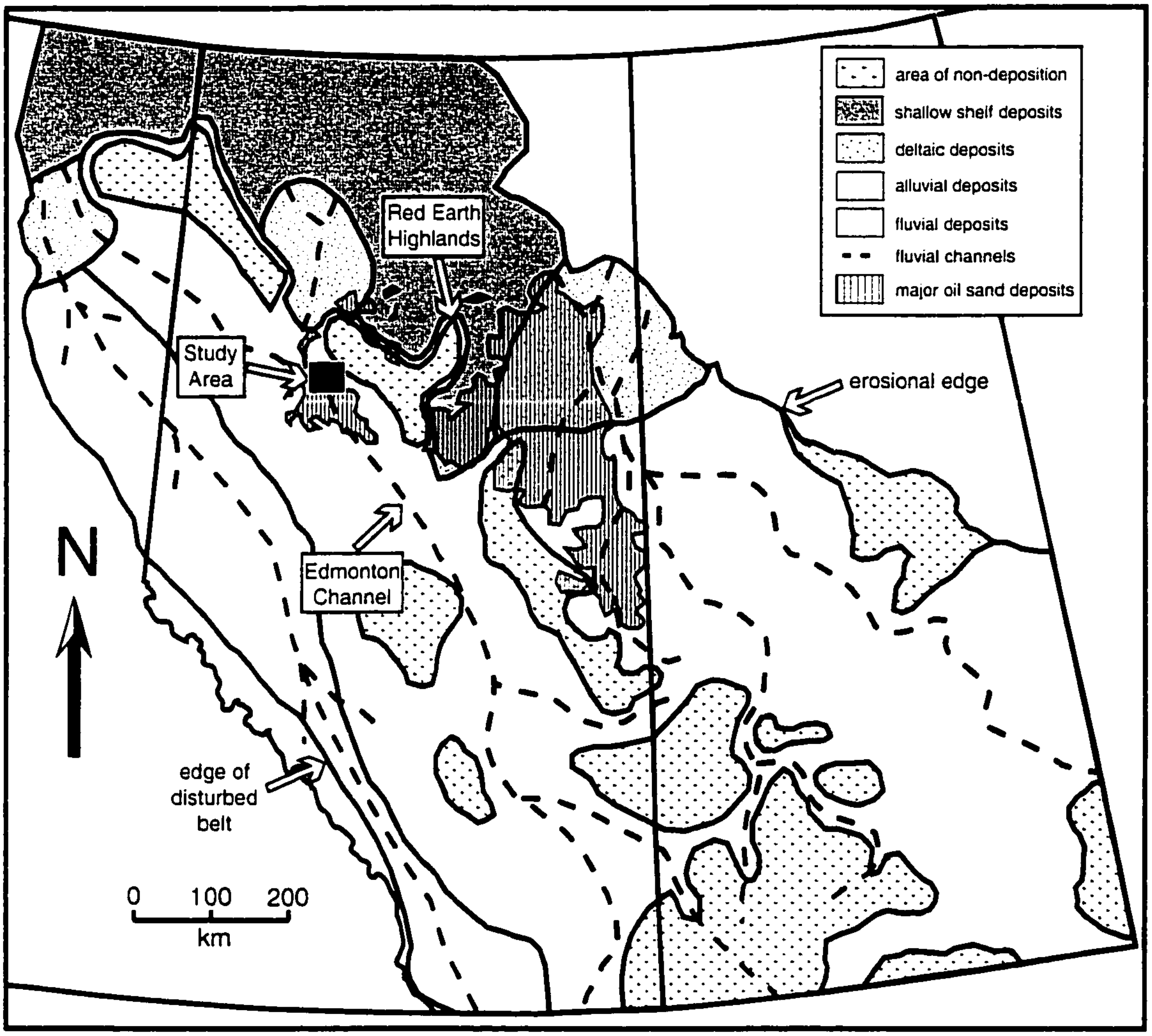


Fig. 2.11. Paleogeography of the Western Canada Sedimentary Basin during Lower Cretaceous Gething (and equivalents) time (modified from Smith, 1994).

complex as defined by Williams (1963).

As fluvial sedimentation and flow from the south and west waned, a marine incursion from the north took place. Deposits of the Ostracode Zone accumulated in a large, brackish water embayment over much of southern and central Alberta, including the Peace River area (McLean and Wall, 1981). The northern limit of this embayment was controlled by the location of the Aptian Archipelago, separating fully marine conditions to the north from the brackish bay to the south.

Upon further transgression, marine sediments of the Bluesky Formation were deposited over west-central Alberta. Coarsening upwards cycles deposited in shoreface, barrier-bar and offshore bar environments have been interpreted in the area (Jackson, 1984; O'Connell, 1988). Previous interpretations of the Bluesky Formation at Peace River described tide-dominated estuarine, marine transgressive shoreline, and deltaic deposition (Howard, 1976; Rottenfusser, 1983, 1984 , 1986).

SEDIMENTOLOGY

Eleven facies (F1 – F11) are recognized in the study area and are summarized in Table 2.2. Four facies associations (FA1 – FA4) have subsequently been interpreted based on genetic, or environmental relationships. Facies Association 1 characterizes deposits from the Ostracode Zone, which were deposited in a large brackish bay that extended across most of the study area. The Bluesky Formation is interpreted as a wave-dominated estuarine complex and is represented by FA2 and FA3. Facies association 4 represents transgressive shoreline deposits of the Bluesky Formation. Four detailed core descriptions are included in the paper to show the relationships between some of the most prevalent facies (Figs. 2.5, 2.12, 2.13, 2.14). Table 2.3 summarizes the symbols utilized in these descriptions.

CROSS-SECTIONS

Regional cross-sections show the complexity in estuarine deposits of the Bluesky Formation (Fig. 2.15). A consistent, gamma-ray log kick in the lower part of the Wilrich Member shales was used as a datum. Generally, the thickest sandstones are located in the west-central (tidal-delta, tidal-channel, shoreface) and southeast (bayhead delta) regions of the study area (Fig. 2.8e-h). Delineating the contact between the Bluesky Formation and Ostracode Zone can be difficult where mud-dominated facies of the Bluesky Formation overlie brackish bay deposits of the Ostracode Zone (Fig. 2.15). Where localized sands of the Ostracode Zone underlie sands of the Bluesky Formation this contact is also often indiscernible, especially through the use of geophysical well-

FACIES	FACIES ASSOCIATION	INTERPRETATION	ASSOCIATED STRATIGRAPHIC INTERVAL
F1 burrowed interbedded siltstone and mudstone	FA1	quiescent brackish bay	Ostracode Zone
F2 chert rich sandstone interbedded with mudstone		fluvial/bayhead delta	
F3 quartzose sandstone interbedded with mudstone	FA2	bayhead delta	Bluesky Formation
F4 burrowed heterolithic mudstone and sandstone		central basin	
F5 burrow mottled sandstone and mudstone		tidal flat	
F6 well-sorted burrowed sandstone	FA3	tidal channel	
F7 burrowed mudstone interbedded with sandstone		lagoon	
F8 well-sorted cross-bedded sandstone with rare mud laminae		tidal delta	
F9 sandstone with common wood and coal debris		washover deposits	
F10 diversely burrowed, oscillation rippled sandstone		shoreface	
F11 glauconitic muddy sandstone	FA4	transgressive shoreline	

Table 2.2. Summary of facies from the Bluesky Formation and Ostracode Zone at Peace River.

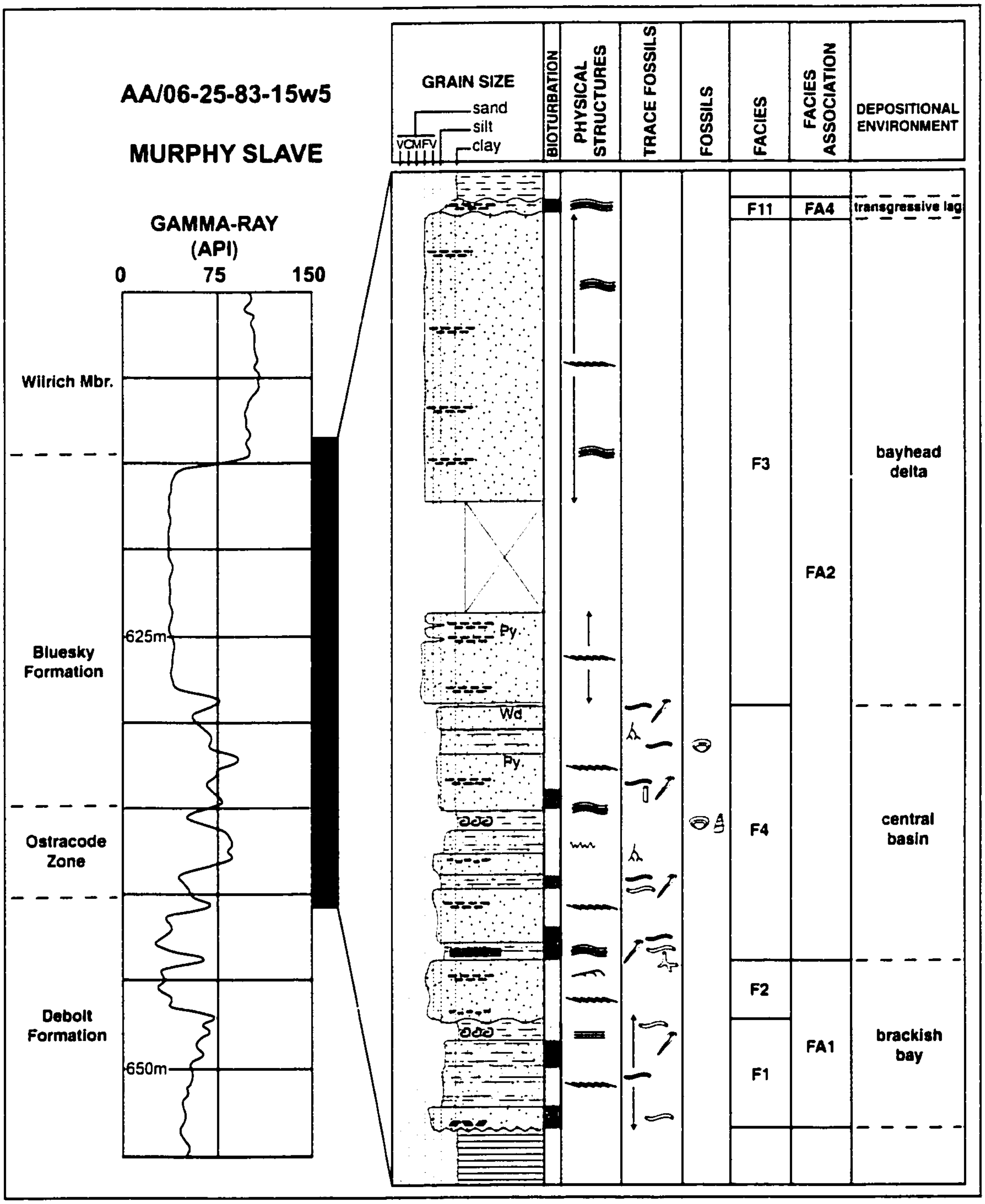


Fig. 2.12. A typical well (06-25-83-15W5) from the southeastern portion of the study area showing upper estuary deposits of the Bluesky Formation and brackish water deposits of the Ostracode Zone. See Table 2.3 for a legend to the symbols used. Well-location is shown on Figure 2.1.

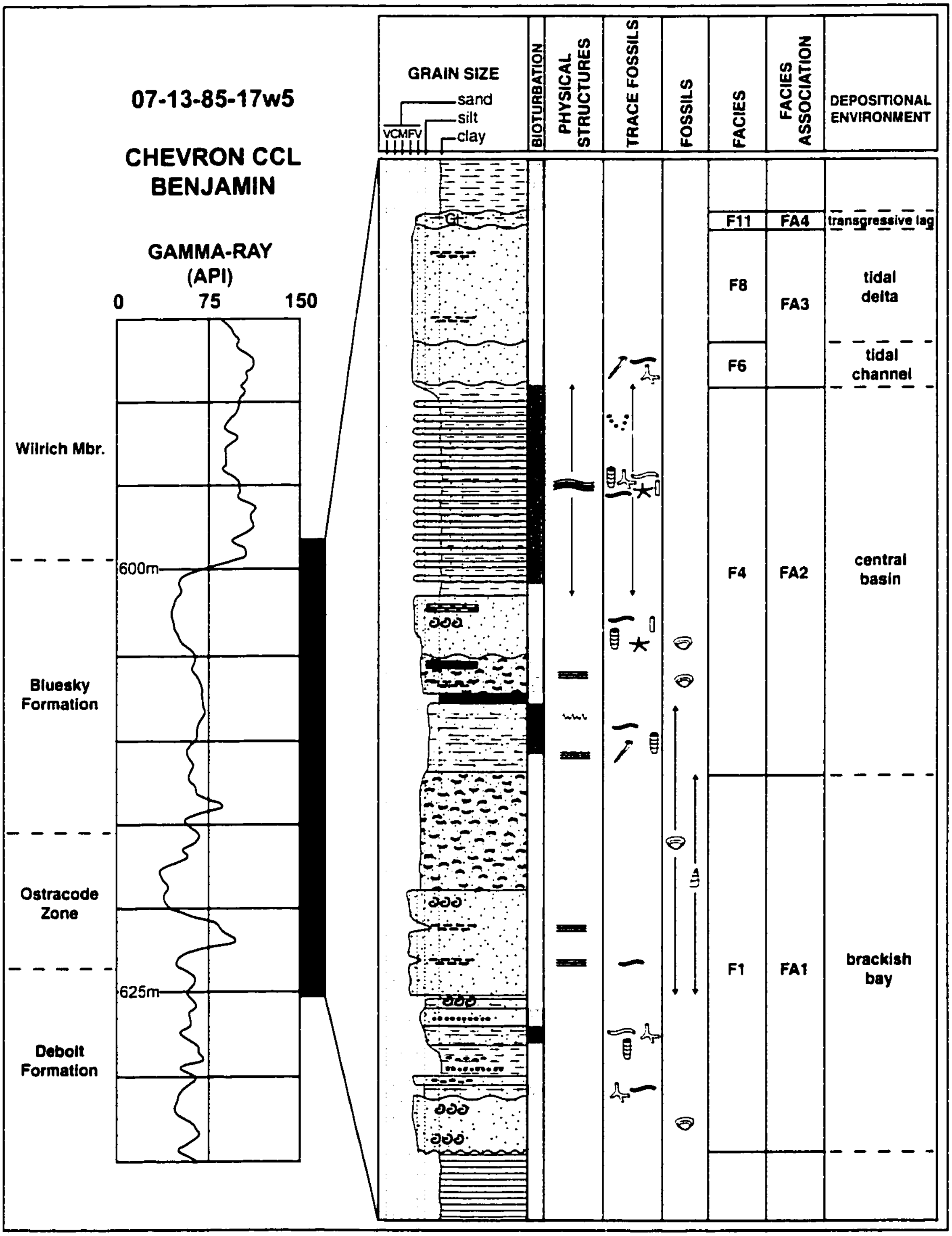


Fig. 2.13. A typical well (07-13-85-17W5) from the central portion of the study area showing upper and lower estuary deposits of the Bluesky Formation, and brackish water deposits of the Ostracode Zone. See Table 2.3 for a legend to the symbols used. Well-location is shown on Figure 2.1.

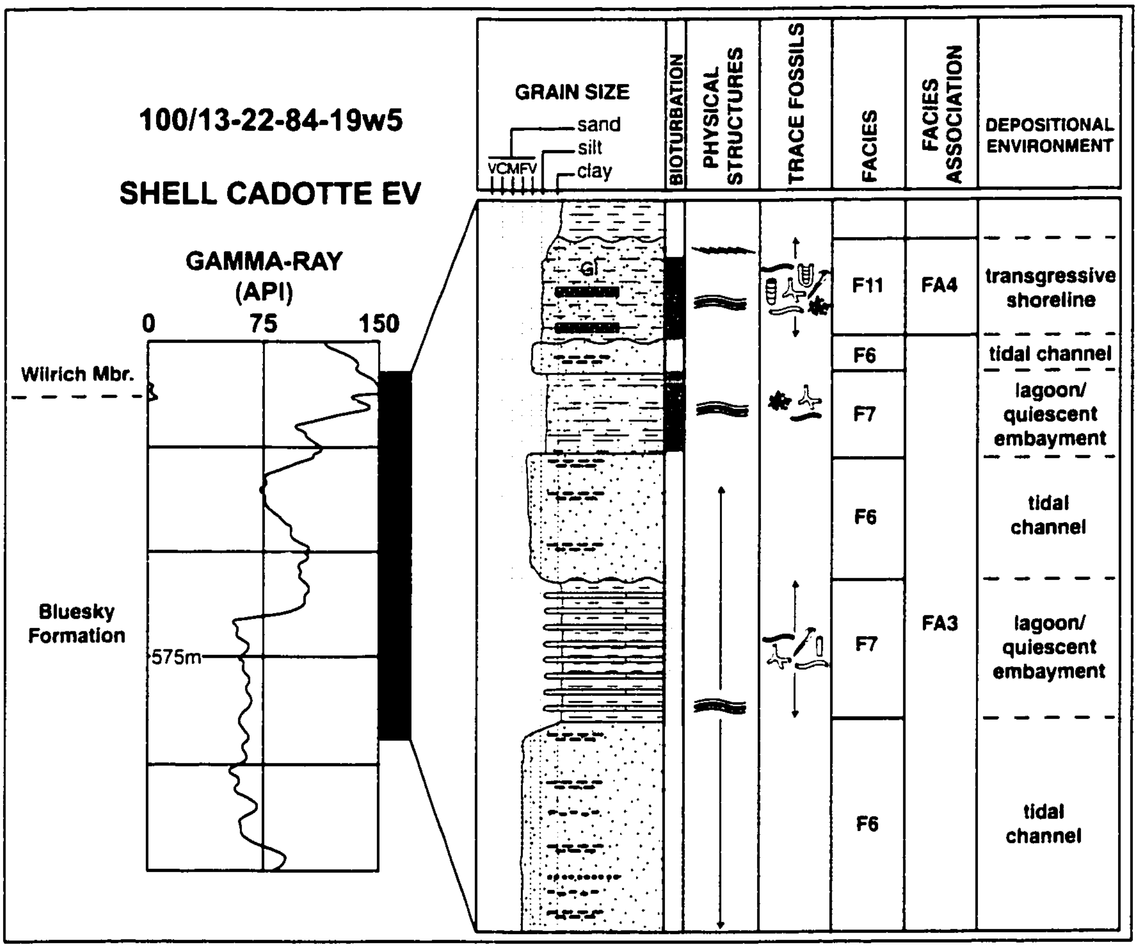


Fig. 2.14. A typical well (13-22-84-19W5) from the western portion of the study area showing lower estuary deposits of the Bluesky Formation. See Table 2.3 for a legend to the symbols used. Well-location is shown on Figure 2.1.

logs alone (Fig. 2.5).

From the sub-Cretaceous unconformity to the Wilrich Member shales, the basal Cretaceous section at Peace River is considered to be a continuous transgressive succession that is conformable throughout. Discontinuity surfaces are recognized locally, the most widespread and significant of which occurs at the top of the Bluesky Formation and is interpreted as a transgressive surface of erosion (Fig. 2.15). More detailed descriptions of these surfaces are included in the discussion of facies.

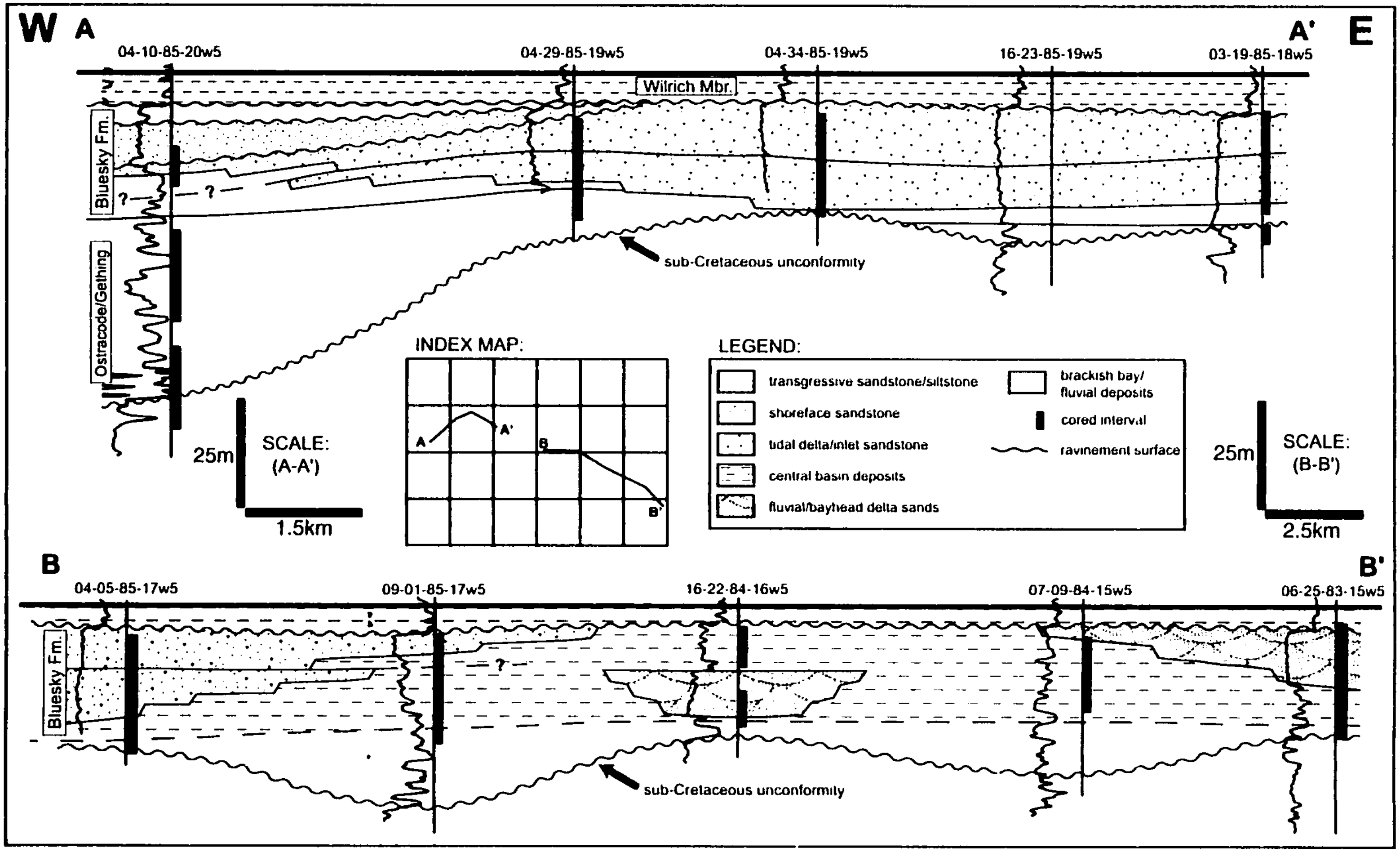
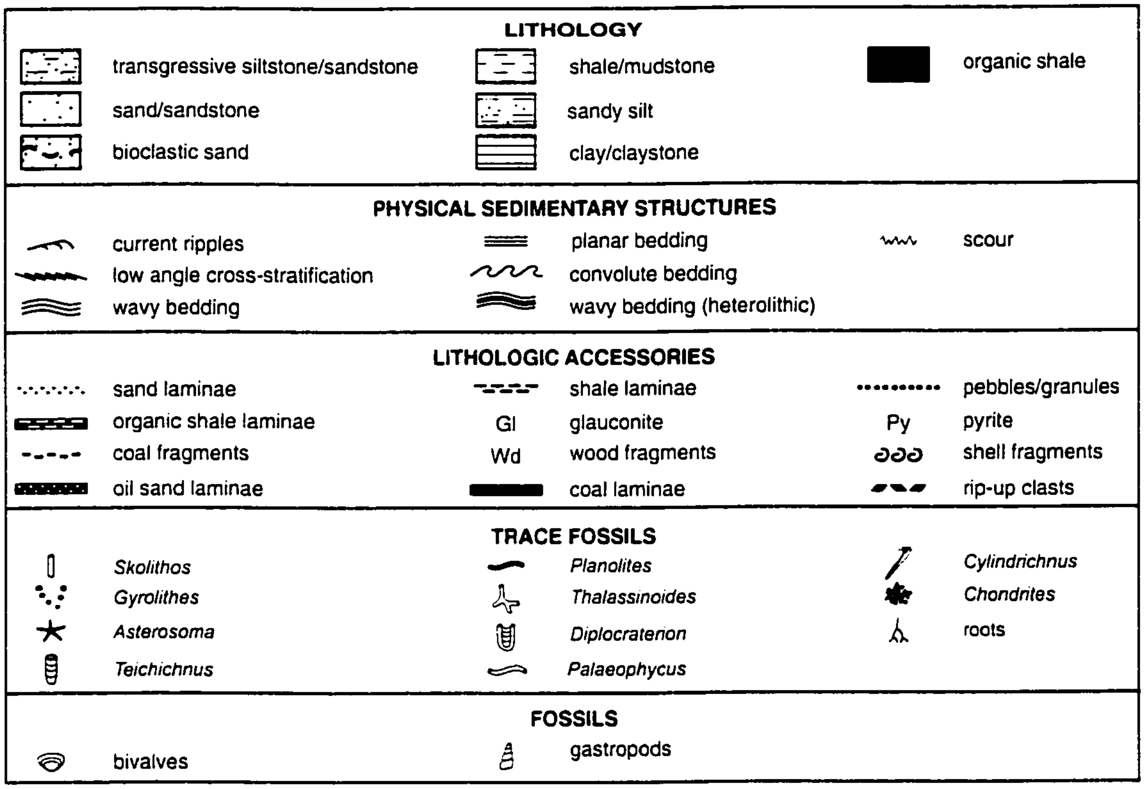


Fig. 2.15. Detailed cross-sections along depositional dip showing stratigraphic relationships between estuarine facies of the Bluesky Formation. A consistent, gamma-ray log kick in the lower part of the Wilrich Member shales was used as a datum. A-A' shows progradation of ebb-tidal delta sandstones in a basinward direction. B-B' shows progradation of flood-tidal delta sandstones in a landward direction. Gamma-ray logs are shown.



		LITHOLOGY			
▤	transgressive siltstone/sandstone	▤	shale/mudstone	■	organic shale
▭	sand/sandstone	▤	sandy silt		
▭	bioclastic sand	☰	clay/claystone		
		PHYSICAL SEDIMENTARY STRUCTURES			
⌒	current ripples	═	planar bedding	〰	scour
〰	low angle cross-stratification	∿	convolute bedding		
≋	wavy bedding	≋	wavy bedding (heterolithic)		
		LITHOLOGIC ACCESSORIES			
······	sand laminae	- - -	shale laminae	●●●●●●	pebbles/granules
▬	organic shale laminae	Gl	glauconite	Py	pyrite
- - - -	coal fragments	Wd	wood fragments	ɵɵɵ	shell fragments
▬	oil sand laminae	▬	coal laminae	◆◆◆	rip-up clasts
		TRACE FOSSILS			
▯	*Skolithos*	⌒	*Planolites*	/	*Cylindrichnus*
⁖	*Gyrolithes*	⅄	*Thalassinoides*	✱	*Chondrites*
★	*Asterosoma*	∪	*Diplocraterion*	⅄	roots
▯	*Teichichnus*	⌒	*Palaeophycus*		
		FOSSILS			
◎	bivalves	∆	gastropods		

Table 2.3. Legend to symbols used in Figures 2.5, 2.12, 2.13, and 2.14.

FACIES ASSOCIATION 1: BRACKISH BAY DEPOSITS

Facies Association 1 is exclusive to the Ostracode Zone in the Peace River study area. It consists of two recurring facies including F1, burrowed interbedded siltstone and mudstone, and F2, chert-rich sandstone interbedded with mudstone (Table 2.2). Deposits of FA1 range in thickness from 10-15m, and they gradationally overlie deposits of the Gething Formation in the south and west regions of the study area. In the structurally higher north and east portions of the study area, FA1 was not deposited, or it overlies the sub-Cretaceous unconformity (Figs. 2.12 and 2.13).

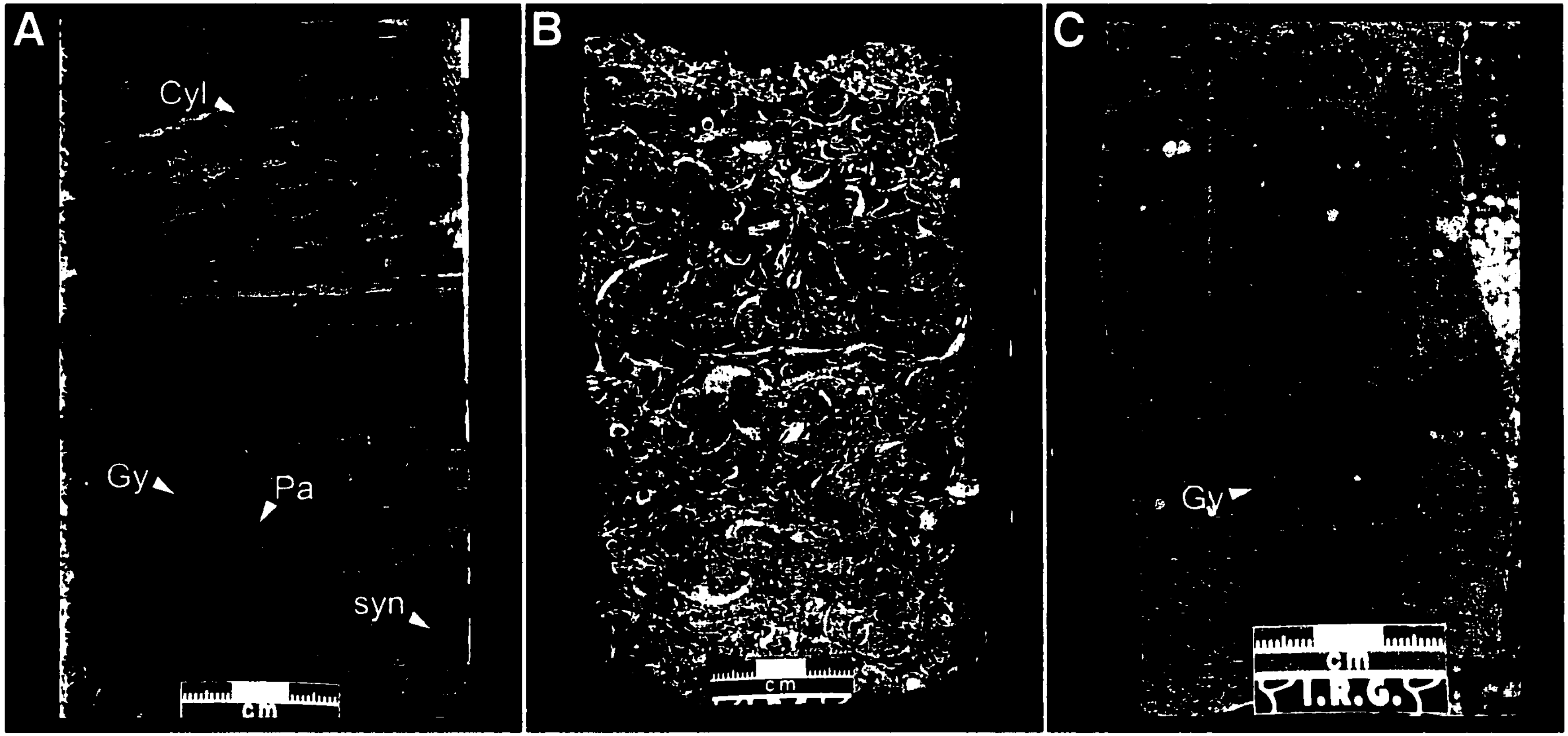


Fig. 2.16. Brackish bay deposits of the Ostracode Zone (Facies F1). **a)** Quiescent bay deposit with syneresis cracks (syn) and a brackish water trace fossil assemblage including *Cylindrichnus* (Cyl), *Gyrolithes* (Gy), and *Palaeophycus* (Pa)(11-17-83-18W5, 632.5m). **b)** Bioclastic accumulation consisting of a mixed assemblage of bivalves and gastropods (02-09-83-15W5, 652.0m). **c)** Monospecific trace fossil assemblage consisting of *Gyrolithes* (Gy) (14-02-84-20W5, 578.0m).

FACIES 1 - BURROWED INTERBEDDED SILTSTONE AND MUDSTONE

Description

Within the Ostracode Zone F1 is very widespread, varying considerably across the study area. Interbedded silty mudstones and sandy siltstones are prevalent throughout the interval (Fig. 2.16a). Rare sandstone units typically <2m in thickness are also present locally. Bioclasts and bioclastic debris, comprised of numerous bivalve and gastropod species, are common in finer grained deposits. In some instances, bioclasts make up dense coquinal deposits (Fig. 2.16b). Facies F1 gradationally overlies interbedded sandstones and mudstones of the Gething Formation where present. In the northern and eastern regions of the study area, F1 unconformably overlies Mississippian carbonates (Fig. 2.12).

The dominant physical structures present include planar parallel and heterolithic wavy bedding within interbedded mudstones and sandstones, and low angle cross-stratification in sandstone units. Diminutive syneresis cracks are moderately abundant in interbedded deposits (Fig. 2.16a). Coally debris, wood fragments, carbonaceous mud laminae, pyrite and siderite are common throughout the stratigraphic interval.

Trace Fossils common in deposits of the western half of the study area include *Helminthopsis, Cylindrichnus, Planolites, Palaeophycus, Gyrolithes, Teichichnus, Skolithos,* fugichnia, *Thalassinoides, Chondrites, Rosselia* and rootlets. In the central and eastern parts of the study area, a less diverse assemblage of traces is characteristic. Assemblages are typically comprised of 3 to 5 trace fossil forms that are generally more diminutive than similar forms observed in deposits to the west. *Planolites, Palaeophycus, Cylindrichnus, Gyrolithes, Teichichnus* and *Skolithos* are the most common traces observed in this portion of the study area. Often an individual ichnogenus completely dominates units of this interval (Fig. 2.16c). Other traces present in low abundances include *Chondrites, Thalassinoides, ?Asterosoma,* and *Arenicolites.*

Interpretation

Facies 1 is interpreted as quiescent brackish bay deposits due to its broad lateral extent, the prevalence of mudstones, and the ichnofossil assemblage present. Trace fossil assemblages within F1 are closely linked to varying water salinities prevalent during the time of substrate colonization. In the western portion of the study area, the diverse assemblage of robust trace fossils suggests proximity to a marine influence whereas less diversity and diminution of forms indicates more stressed environmental parameters further eastward. Numerous authors have observed similar zonations of trace fossils within modern (Sanders *et al.*, 1965; Dörjes and Howard, 1975; Gingras *et al.*, 1999) and ancient brackish water deposits (Pemberton *et al.*, 1982; Beynon *et al.*, 1988; Pattison and Walker, 1998). Sediments deposited in stressed environmental settings are known to contain low diversity trace fossil assemblages consisting of diminutive, marine forms relative to fully marine environments (Howard and Frey, 1973; Wightman *et al.*, 1987; Pemberton and Wightman, 1992). Brackish water deposits are also commonly characterized by monospecific associations of traces (Pemberton *et al.*, 1992).

Syneresis cracks and the co-existence of pyrite and siderite are thought to be indicative of fluctuating salinities within deposits of marginal marine depositional settings as well (Plummer and Gostin, 1981; Wightman *et al.*, 1987). The presence of these features further supports the interpretation that units of the Ostracode Zone were deposited in a quiescent brackish water embayment within the Peace River study area.

FACIES 2 – CHERT-RICH SANDSTONE INTERBEDDED WITH MUDSTONE

Description

Facies 2 is characterized by sandy deposits prevalent within the Ostracode Zone at various localities across the study area (Figs. 2.8a-d). Mudstone interbeds range from absent to common locally. These units typically fine-upwards subtly from lower medium to upper fine grained and in some instances 3-4m thick mudstones are observed gradationally overlying the sands (Fig. 2.5). Sands are composed predominantly of chert with a minor quartz component. Mud laminae and coally debris typically comprise less than 10% of the total rock unit. Facies 2 sharply overlies the Mississippian Debolt and Shunda Formations, and commonly contains a conglomeratic lag composed of sub-rounded chert clasts.

Low- to high-angle cross-stratification is the most prevalent characteristic of the sandy units whereas heterolithic wavy bedding characterizes intervals with common mud laminae. Biogenic reworking of the muddy units can be quite extensive in some cases. A stressed trace fossil assemblage consisting of *Planolites, Skolithos, Cylindrichnus, Gyrolithes* and *Palaeophycus* is observed. Burrowing within sandstones is rare to absent. Lithologically-defined *Planolites, Cylindrichnus, Gyrolithes* and *Palaeophycus* are locally present.

Interpretation

Sandstone units lacking common mud interbeds of F2 are interpreted as fluvial deposits. Overlying mudstones deposited during channel abandonment are sometimes preserved, however, they are typically reworked during later erosion. Proximity of fluvial deposits to the areas of non-depostion in the northern and eastern portions of the study area suggest they originated from rivers sourced from the Red Earth Highlands (Figs. 2.8a-c). The highlands supplied chert and other sediments into the basin locally. The mixing of fresh and brackish water, along with high-energy conditions, created stressed environmental conditions. This is reflected by the low diversity trace fossil assemblage characteristic of these units.

More basinward, sandy deposits of F2 contain numerous mud-laminae. The heterolithic nature and a more diverse trace fossil assemblage suggest deposition in a somewhat more quiescent environment. These units are interpreted as bayhead delta deposits. Facies mapping shows shore-parallel orientations of elongate sand bodies in some instances (Figs. 2.8a-b), suggesting reworking of bayhead deltaic deposits by longshore currents. Similar sand bodies within the Western Canada Sedimentary Basin have been recognized in the Ostracode Zone of southeastern Alberta (Karvonen and Pemberton, 1997) and the Upper Albian Viking Formation at Joffre (MacEachern *et al.*, 1998).

FACIES ASSOCIATION 2: UPPER TO MIDDLE ESTUARY DEPOSITS

Three facies comprise FA2 within the Bluesky Formation at Peace River: F3, quartzose sandstone interbedded with mudstone; F4, burrowed heterolithic mudstone and sandstone; and F5, burrow mottled sandstone and mudstone (Table 2.2). These facies are restricted to the central and eastern regions of the study area. The cumulative thickness of this association reaches up to 16m. Deposits of FA2 overlie FA1 except in the northeastern parts of the study area, where they lie directly on the sub-Cretaceous unconformity.

FACIES 3 - QUARTZOSE SANDSTONE INTERBEDDED WITH MUDSTONE

Description

Facies 3 of the Bluesky Formation is similar in many respects to F2 of the underlying Ostracode Zone. A primarily quartzose lithology and its higher stratigraphic position help to differentiate F3 from F2. The sandstone contains 5 to 15% wavy mud laminae. The grain-size of the sand ranges from upper very fine to upper fine, and profiles both fine- and coarsen-up locally. The lower contact is typically sharp and erosive over F4, or deposits of FA1.

Low angle cross stratification is the predominant physical structure within F3, with planar parallel and trough cross bedding present with less regularity (Fig. 2.17a). Heterolithic wavy bedding is common in muddier intervals. Coally debris and laminae are present in moderate abundances.

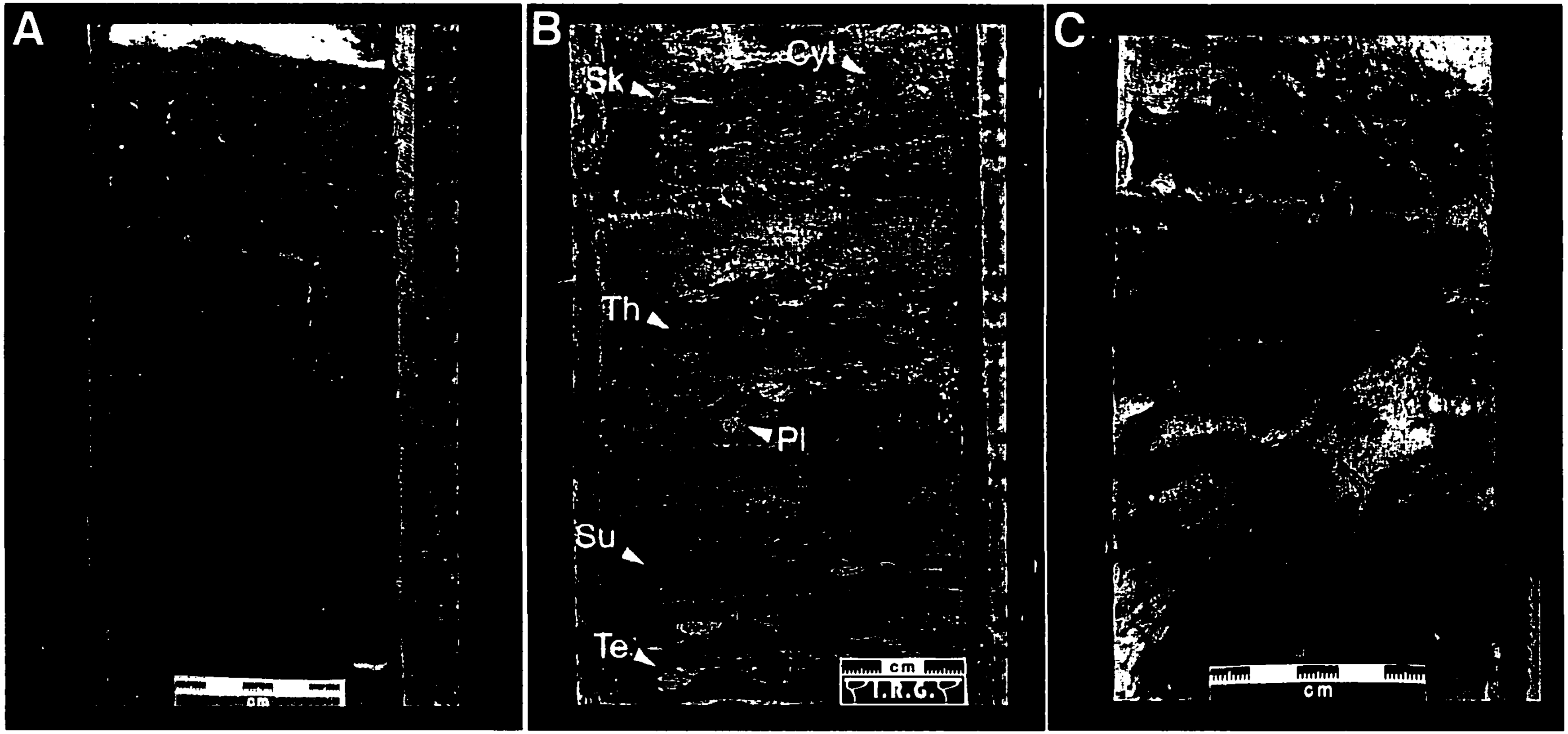


Fig. 2.17. Upper estuary deposits of the Bluesky Formation. **a)** Facies F3, bitumen saturated bayhead delta sandstone with characteristic cross-bedding (06-25-83-15W5, 632.25m). **b)** Facies F4, silty mudstone deposited in the central basin of the estuary. The trace fossil assemblage consists of *Skolithos* (Sk), *Cylindrichnus* (Cyl), *Thalassinoides* (Th), *Planolites* (Pl), *Subphyllochorda* (Su), and *Teichichnus* (Te) (04-24-84-16W5, 635.5m). **c)** Facies F6, burrow-mottled sandstone and mudstone deposited on a tidal flat (06-25-83-15W5 @ 628.0 m).

Bioturbation within F3 is rare to absent. A trace fossil assemblage consisting of *Planolites, Skolithos, Thalassinoides* and *Cylindrichnus* is present in rare instances, exclusively within mudstone interbeds.

Interpretation

Facies 3 is attributed to bayhead delta deposition on the basis of several sedimentary features. The mild degree of bioturbation and the low diversity of ichnofossils suggests deposition in an extremely stressed environment. In this particular case, low salinity brackish water and highly variable hydraulic energy likely inhibited organisms from colonizing these deposits. The predominance of cross-bedded sands and wavy mud laminae, as well as a restriction of the facies to the southeastern corner of the study area support the interpretation that these sediments were deposited in an ancient bayhead delta (Figs. 2.8d-h). Furthermore, their position more landward of muddy deposits associated with the central basin of an estuary supports this interpretation (Fig. 2.15).

FACIES 4 - BURROWED HETEROLITHIC MUDSTONE AND SANDSTONE

Description

Facies 4 consists exclusively of interbedded very fine sand/silt and shale (Fig 2.17b). Pyrite and carbonaceous mud laminae are present locally in moderate abundances. Bioclastic debris consisting of disarticulated and fragmented bivalves is rarely present. Facies 4 is often preserved in close association with F5 and gradationally overlies mud-dominated deposits of FA1 (Fig. 2.12).

The most diagnostic characteristics of F4 include a prevalence of heterolithic wavy bedding and a trace fossil assemblage consisting predominantly of *Planolites, Skolithos, Arenicolites, Palaeophycus, Cylindrichnus* and ?*Asterosoma* (Fig. 2.17b). Other trace fossils present in varying abundances from these deposits include *Thalassinoides, Subphyllochorda,* and *Teichichnus.* Bioturbation can be pervasive however units rarely contain a diversity of trace fossils consisting of more than 5 or 6 individual ichnogenera.

Interpretation

Facies 4 is interpreted as central basin deposits of an estuarine complex. The prevalence of muddy deposits and the low diversity trace fossil assemblage suggests deposition within a quiescent, salinity stressed depositional environment. Their close relationship with more landward, fluvially influenced bayhead delta deposits, and more basinward marine sandstones supports central basin deposition within a wave-dominated estuary as described by Dalrymple *et al.* (1992) (Fig. 2.15).

Trace fossil assemblages within quiescent basin deposits (F4) of the Bluesky Formation help distinguish them from brackish bay deposits (F1) of the underlying Ostracode Zone. More marine forms are observed within F4 including *Subphyllochorda* and ?*Asterosoma*. Syneresis cracks and siderite are also rare to absent in the more marine influenced central basin deposits of the Bluesky Formation.

FACIES 5 – BURROW MOTTLED SANDSTONE AND MUDSTONE

Description

Facies 5 is generally restricted to the south-central part of the study area. It varies in lithology, typically fining-upwards from muddy sandstone to sandy mudstone. Thicknesses of individual units are generally <1.5m, although individual beds of F5 are normally amalgamated on top of one another. Disseminated pyrite, shelly debris, coal fragments and organic detritus are rarely present. Heterolithic wavy bedding is present locally however primary physical structures are generally obliterated by high degrees of bioturbation (Fig. 2.17c). Localized scour surfaces are present in some instances. Rootlets commonly descend from the upper contact, which is sharp and scoured locally. The lower contact of F5 is abrupt to sharp and is commonly bioturbated (Fig. 2.17c).

Individual trace fossils are typically indistinguishable in F5. A low to moderate diversity trace fossil assemblage consisting of *Thalassinoides, Planolites, Skolithos, Cylindrichnus,* and rootlets is recognized. Rootlets are the most diagnostic feature of this facies as they are typically coalified (Fig. 2.17c).

Interpretation

Facies 5 is attributed to deposition on tidal flats. Obliteration of primary physical structures by extreme bioturbation is typical in this environment (Weimer *et al.*, 1982; Gingras *et al.*,1999). The low diversity trace fossil assemblage is a consequence of numerous stresses such as fluctuating currents, extremes in salinity, periodic desiccation (in the upper intertidal zone), and sporadic deposition (Weimer *et al.*, 1982). Roots are associated with overlying supratidal deposits that have been largely removed by erosion. Localized scour surfaces are likely related to associated tidal runoff creeks.

FACIES ASSOCIATION 3: LOWER ESTUARY DEPOSITS

Facies Association 3 is comprised of five commonly recurring facies. These facies include: F6, well-sorted burrowed sandstone; F7, burrowed mudstone interbedded with sandstone; F8, well-sorted cross-bedded sandstone with rare mud laminae; F9, sandstone with common wood and coal debris; and F10, diversely burrowed, oscillation rippled sandstone (Table 2.2). Deposits of this facies association are predominantly located in the western half of the study area, range from 8 to 20m in thickness, and are typically underlain by FA1 of the Ostracode Zone.

FACIES 6 - WELL SORTED BURROWED SANDSTONE

Description

Facies 6 is composed of well-sorted, very-fine to fine-grained sands. Grain size profiles of the sharp-based deposits are typically blocky although they may fine upwards subtly (Fig. 2.14). In some cases, thick coarse grained lags composed of argillites, chert pebbles and bioclastic debris are present. Individual bivalve shells are disarticulated and aligned along low-angle bedding planes in the concave-down position. Mudstone laminae are rare to moderate and typically comprise less than 5% of the deposits. Wood fragments, coally debris and laminae, and carbonaceous mud laminae are rarely present. Calcareous sand stringers with shell debris are also observed in rare instances. Facies 6 erosionally overlies F4 and F1, and is commonly interbedded with F7 (Figs. 2.13,2.14).

Physical structures are variable within F6. Planar parallel bedding, low angle cross-stratification and inclined stratification are all present with moderate to high abundance in associated deposits. In units with common mud laminae, sand-dominated heterolithic wavy bedding is prevalent.

The most diagnostic characteristic of this facies is the presence of robust, mud-lined burrows within the sandstones (Fig. 2.18a). *Rosselia* and *Cylindrichnus* are common, with *Skolithos* more rarely present. Escape-traces are observed in mudstone units.

Interpretation

Facies 6 was deposited in broad tidal channels. Typical sharp basal contacts, coarse-grained lag deposits, blocky to fining upwards grain size profiles, and association with other estuarine facies support this interpretation. The low diversity and abundance of robust trace fossils suggests deposition within a stressed environment. Stresses prevalent included brackish water, high sedimentation rates and high-energy currents. The clean, well-sorted sands present are indicative of strongly directed, high-energy currents of tidal channels (Weimer *et al.*, 1982). Disarticulated bivalve shells in the concave down position are also indicative of current processes (Middleton, 1967; Emery, 1968).

FACIES 7 - BURROWED MUDSTONE INTERBEDDED WITH SANDSTONE

Description

Facies 7 is comprised of interbedded very fine-grained sand and mudstone. Associated deposits are restricted to the western portion of the study area. Shales are the predominant constituent of these 4 to 5m thick units, normally making up 60–80 % of the total sediment package. Wood fragments, carbonaceous mud laminae and pyrite are

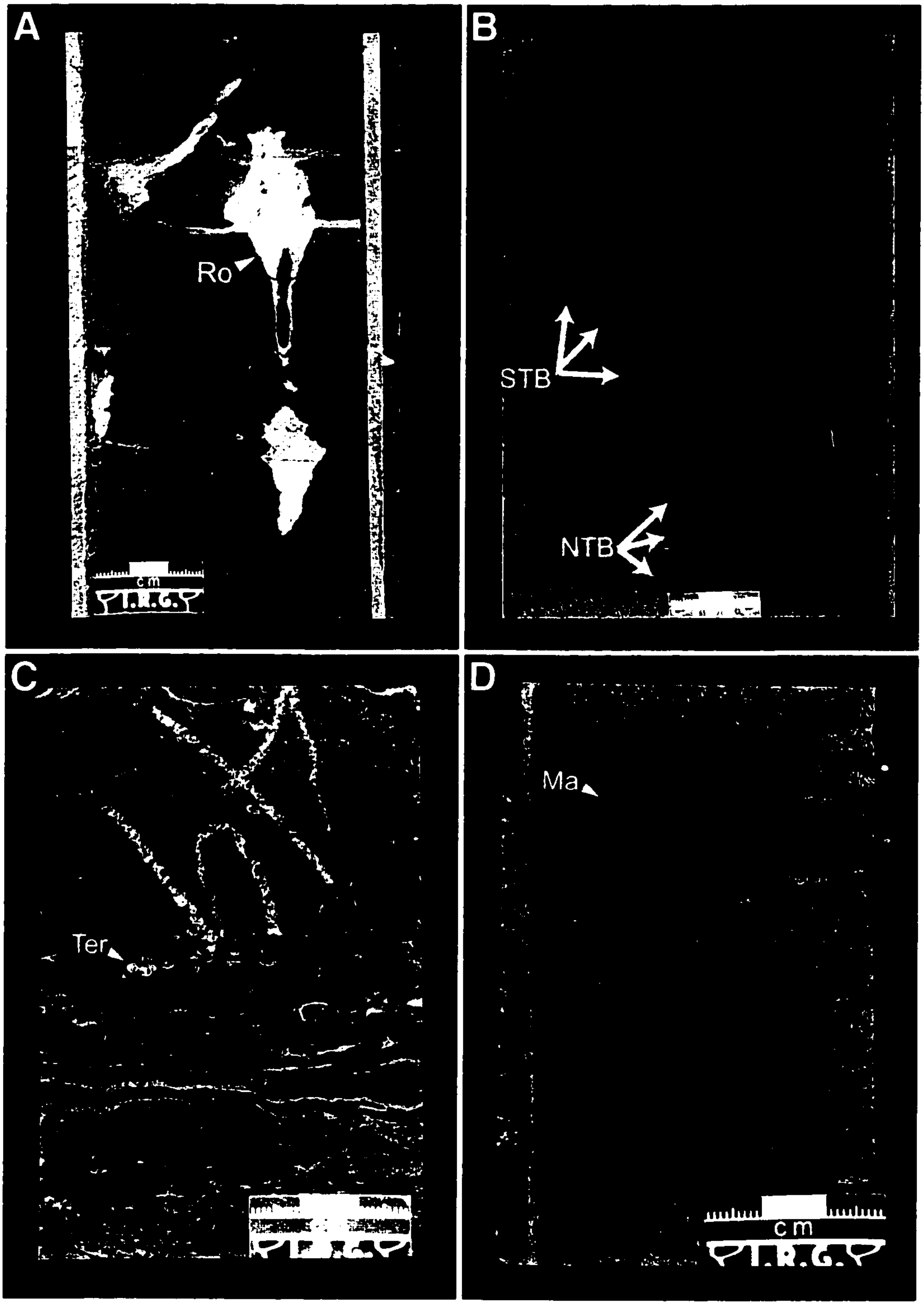


Fig. 2.18. Lower estuary deposits of the Bluesky Formation. **a)** Facies F6, bitumen saturated tidal channel sandstone with robust *Rosselia* (Ro) (14-11-83-20W5, 597.54m). **b)** Facies F8, well-sorted tidal delta deposits with distinctive spring-tidal beds (STB) and neap-tidal beds (NTB). The angle of cross-bedding is exaggerated as the core is from a deviated well (09-16-85-18W5, 624.1m).---------->

-----> **c)** Facies F9, washover sandstone with common coal beds. Note the *Teredolites* (Ter) with the *in-situ* boring bivalves preserved (13-17-83-20W5, 578.8m). **d)** Facies F10, *Macaronichnus* (Ma) within shoreface sandstone (14-02-84-20W5, 552.88m).

present in varying abundances. Facies 7 typically gradationally overlies, and is interbedded, with F6 (Fig. 2.14).

Heterolithic wavy bedding is the most common primary physical structure observed, with planar parallel bedding present in mud-dominated intervals. The trace fossil suite consists of common *Planolites, Skolithos, Cylindrichnus* and *Palaeophycus*, with *Thalassinoides, Rosselia, Chondrites, ?Subphyllochorda, Teredolites* and *Teichichnus* also present locally. Individual units commonly contain 8 to 10 ichnogenera, with moderate to abundant degrees of bioturbation typical.

Interpretation

Facies 7 is interpreted as back-barrier lagoon deposits. Mud dominated units interrupted by sand beds are typical of estuaries within quiet, protected areas such as the lagoon (Oertel, 1985). The low diversity trace fossil assemblage also supports this interpretation (Stewart *et al.*, 1991). These units are differentiated from quiescent bay deposits from the Bluesky Formation by their association with tidal channel, tidal delta, and shoreface deposits (Fig. 2.14). Lagoonal deposits are also characteristically thinner than deposits of the central basin at Peace River.

FACIES 8 - WELL-SORTED CROSS-BEDDED SANDSTONE WITH RARE MUD LAMINAE

Description

Well-sorted, medium grained, quartzose sandstone within the Bluesky Formation characterizes F8 (Fig. 2.5). Deposits of this facies grade laterally into sandstones with common shale interbeds (5-20 %). The average thickness of these units ranges from 15 to

20m. Discontinuous mud-laminae, wood fragments and coally debris is present in rare to moderate abundance. Within this facies, 3 or 4 distinct stratigraphic units can be recognized. The 5 to 6m thick units are typically sharp-based although contacts may be overlooked due to the masking effects of extensive bitumen staining. In the north-central part of the study area, deposits directly overlie Mississippian carbonates. Where the quartzose sands sharply overlie more chert-rich fluvial/deltaic deposits of the Ostracode Zone, the lower contact is often difficult to discern in core (Fig. 2.5). As a whole, the sandstones demonstrate a blocky grain-size profile, with a characteristic thin (<3m) coarser grained lag present locally.

Dominant physical sedimentary structures change vertically through F8. Low angle cross-stratification is pervasive in the lower sands, grading into units characterized by planar parallel bedding upwards. Within low to high angle cross-stratified units, individual beds range in thickness from 0.4cm to 1.2cm, and occur in bundles with regular cyclicity (Fig. 2.18b). Massive sandstones are also common locally. Bioturbation is rare to absent within this facies. Diminutive *Thalassinoides*, *Cylindrichnus* and *Planolites* are observed exclusively within mudstone laminae.

Interpretation

Clean, well-sorted sandstones of F8 are interpreted as tidal delta deposits. More marginal of clean sands, deposits are muddier and characterized by more biogenic reworking. The lack of burrowing in the clean sands relative to more marginal deposits is controlled by the lateral decrease in flow energy and the subsequent changes in sedimentation rates within the delta (Rossetti, 1998). The thinning and thickening of tidal bundles within F8 may be indicative of spring-neap tidal cycles (Boersma and Terwindt, 1981; Yang and Nio, 1985; Fig. 2.18b). The thicker bundles were likely deposited by higher-energy spring tides whereas bundles characterized by thinner beds were deposited in less energetic neap tidal cycles.

The linear trend of the large sand body perpendicular to the paleo-shoreline also supports a tidal delta interpretation (Figs. 2.8e,f). Sandstones of F8 prograde in both an east and west direction due to flood- and ebb-tidal currents respectively (Fig. 2.15). Quartzose sand grains are also well-sorted and rounded; this is typical of tidal delta sediments which have undergone significant reworking by waves and currents (Imperato *et al.*, 1988).

FACIES 9 - SANDSTONE WITH COMMON WOOD AND COAL DEBRIS

Description

Medium grained, moderately well-sorted sandstone with numerous (25-35%) organic shale and coal laminae characterize F9 (Fig. 2.18c). Wood fragments and reworked shelly material is moderately abundant within this facies. These deposits lie exclusively in the western part of the study area, occurring with limited areal extent. Facies 9 is difficult to characterize due to poor core control in the western portion of the study area (Fig. 2.1). Deposits of F9 sharply overlie sandstone facies of FA3.

Diagnostic physical structures include common, sand-dominated heterolithic wavy bedding. Oscillation ripples within clean, <1m thick sandy units are present in moderate abundances locally. The trace fossil suite consists of rare *Cylindrichnus*, and *Teichichnus*. *Teredolites* is present in some coally laminae (Fig. 2.18c).

Interpretation

Facies 9 is interpreted to represent washover-fan deposits. Abundant wood and coal suggest proximity to an exposed area, in this case possibly the associated barrier bar. Sandy units with oscillation ripples were deposited during major storm events. Strong marine influence is suggested by the trace fossil assemblage present, especially *Teredolites*. This individual trace fossil is known to occur only in fully marine or high-salinity brackish water settings (Bromley *et al.*, 1984). Geometry of these deposits is poorly understood in the study area due to the poor core control in the western portion of the study area.

Fine-grained coally units represent deposition between storms, thus separating individual washover deposits. Individual sand units are typically less than 4cm thick, characteristic of washover units deposited within a single storm event (Reinson, 1992). The cumulative thickness of washover fan deposits can reach up to 7 m in the westernmost portion of the study area. Composite bodies created by washover fans are common due to the fact that storms often iteratively exploit major breaches through the barrier island in successive storms (McGowen and Scott, 1975).

FACIES 10 - DIVERSELY BURROWED, OSCILLATION RIPPLED SANDSTONE

Description

Sandstones and silty sandstones with rare mud are characteristic of F10. This facies is present exclusively within cores located west of Township nineteen West of the Fifth Meridian. Well-sorted, calcareous sands are also common locally. All sands are characteristically fine-grained. Wood fragments and organic shale laminae are rare to absent. The facies sharply overlies F7, F8 and F9 (Fig. 2.15).

Oscillation ripples are the most common physical sedimentary structure present. Hummocky cross-stratification and planar parallel bedding is rarely observed. Calcareous sands are characteristically massive.

Trace fossil assemblages vary considerably within F10. Common traces present include robust *Macaronichnus, Helminthopsis, Asterosoma, Schaubcylindrichnus, Chondrites, Teichichnus, Planolites, Skolithos, Rosselia,* and *Cylindrichnus*. Overall, bioturbation is rare to moderate however individual deposits typically contain diverse ichnofossil assemblages.

Interpretation

The moderate degree of bioturbation, with a *Skolithos* to mixed *Skolithos-Cruziana* ichnofacies suggests deposition in a fully marine, shoreface environment. *Macaronichnus* is diagnostic of shoreface deposits (Clifton and Thompson, 1978; Saunders and Pemberton,1986; Fig. 2.18d). Common oscillation ripples and hummocky cross-stratification attributed to wave reworking are also typical of shoreface deposits. The location of marine sandstones west of estuarine sandstones and mudstones, and their association with washover fan deposits, further supports the interpretation (Fig. 2.15).

The sharp, lower contact of facies F10 is interpreted as a ravinement surface (Fig. 2.15). As the shoreface transgressed in an eastward direction, estuarine deposits were eroded and reworked. This surface is restricted to the western portion of the study area and is not considered to have temporal significance. Shoreface deposition in this area is consistent with regional interpretations of the Bluesky Formation from western Alberta (O'Connell, 1988; 1998; Ranger and Pemberton, 1991; Brekke and Pemberton, 1994).

FACIES ASSOCIATION 4: TRANSGRESSIVE SHORELINE DEPOSITS

Glauconitic muddy sandstone (F11) is the predominant recurring facies within FA4. FA4 occurs in 1 to 4m thick intervals, and is bound by discontinuity surfaces across the southern and western reaches of the study area. Facies Association 4 overlies the various facies of the Bluesky Formation, and it is sharply overlain by deep-marine shales of the Wilrich Member (Spirit River Formation) (Figs. 2.12-2.15).

FACIES 10 - GLAUCONITIC MUDDY SANDSTONE

Description

Facies 11 is a thin, transgressive unit varying from sandy shale to silty sand. Associated deposits are present over most of the southern and western portions of the study area. Abundant glauconite gives the deposits a characteristic green colour. The deposit is sharp based across the study area, and it is often associated with a lag consisting of argillite granules and chert pebbles less than one centimeter in diameter.

This facies is typically sharply overlain by deep marine mudstones of the Wilrich Member.

Primary physical structures within transgressive deposits are typically obliterated by biogenic reworking. In some cases heterolithic wavy bedding or planar parallel bedding is preserved. Mudstone laminae, sandstone laminae and coally debris are rarely present.

The glauconitic units are typically extensively bioturbated (Fig. 2.19). Robust *Diplocraterion, Teichichnus* and *Palaeophycus* are the most common traces observed, with *Arenicolites, Planolites, Skolithos, Thalassinoides, Cylindrichnus, Rosselia* and *Chondrites* also observed locally.

Interpretation

Facies 11 is interpreted to be a transgressive shoreline deposit. The upper and lower contacts of the facies represent transgressive surfaces of erosion, resulting from significant fluctuations in sea-level (Fig. 2.15). The sharp based nature of the deposits, a

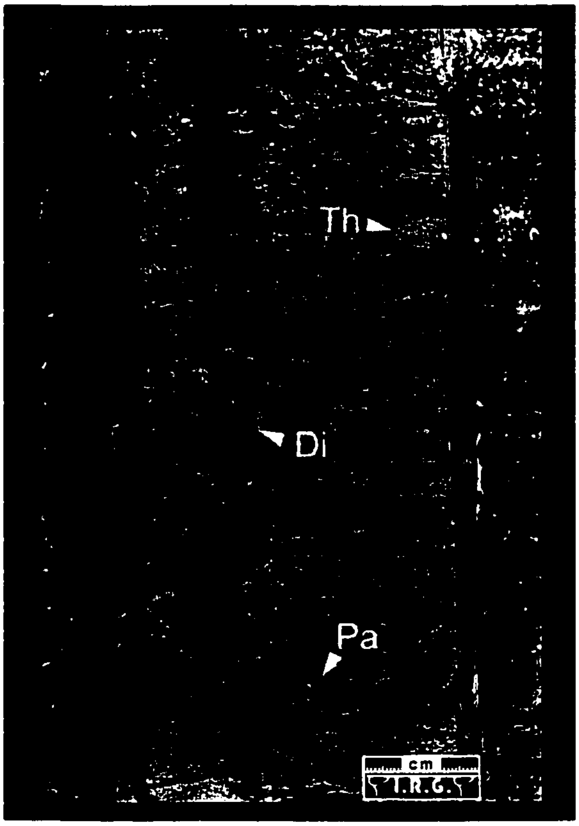


Fig. 2.19. Transgressive shoreline deposit of FA4 (Bluesky Formation): facies F10, glauconitic sandstone in the uppermost unit of the Bluesky Formation in the study area. The fully marine deposit contains robust *Thalassinoides* (Th), *Diplocraterion* (Di), and *Palaeophycus* (Pa) (16-08-84-20W5, 525.2m).

basal lag consisting of pebbles and granules, and a regional persistence of the facies supports this interpretation. This unit has been recognized across central Alberta (O'Connell, 1988; Brekke and Pemberton, 1994; Terzuoli and Walker, 1997; O'Connell, 1998), deposited as the Boreal Sea transgressed across the region at the end of Bluesky time. Fully marine deposition is supported by the diverse trace fossil assemblage present (Raychaudhuri *et al.*, 1992). Facies 11 represents the uppermost unit of the Bluesky Formation where present (Figs. 2.12-2.15).

DISCUSSION

The lowermost 10-12m of the study interval (Ostracode Zone) is summarized depositionally in Figure 2.20a. Facies analyses indicate that this interval is predominantly mudstone with silty and sandy beds throughout. Localized sands are also present across the study area, typically located in proximity to the Red Earth Highlands. The interpreted depositional environment consists of small fluvial channels draining off the highlands into a large brackish-water basin. As the sands accumulated along the margin of the bay in localized deltas, reworking by longshore currents resulted in the formation of elongate, shore-parallel sand bodies. The local interpretation corresponds with the regional paleogeographic interpretation of the Ostracode Zone as proposed by McLean and Wall (1981).

The Bluesky Formation is represented by the upper 15-20m of the study interval at Peace River. The interpreted depositional model consists of a complex, wave-dominated, micro- to meso-tidal estuarine environment consisting of bayhead delta/ fluvial sandstones, central basin mudstones and marine sandstones (Fig. 2.20b). This tripartite facies zonation conforms to the wave-dominated estuary facies model as proposed by Dalrymple *et al.* (1992). Figure 2.21 compares the facies distribution in a longitudinal section through an idealized wave-dominated estuary with a similarly oriented cross-section through the Bluesky Formation at Peace River.

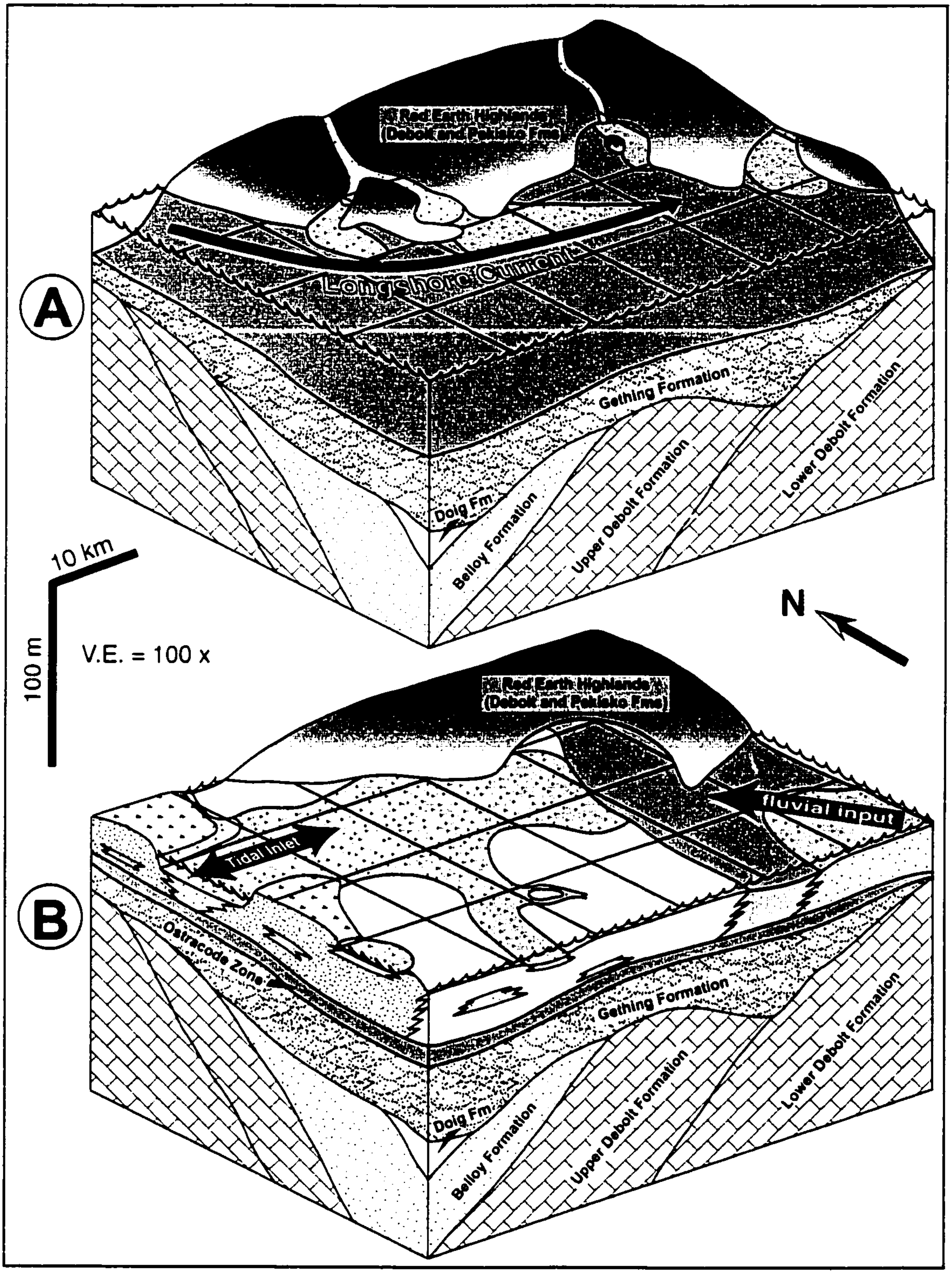
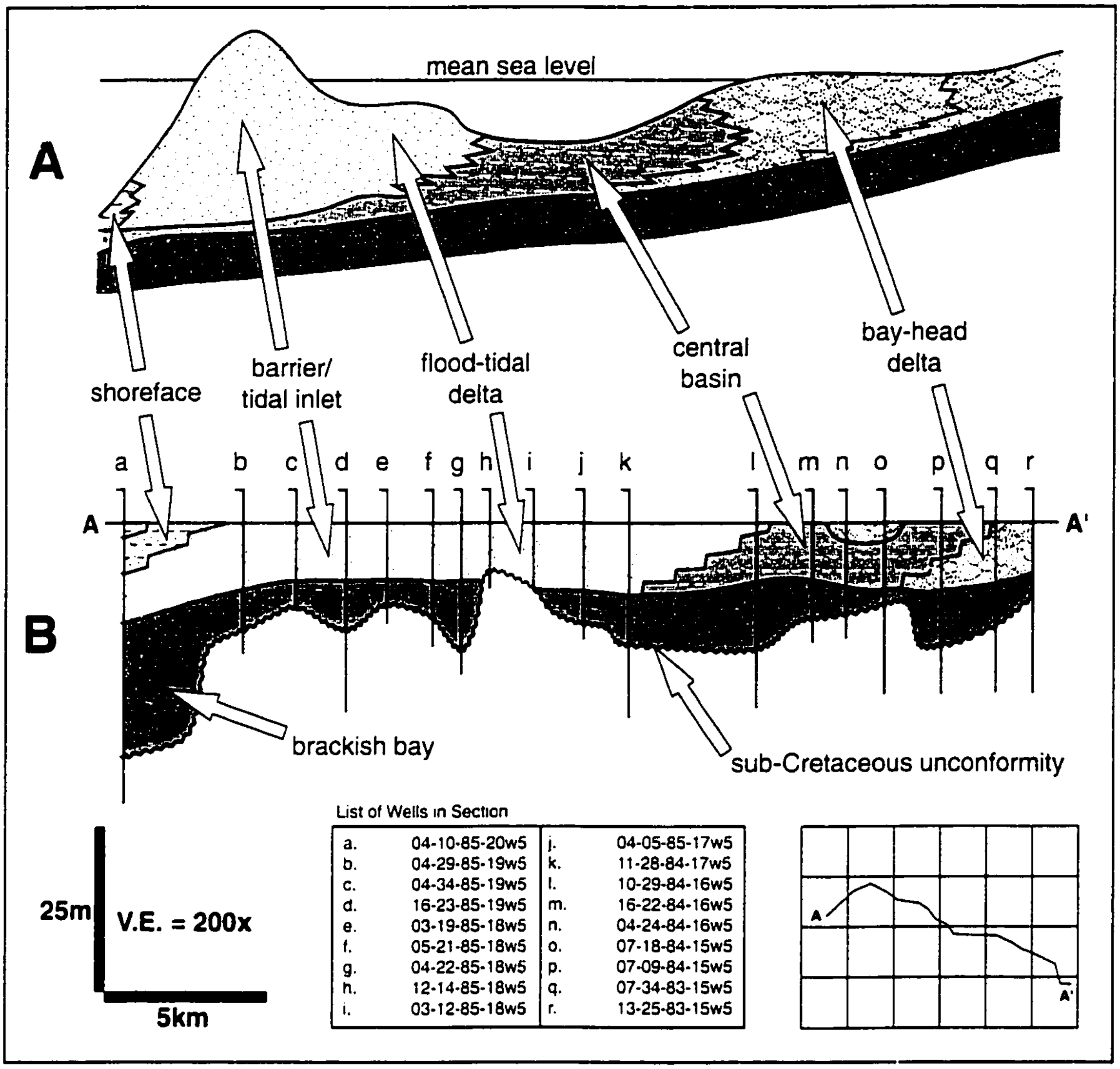


Fig. 2.20. Schematic diagram illustrating the generalized depositional environments interpreted within the study interval at Peace River: **a)** brackish bay of the Ostracode Zone; **b)** wave-dominated estuarine complex of the Bluesky Formation.



List of Wells in Section

a.	04-10-85-20w5	j.	04-05-85-17w5
b.	04-29-85-19w5	k.	11-28-84-17w5
c.	04-34-85-19w5	l.	10-29-84-16w5
d.	16-23-85-19w5	m.	16-22-84-16w5
e.	03-19-85-18w5	n.	04-24-84-16w5
f.	05-21-85-18w5	o.	07-18-84-15w5
g.	04-22-85-18w5	p.	07-09-84-15w5
h.	12-14-85-18w5	q.	07-34-83-15w5
i.	03-12-85-18w5	r.	13-25-83-15w5

Fig. 2.21. Facies distribution in a longitudinal section through an idealized wave-dominated estuary (**a**), with a similarly oriented cross-section through the Bluesky Formation at Peace River (**b**). Part A is modified from Dalrymple *et al.* (1992). Datum utilized in part B is the top of the Bluesky Formation.

Deposits of certain sub-environments in wave dominated estuaries are absent from the Lower Cretaceous sedimentary record at Peace River. Specifically, barrier-bar and tidal inlet deposits are not present. This is not uncommon in transgressive successions as these deposits are cannibalized due to shoreface retreat in a landward direction (Dalrymple *et al.*, 1992). Additionally, poor well control in the westernmost reaches of the study area has a limiting effect on the interpretations made.

Cretaceous wave-dominated estuarine deposits from the Western Canada Sedimentary Basin have been documented in the literature (Karvonen, 1989 – Ostracode Zone; Zaitlin and Shultz, 1990 – Lloyminster Member; Pattison, 1992 – Viking Formation; Terzuoli and Walker, 1997 – Bluesky Formation; Broger *et al.*, 1997- Glauconitic Sandstone). Phased advances of the Boreal Sea from the north across the basin created optimum conditions for wave-dominated estuary development periodically throughout the time period.

Across most of northwestern Alberta, the Bluesky Formation consists of coarsening upwards cycles deposited in shoreface and offshore bar, marine environments (Jackson, 1984). At Peace River however, facies present are lithologically diverse, typical of estuarine environments (Howard and Frey, 1973; Clifton, 1982; Gingras *et al.*, 1999). Estuarine deposits at Peace River and fully marine deposits observed further westward are separated by a hinge line that roughly mimics the Permian Belloy Formation subcrop edge in the western portion of the study area (Fig. 2.7). This is attributed to the resistant nature of the Mississippian carbonates further eastward of the less resistant Belloy Formation sandstones. Differential erosion of these units, in effect, provided the location of the shelf-break separating estuarine from more fully marine deposition to the west. The interpreted paleogeographic setting prevalent during deposition of the Bluesky Formation and equivalent lithostratigraphic units across central Alberta is outlined in Figure 2.22.

SUMMARY AND CONCLUSIONS

1) With greater than 100 billion barrels of heavy oil contained in the deposit, the Peace River Oil Sands represent a significant part of the future of the oil and gas industry in Western Canada.

2) The basal Cretaceous depositional framework in the Peace River area consists of a transgressive succession comprised of: i) fluvial/non-marine deposits of the Gething

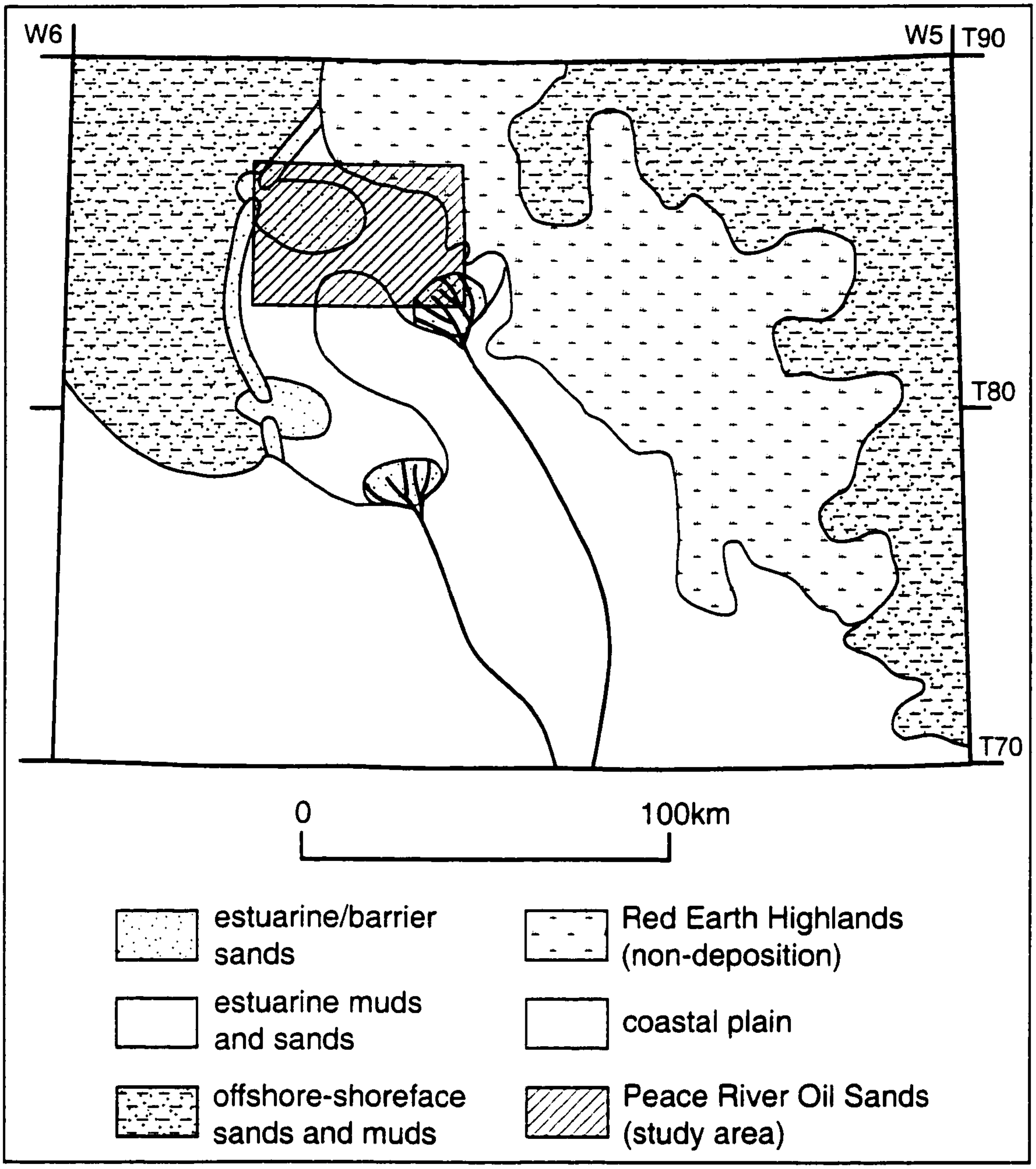


Fig. 2.22. Schematic diagram of the interpreted regional paleogeographic setting prevalent during deposition of the Bluesky Formation and equivalent lithostratigraphic units across central Alberta.

Formation, ii) brackish bay and associated deposits of the Ostracode Zone, and iii) wave-dominated estuarine deposits of the Bluesky Formation.

3) Exploitable bitumen from the Peace River Oil Sands is predominantly in the Ostracode Zone and Bluesky Formation. Where sandstones of both lithostratigraphic

units coincide vertically, net sand can reach thicknesses of > 30 m.

4) Basin paleotopography played a key role in sedimentation during deposition of basal Cretaceous strata at Peace River. Specifically, the Red Earth Highlands and faults associated with the underlying Peace River Arch were of utmost importance.

5) Post-Bluesky deposition faulting is present locally, affecting facies distribution trends and steam chamber development during bitumen production.

Through an understanding of reservoir facies distribution, future development of bitumen from the Peace River Oil Sand Deposit should be significantly enhanced. Sedimentologically, the study provides an understanding of the relationship between marginal marine/shoreface deposits of the Wabiskaw Member to the east, and the Bluesky Formation to the west of the study area.

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CHAPTER 3 - A SEDIMENTOLOGICAL COMPARISON OF A LOWER CRETACEOUS ESTUARINE DEPOSIT FROM WESTERN CANADA WITH MODERN AND PLEISTOCENE ANALOGS FROM WILLAPA BAY, WASHINGTON

INTRODUCTION

Modern estuarine deposits have been utilized widely to assist in identifying similar accumulations in the rock record. Several researchers have demonstrated the utility of actualistic studies where applied to ancient estuaries (e.g., Reineck and Singh, 1967; Howard and Frey, 1973; Clifton and Phillips, 1980). However, there is a marked paucity of comparative (subsurface to actualistic) research in the recent literature. This is unfortunate as the recognition of lateral variation and the delineation of key subenvironments provide the tools needed for resolving complex geometric problems, predicting compartmentalization of potential reservoirs, and identifying pool-edge indicators in the subsurface. Outcrop-based studies and an understanding of modern estuarine processes may provide some of the solutions to these complex geological problems.

At Willapa Bay in southwestern Washington, Pleistocene outcrops present a unique opportunity to compare modern data with analogous ancient data and consider their significance in the light of a well-documented sedimentologic and stratigraphic framework (Clifton and Phillips, 1980; Clifton, 1982; Anima *et al.*, 1989). These comparisons reveal the complexities that are inherent in estuarine deposits. These complexities are exemplified when attempting to use modern and Pleistocene deposits from Willapa Bay as analogs to older deposits from the Western Canada Sedimentary Basin.

Numerous examples of estuarine deposits from across the Western Canada Sedimentary Basin have been recognized over the past two decades (Pemberton *et al.*, 1982; Reinson *et al.*, 1988; Beynon *et al.*, 1988; Bhattacharya, 1989; Karvonen, 1989; Zaitlin and Shultz, 1990; Boreen and Walker, 1991; MacEachern and Pemberton, 1994; Terzuoli and Walker, 1997; Hubbard *et al.*, 1999). During the Cretaceous, conditions conducive for the development of estuarine systems developed periodically as the Boreal Sea cyclically transgressed from the north across the basin. For this study deposits of the Lower Cretaceous Bluesky Formation (lowermost Albian), from the Peace River (townsite) area of north-central Alberta, are used to compare with deposits from Willapa Bay. Hubbard *et al.* (1999) interpreted the Bluesky Formation in this area as representing a wave-dominated estuarine depositional setting. Locally this formation, along with underlying basal Cretaceous deposits of the Gething Formation and Ostracode Zone, is economically significant as it contains over 80 billion barrels of heavy oil (Alberta Energy and Utilities Board, 1997).

Despite the sedimentologic and stratigraphic complexity characteristic of estuaries, it has been demonstrated that they can be modeled with some success (Roy *et al.*, 1980; Dalrymple *et al.*, 1992). The diagnostic tripartite zonation of wave-dominated estuaries has been recognized in numerous modern (Allen, 1991; Dorjes and Howard, 1975; Nichols *et al.*, 1991; Nichol, 1991; Boyd and Honig, 1992; Nichol *et al.*, 1997) and ancient deposits (Pattison, 1992; MacEachern and Pemberton, 1994; Broger *et al.*, 1997; Lessa *et al.*, 1998; Rossetti, 1998; Hubbard *et al.*, 1999). Commonly individual estuarine complexes do not fall into the tripartite model of the idealized estuarine system. This can result from numerous factors including fluvial sediment supply, tidal range, tectonic setting, stage of estuarine fill, and estuary geomorphology.

The current study aims to: (1) compare and contrast the Lower Cretaceous Bluesky Formation with modern and Pleistocene estuarine deposits from Willapa Bay, (2) enhance evolving estuarine facies models, particularly in the interpretation of ancient, subsurface core-based deposits, and (3) demonstrate the value of understanding and applying ichnology in the interpretation of complex brackish water deposits.

GEOLOGIC SETTING AND STUDY AREA

WILLAPA BAY, WASHINGTON

Willapa Bay is located in the southwest corner of the state of Washington (Fig. 3.1). It measures approximately 40km in a north-south orientation and it is up to 11km wide. Data for the modern component of this study were collected from several locations in the bay. Intertidal flat, tidal point bar, channel and inlet deposits were examined. Analogous Pleistocene deposits are exposed along the eastern and northern margins of the bay (Fig. 3.1). Over 30 measured sections along this outcrop belt form the Pleistocene database for this study. Willapa Bay is a mesotidal estuary with a tidal range of 2 to 3m. The tidal prism exceeds 700,000m^3, comprising about 45% of the bay's total volume (U.S. Army Corps of Engineers, 1975).

Sediment accumulations at Willapa Bay are siliciclastic (Fig. 3.2a). Sandy deposits dominate the lower estuary, whereas the upper estuary is primarily mud-dominated. Fluvial input into the bay is shared by 5 rivers from the east and the north, however, tidal currents deliver the majority of coarse siliciclastics into the bay (Luepke and Clifton, 1983). The bay is separated from the Pacific Ocean to the west by a 27km long spit (North Beach Peninsula) formed from sediment discharged from the Columbia River that was subsequently redistributed by longshore currents in a northward direction. The uplifted Pleistocene deposits, along with highlands comprised of volcanic bedrock confine the bay on the southern, eastern and northern margins.

The Pleistocene deposits have been informally separated into an "older" and a "younger" terrace set (Clifton and Phillips, 1980). Younger Pleistocene deposits were deposited between 100,000 and 200,000 years before present (Kvenvolden *et al.*, 1979); the older strata have not been reliably dated. These strata are interpreted to represent sediment accumulation under estuarine conditions (Clifton and Phillips,1980; Clifton *et*

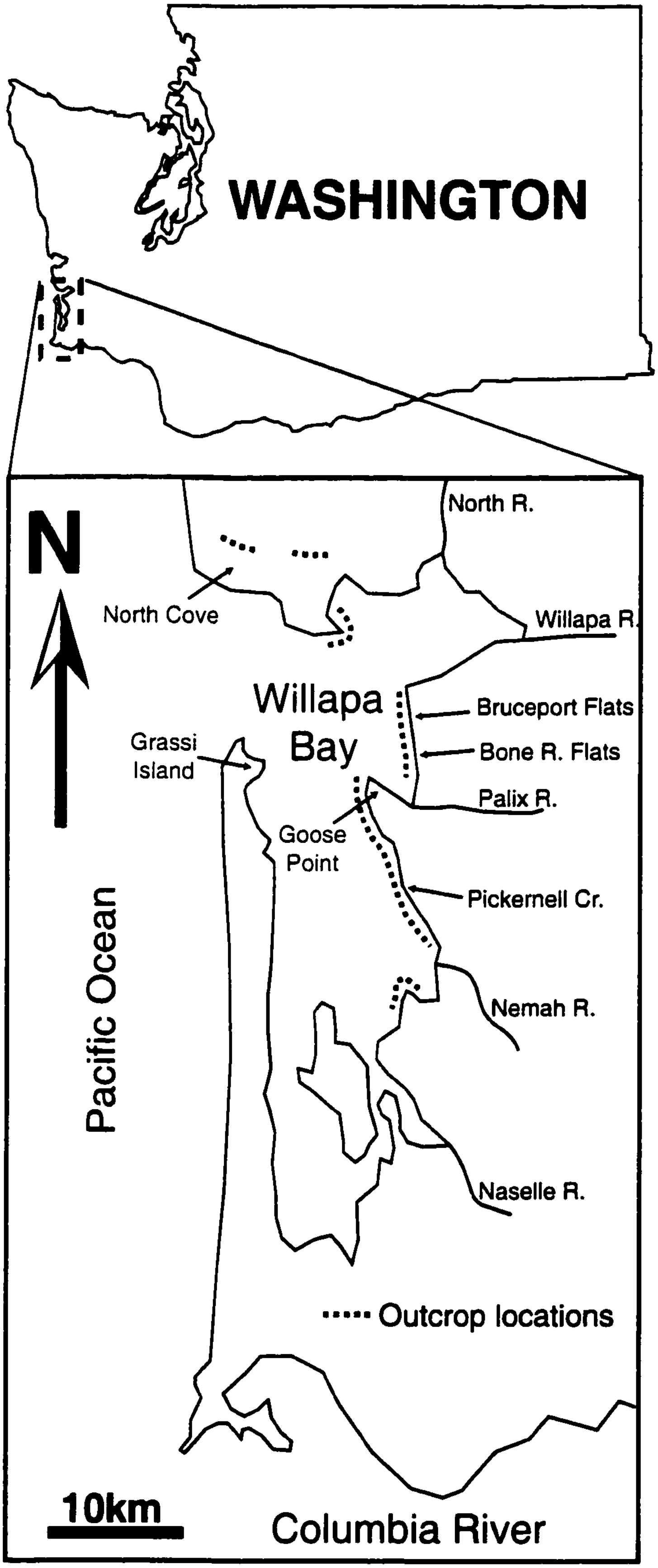

Fig. 3.1. Location map of Willapa Bay, Washington. The locations of Pleistocene outcrops studied are delineated, as are numerous features mentioned in the paper.

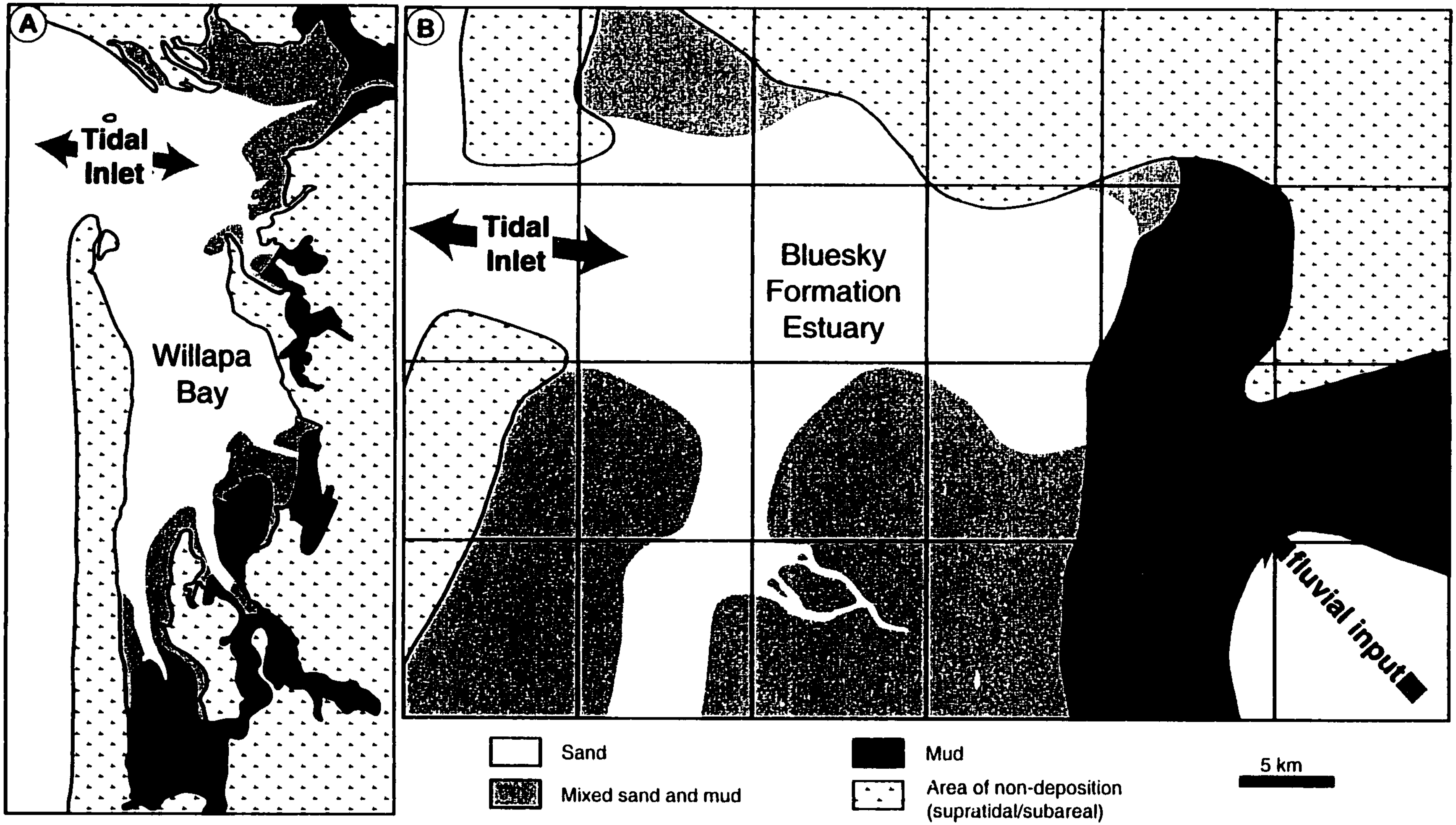

Fig. 3.2. a) Sediment texture of modern deposits in Willapa Bay, Washington (modified from Clifton, 1983). The sands represent lower to middle estuary deposits whereas mud, and areas of mixed sand and mud represent middle to upper estuarine deposits. **b)** Schematic depositional model and sediment ----->

-----> distribution in the Lower Cretaceous Bluesky Formation at Peace River, Alberta (modified from Hubbard *et al.*, 1999). Sandstones in the western/central portion of the study area represent lower estuary deposits; mixed sandstones and mudstones, and mudstone dominated deposits represent middle estuary deposits; sandstones in the southeastern part of the area were deposited in the upper estuary.

al., 1989; Gingras *et al.*, 1999). Sedimentological and ichnological data indicate, that at times, the ancient bay was remarkably similar to the modern bay (Clifton and Phillips, 1980; Gingras *et al.*, 1999). Many examples of subtidal through supratidal deposits have been identified in these strata (Clifton *et al.*, 1989). These data are supported by research carried out in the modern bay.

Intermittent convergence and subduction of the Juan de Fuca Plate beneath the North American Plate throughout Pleistocene to modern times has had a significant impact on the Pacific Coast of North America, including Willapa Bay (Dupré *et al.*, 1991). Repeated tectonic uplift has resulted in the exposure of the Pleistocene deposits surrounding the bay. Another significant factor influencing bay morphology and fill is repeated fluctuations in sea level related to periods of glaciation.

LOWER CRETACEOUS BLUESKY FORMATION ESTUARY

The Lower Cretaceous Bluesky Formation was studied in an area between Townships 83 – 86, and Ranges 15 – 20W5, in the central Alberta plains of the Western Canada Sedimentary Basin (Fig. 3.3). In this area, the main axis of a large estuarine complex extends approximately 55km in an east-west orientation, varying significantly in width (Fig. 3.2b). The maximum width in a north-south direction reaches approximately 27km. The maximum fill thickness of the estuary ranges between 15 and 20m, zeroing out to the north and the east. In the study area, the Bluesky Formation is located exclusively in the subsurface at an average depth between 500 and 600m. The sedimentologic database includes approximately 220 wells, 55 of which were cored

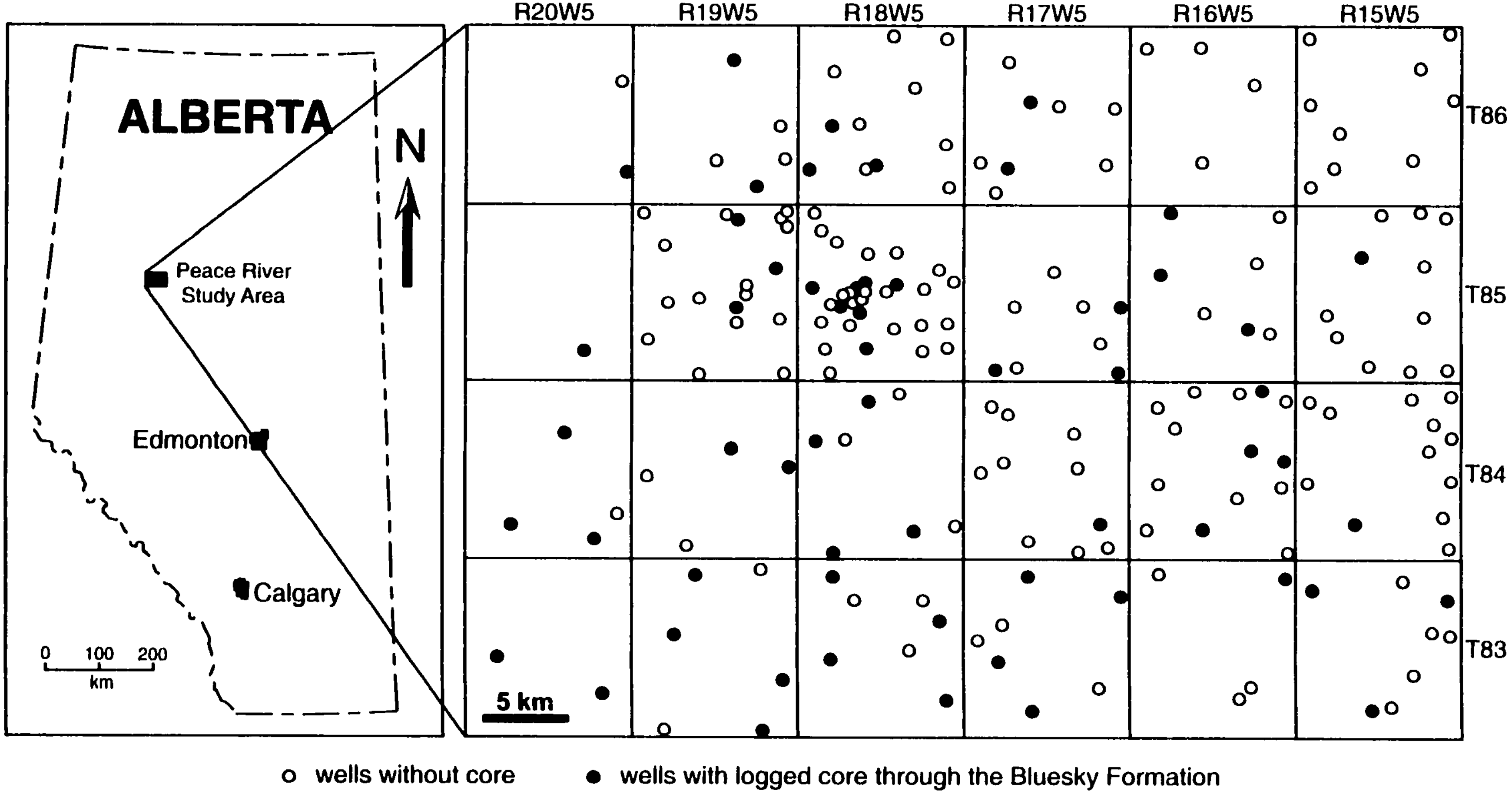

Fig. 3.3. Location map of the Lower Cretaceous study area in north-central Alberta. The detailed map shows the wells utilized in the study.

through the Bluesky Formation (Fig. 3.3). At Peace River, a micro- to meso-tidal range is postulated based on sediment distribution and detailed sedimentologic observations (Hubbard *et al.*, 1999).

Fluvial input into the estuarine complex originated to the southeast of the study area, with bayhead delta deposits restricted to this region (Fig. 3.2b). To the north and east the estuary is bounded by a paleo-highland comprised of Mississippian carbonates which remained exposed throughout Bluesky time. Marine shoreface deposits are present in the westernmost portion of the study area in the Bluesky Formation. Tidal inlet and barrier island deposits have not been recognized as a result of: (a) their erosion by the terminal transgressive event that ceased estuarine depostion, and/or; (b) extremely poor core control in the westernmost portion of the study area. The location of the paleo-tidal inlet is estimated based on the recognition of associated tidal delta, tidal channel, washover fan, lagoon and shoreface deposits.

The Basal Cretaceous sedimentary package overlies the sub-Cretaceous unconformity, a surface representing a hiatus of between 120 and 230 million years across the study area. The stratigraphic interval consists of the dominantly fluviatile Gething Formation and brackish bay deposits of the Ostracode Zone underlying the Bluesky Formation, and overlying marine mudstones of the Spirit River Formation (Fig. 3.4). The succession does not contain a significant, traceable sequence boundary, and it represents an overall transgressive phase from Aptian through to lowermost Albian time.

The Bluesky Formation was deposited in a foreland basin, created by the Middle Jurassic – Lower Cretaceous Columbian Orogeny. Sedimentation trends in basal Cretaceous deposits of the Peace River region are related to topographic lows in the unconformity surface (Fig. 3.4; Hubbard *et al.*, 1999). These lows have been demonstrated to be closely linked with faulting associated with the Peace River Arch, a well-documented basement structural feature known to have gone through cycles of uplift and subsidence throughout the Paleozoic and Mesozoic (Williams, 1958; Jackson, 1984; Cant, 1988).

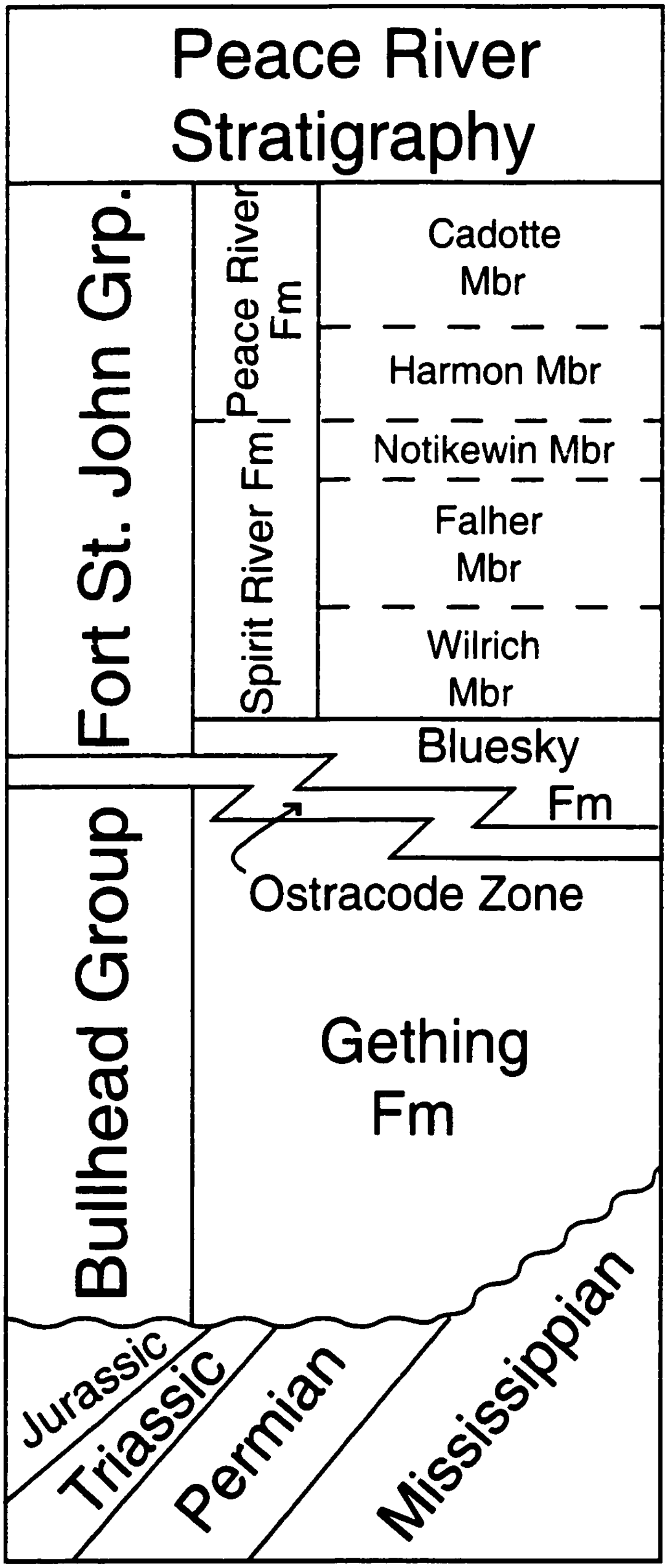

Fig. 3.4. Subsurface Lower Cretaceous stratigraphic nomenclature for the Peace River region of north-central Alberta.

OBSERVATIONS

A summary of facies from modern and Pleistocene deposits at Willapa Bay has been established (Clifton and Phillips, 1980; Clifton *et al.*, 1989; Gingras *et al.*, 1999), and included in Table 3.1. A detailed facies analysis of the Bluesky Formation has previously been completed from the Peace River area (Hubbard *et al.*, 1999). A summary of the results of this study is provided in Table 3.2. For comparative purposes, the deposits are summarized in three distinctive estuarine divisions: 1) upper estuary, 2) middle estuary, and 3) lower estuary.

UPPER ESTUARY DEPOSITS

The upper estuary at Willapa Bay consists of large, mud-dominated fluvial channels with associated point bars, as well as intertidal-creeks, -point-bars and -flats (Table 3.1). Deposits are composed predominantly of mud with rare thin sand laminations present locally (Fig. 3.5a). Individual units throughout the upper estuary range from 1 to 5m in thickness. Horizontal bedding in tidal flat deposits, and ripple lamination, low angle cross-bedding and inclined stratification in point bar deposits are typical. Terrestrially derived organic detritus is common throughout upper estuary deposits.

Bioturbation intensity in the upper estuary varies from absent to pervasive. Intertidal point-bars, contain a diminutive assemblage of traces that can include *Palaeophycus-*, *Planolites-*, *Arenicolites-*, *Gyrolithes-* and *Skolithos-* like burrows. A higher diversity assemblage is observed on intertidal flats and on the point bars of the main channels; this assemblage includes *Thalassinoides-*, *Psilonichnus-*, *Cylindrichnus-*, *Siphonichnus-*, *Skolithos-*, *Arenicolites-*, *Gyrolithes-*, *Palaeophycus-* and *Planolites-* like traces. Further up-estuary, the size and diversity of trace fossils is considerably lower however

Depositional Environment	Facies Analog (Bluesky)	Association	Biogenic Structures	Degree of Bioturbation	Physical Structures	Lithology / Accessories	Contacts / Thickness
modern muddy intertidal flat	Facies B, C(?)	upper and middle estuary	Th, Ps, Cy, Tr, Si, Sk, Ar, Pa, Pl, Ro	mod. to complete	typically vestigial horizontal bedding normally	organic detritus, oxide stain, shell debris, 50-60% < phi 4 sand typ fine to v. fine	gradational / burrowed with intertidal point-bar undetermined tk.
Pleistocene muddy intertidal flat	Facies B, C(?)	upper and middle estuary (?)	Sk, Ar, Gy, Cy, Pl, Pa, Th, Ps; typically diminutive	mod. to complete	typically vestigial horizontal bedding	abundant organic detritus fine sand laminae appx. 60 to 80% < phi 4	gradational / burrowed with intertidal point-bar 1 to 3 m tk.
modern intertidal point-bar	Facies B(?)	upper and middle estuary	diminutive Pa, Pl, Ar, Tr, Sk	absent to mod.	ripple lamination, low angle lamination, inclined bedding, soft sediment deformation	terrestrial organic detritus TOC 5 to 8%, thin sand lam appx. 50% finer than phi 4	scoured lower contact demarcated by shells and wood, 1 to 3 m tk.
Pleistocene intertidal point-bar	Facies B(?)	upper and middle estuary	diminutive Pa, Pl, Ar, Gy, Sk	absent to mod.	ripple lamination, low angle lamination inclined bedding, soft sediment deformation, mud couplets, rhythmic bedding	terrestrial organic detritus transported rhizomes (g.s. not measured, appx. Mud)	scoured lower contact demarcated by shells and wood, 1 to 3 m tk.
modern main channel point-bar (mud-dominated)	Facies C and E(?)	upper to middle estuary	Gy, Cy, Pa, Pl, Sk, Ar, Ps	low to mod.	starved ripple lamination, pin stripe lam inclined stratification	terrestrial organic detritus TOC 5 to 11%, thin sand lam variable grain size	scoured lower contact demarcated by shells and wood, several m tk.
modern main channel point-bar (sand-dominated)	Facies D	middle estuary	Gy, Th(r), Cy, Op(r), Pa, Pl, Sk, Ar	low to mod.	ripple lamination, wavey to flaser bedding, inclined heterolithic stratification (IHS), trough cross strat (rare), climbing ripples	terrestrial organic detritus TOC 1 to 6% variable grain size	scoured lower contact demarcated by shells and wood, several m tk.
modern quiescent bay to low energy tidal channel	Facies C, E	middle estuary	Th, Pl, Op(?)	moderate to thorough locally absent	ripple lamination (vestigial ?) planar lam (vestigial ?)	organic detritus, woody and shelly debris, unconsolidated (g.s. varies)	contacts not observed, subtidal several meters thick
Pleistocene quiescent bay deposit	Facies C, E	middle estuary	Op, Th, Te, Ps, Pl, Pa	moderate to thorough	ripple lamination (vestigial ?) planar lam (vestigial ?)	organic detritus, oxide stain rare woody and shelly debris (g.s. varies, typ 60%<phi 4)	variable
modern sandy intertidal flat	Facies B, D rarely H	middle and lower estuary	Th, Ar, Gy(r), Cy(r), Si, Sk, Pl, Pa, generally robust	low or complete	ripple lamination, low angle lamination, thin bedded, scour and fill runoff channels	rare organic detritus appx 80% phi 1 to 3	abrupt to gradational with intertidal point-bar; undetermined tk.
Pleistocene sandy intertidal flat	Facies B, D	middle and lower estuary (?)	Sk, Ar, Pl, Pa, Si, Th, Op typically robust	low or complete	locally massive-appearing ripple lamination, low angle lamination, thin bedded, scour and fill runoff channel	abundant organic detritus fine sand laminae f.g. to m.g. sand (visual est.)	gradational / burrowed with intertidal point-bar 2 to 3 m tk.
modern sandy mid-channel bar	Facies D, G, F(?)	lower estuary	Op, Sk, Th, Pl, Pa	absent to moderate	ripple lamination, low angle lamination inclined bedding (10 degrees), trough cross strat perp to inclined beds	rare organic detritus rare heavy minerals typically m.g. sand	contacts not observed subtidal
Pleistocene sandy mid-channel bar	Facies D, G, F(?)	lower estuary	Op, Th, Te, Sk, Po	absent to rare	ripple lamination, scour and fill, inclined bedding, local flaser to wavey bed rythmic bedding, trough cross strat	organic detritus, oxide stain rare mm-scale shelly debris concentrations of heavy min	sharp lower contact demarcated by shells and wood, meter-scale thickness
Pleistocene sandy tidal inlet/delta	Facies F,D	lower estuary	Th, Ma?, Si	absent to rare	inclined stratification, trough cross-bedding, planar tabular bedding,ripple lamination, sigmoidal bedding	organic detritus, oxide stain, calcareous material, wood clasts, m.g. sand to granule/pebble	sharp, scoured lower contacts with associated pebble lags units 5-7m thick; up to 30m thick

Table 3.1. Summary of modern and Pleistocene facies from deposits studied at Willapa Bay, Washington (Gingras et al., 1999). Abbreviations of trace fossil ---->

---> names included in Tables 3.1 and 3.2: An – *Anconichnus*, Ar – *Arenicolites*, As – *Asterosoma*, Ch – *Chondrites*, Cy – *Cylindrichnus*, Gy – *Gyrolithes*, He – *Helminthopsis*, Ma – *Macaronichnus*, Op – *Ophiomorpha*, Pa – *Palaeophycus*, Pl – *Planolites*, Ps – *Psilonichnus*, Ro – *Rosselia*, Ryz – rhizomes, Sch – *Schaubcylindrichnus*, Si – *Siphonichnus*, Sk – *Skolithos*, Sub – *Subphyllochorda*, Te – *Teichichnus*, Ter – *Teredolites*, Th – *Thalassinoides*, Tr – *Terebellina*.

the degree of bioturbation is sporadically distributed and intense locally.

The Pleistocene record of the upper estuary at Willapa Bay consists of supratidal flat, intertidal flat and point bar deposits. Gravelly lenses are present in sparsely bioturbated channel deposits that outcrop near Pickernell Creek on the west side of the bay. Although no modern analog for these gravels has been observed at Willapa Bay, it is probable they represent Pleistocene upper estuarine deposits.

In the subsurface at Peace River the upper estuary is restricted to the southeastern corner of the study area and consists predominantly of units attributed to bayhead delta deposition (Table 3.2 - facies A). These deposits consist mainly of bitumen saturated lower to upper fine-grained sandstones with varying proportions and thicknesses (up to 0.3m) of interbedded mudstones. The total thickness of these deposits reaches 14m. Cross-bedding and common organic detritus/debris and laminae are characteristic of upper estuary deposits in the Bluesky Formation.

Bayhead delta deposits of the upper estuary in the Bluesky Formation vary considerably with respect to bioturbation intensity. Trace fossils are absent in well-sorted sandy units whereas mudstone interbeds in distal delta deposits contain a trace fossil assemblage consisting of diminutive *Planolites, Thalassinoides, Cylindrichnus* and rare *Skolithos*. Rarely does an individual unit contain a diversity of trace fossils of more than two ichnogenera.

Facies	Physical Sedimentary Structures	Biogenic Sedimentary Structures	Bioturbation and Diverstiy	Lithology/ Accessories	Contacts/ Thickness	Depositional Environment
A Quartzose sandstone with mudstone interbeds	Low angle cross-stratification, planar parallel bedding, trough cross-bedding, HWB	Pl, Sk, Th, Cyl	rare to absent 1 or 2 forms	Wood fragments	Sharp (erosive locally); up to 14m	Upper Estuary
B Burrow-mottled sandstone and mudstone	Sand-dominated HWB, overall fining-upwards profile	Th, Pl, Sk, Cyl, Ryz	high 2 to 4 forms	Pyrite, bioclastic debris, coal fragments	Sharp; <1.5m	Upper to Middle Estuary
C Burrowed heterolithic mudstone and sandstone	HWB	Pl, Sk, Ar, Pa, Cyl, As, Th, Sub, Te	high to pervasive 5 or 6 forms	Pyrite, carbonaceous mud laminae, bioclastic debris	gradational; 6 to 9 m	Middle Estuary
D Well-sorted burrowed sandstone	Planar parallel bedding, low angle cross-stratification, inclined stratification, HWB	Ro, Cyl, Sk, Gyr, escape trace	low 1 to 3 forms	Wood debris, carbonaceous mud laminae, calcareous sand stringers	Sharp (erosive locally with an associated lag); 10 to 15 m	Middle to Lower Estuary
E Burrowed mudstone interbedded w/ sandstone	HWB, planar parallel bedding	Pl, Sk, Cyl, Pa, Th, Ro, Ch, Sub, Ter, Te	moderate to abundant 8 to 10 forms	Wood fragments, carbonaceous mud laminae, pyrite	Gradational; 4 - 5 m	Middle to Lower Estuary
F Well-sorted cross-bedded sandstone	Low angle cross-stratification, planar parallel bedding, tidal bundles, massive locally	Th, Cyl, Pl	rare to absent 1 or 2 forms	Mud laminae, wood debris	Sharp; 5 or 6 m (cumulative - up to 20 m)	Lower Estuary
G Sandstone with common wood debris	HWB, oscillation ripples locally	Cyl, Te, Ter	rare 1 or 2 forms	Wood fragments/ debris, organic mudstone laminae	Sharp; < 10 m	Lower Estuary
H Diversely burrowed, oscillation rippled sand	Oscillation ripples, Hummocky cross-stratification, planar parallel bedding	Ma, He, As, An, Sch, Ch, Te, Pl, Sk, Ro, Cyl	rare to moderate 6 to 10 forms	Calcareous sand beds, wood fragments, organic shale laminae	Sharp; up to 12 m	Lower Estuary/ Shoreface

Table 3.2. Summary of facies from the Bluesky Formation at Peace River, Alberta . Abbreviations are the same as utilized in Table 1.

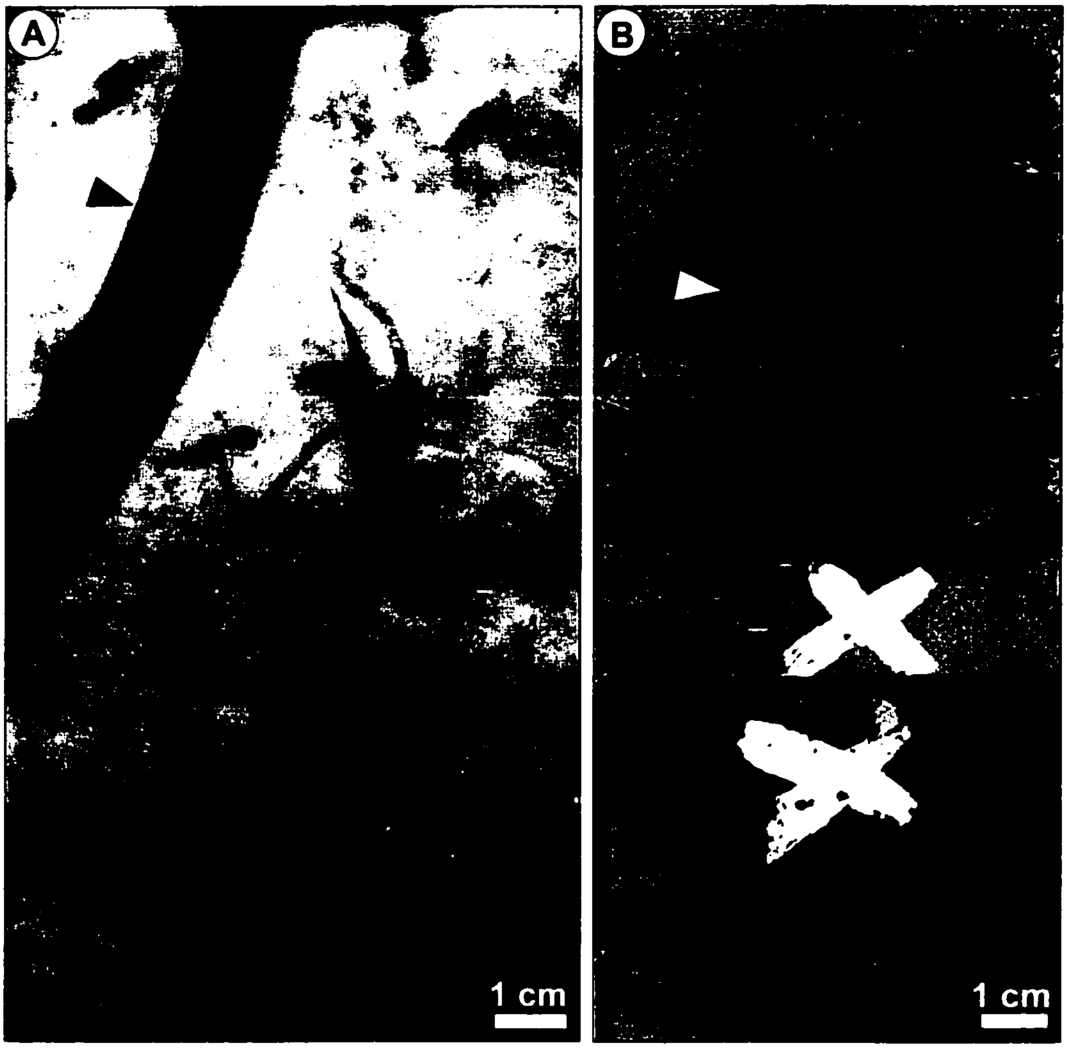

Fig. 3.5. Muddy intertidal flat deposits. **a)** Radiograph of modern sediments from Willapa Bay (Goose Point Mud Flats). **b)** Facies B - Bluesky Formation, 06-33-83-17W5 @ 630m. Arrows point to shrimp burrows in both deposits.

MIDDLE ESTUARY DEPOSITS

The middle estuary at Willapa Bay consists of deposits of numerous sub-environments including tidal channel, subtidal point bar, quiescent bay, intertidal flats, supratidal flats and point bars associated with tidal creeks (Table 3.1). Generally, facies are mud-dominated towards the upper estuary (Figs. 3.5a, 3.6a, 3.7b), and are coarser towards the lower estuary (Figs. 3.8b, 3.9a, 3.10a). Individual facies units are generally

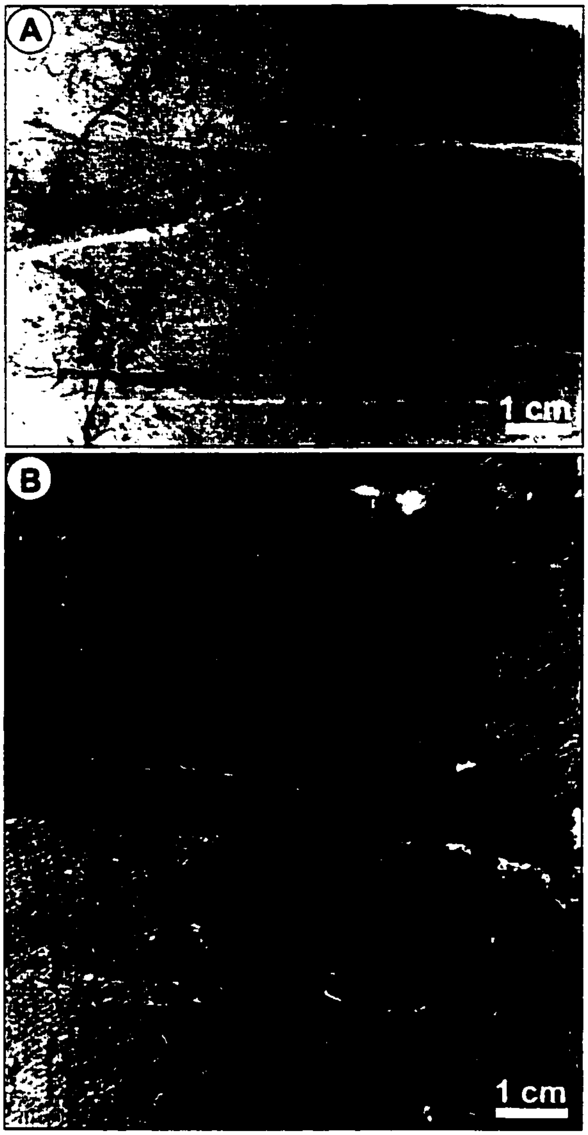

Fig. 3.6. Rootlets in supratidal flat deposits. **a)** Radiograph of modern supratidal flat deposit from Willapa Bay. **b)** Bluesky Formation, 06-33-83-17W5 @ 625.9m.

less than 5m thick. Shell debris and wood fragments are common above scour surfaces associated with point bar deposition. Terrestrial organic detritus is common throughout many facies of the middle estuary.

Bioturbation intensity is variable within middle estuary deposits of Willapa Bay however it typically falls between low to moderate. Although characteristically more thoroughly bioturbated, mud-dominated deposits proximal to the upper estuary contain a relatively low diversity, diminutive assemblage of biogenic structures which can consist of *Gyrolithes-*, *Cylindrichnus-*, *Palaeophycus-*, *Planolites-*, *Skolithos-*, *Arenicolites-*, *Psilonichnus-*, *Thalassinoides-* and *Ophiomorpha*(?)- like burrows. Sand dominated

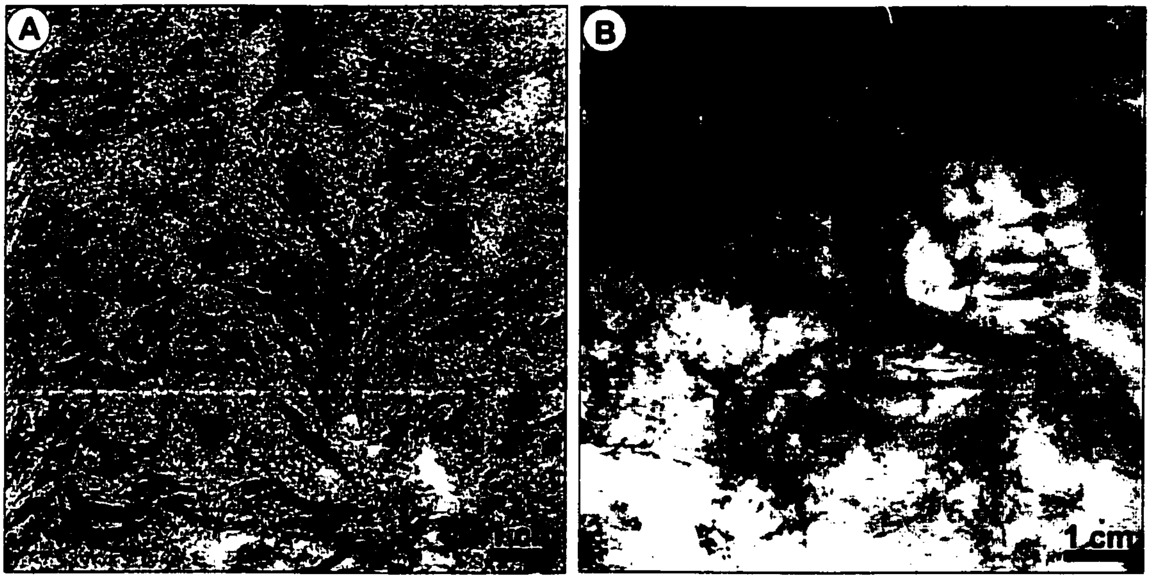

Fig. 3.7. Thoroughly bioturbated quiescent bay deposits. **a)** Facies C - Bluesky Formation, 07-29-84-18W5 @ 573.2m. **b)** Radiograph of modern deposit from Willapa Bay (Grassi Island).

deposits, such as sandy point bars and tidal flats contain a more robust modern biogenic trace assemblage in comparison to mud-dominated deposits. Traces observed are *Thalassinoides-*, *Arenicolites-*, *Siphonichnus-*, *Skolithos-*, *Planolites-*, *Palaeophycus-*, *Gyrolithes-*, *Cylindrichnus-*, and *Ophiomorpha-* like.

Pleistocene middle estuary deposits surrounding Willapa Bay consist of muddy intertidal flat, intertidal point bar and quiescent bay deposits, as well as sandy intertidal flat deposits (Table 3.1). These deposits are typically no greater than 3m in thickness. Physical structures are variable including planar parallel lamination in muddy intertidal flat and quiescent bay deposits, low angle cross bedding in intertidal point bar and sandy intertidal flat deposits, and mud couplets and rhythmic bedding in intertidal point bar deposits. Organic detritus is common in middle estuarine deposits with wood and shell fragments present with less regularity than in the upper estuary.

Generally, facies of the middle estuary in the Pleistocene record at Willapa Bay are moderately to thoroughly bioturbated. Muddy intertidal deposits are characterized by diminutive *Skolithos*, *Arenicolites*, *Gyrolithes*, *Cylindrichnus*, *Planolites*, *Palaeophycus*,

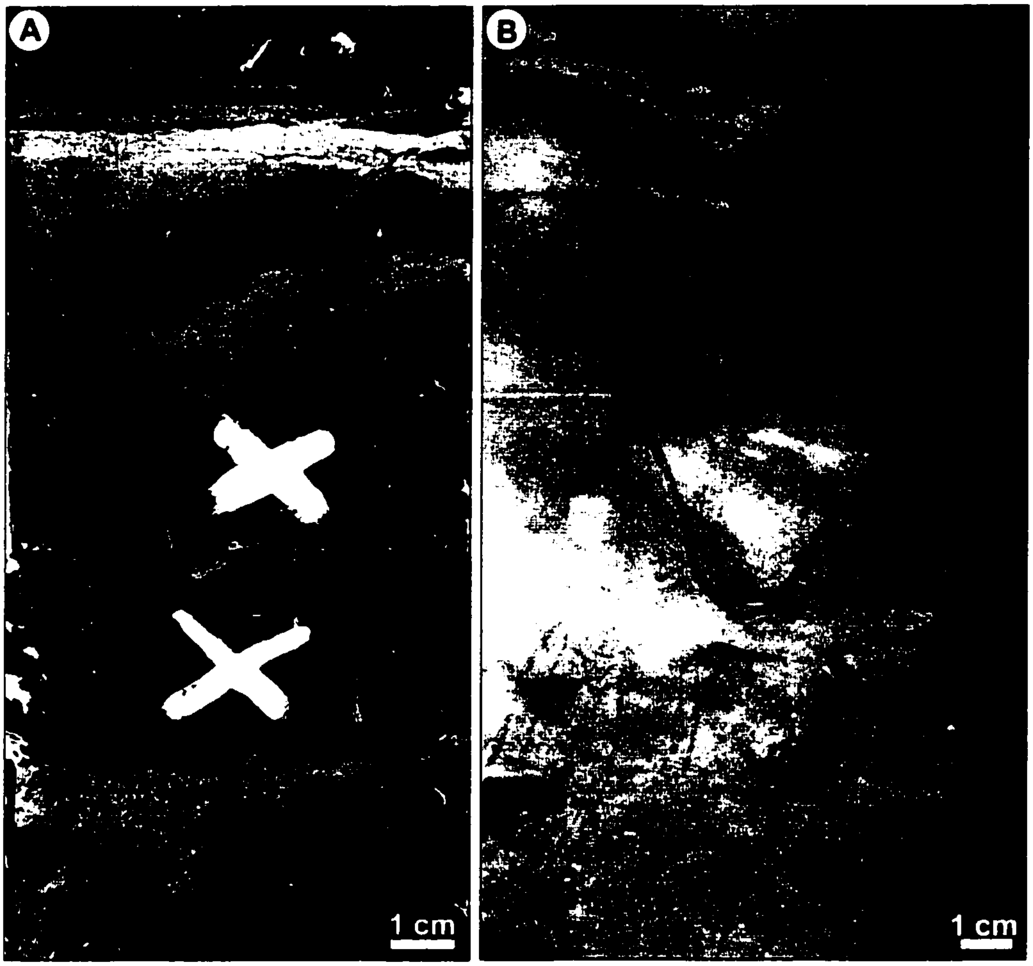

Fig. 3.8. Sandy intertidal flat deposits. **a)** Facies B - Bluesky Formation, 06-33-83-17W5 @ 630.8m. **b)** Radiograph of modern sediments from Willapa Bay (Bone River Sand Flats).

Thalassinoides and *Psilonichnus* while *Ophiomorpha, Thalassinoides, Teichichnus, Psilonichnus, Planolites* and *Palaeophycus* are present in quiescent bay deposits. Sandy intertidal flat deposits contain trace fossils which are typically more robust relative to those observed in mud-dominated units. Trace fossils observed include *Skolithos, Arenicolites, Planolites, Palaeophycus, Siphonichnus, Thalassinoides* and *Ophiomorpha.*

In the Peace River area, deposits of the middle estuary in the Bluesky Formation include those of a quiescent bay (the central mud basin) (facies C, F, Fig. 3.7a), intertidal flats (facies B, Figs. 3.5b, 3.8a), channel (facies D, Fig. 3.9b), and rare supratidal flats (Fig. 3.6b) (Table 3.2). Units are characteristically comprised of mudstone with common sandstone interbeds, except in the case of fining-upwards sandy tidal flat deposits.

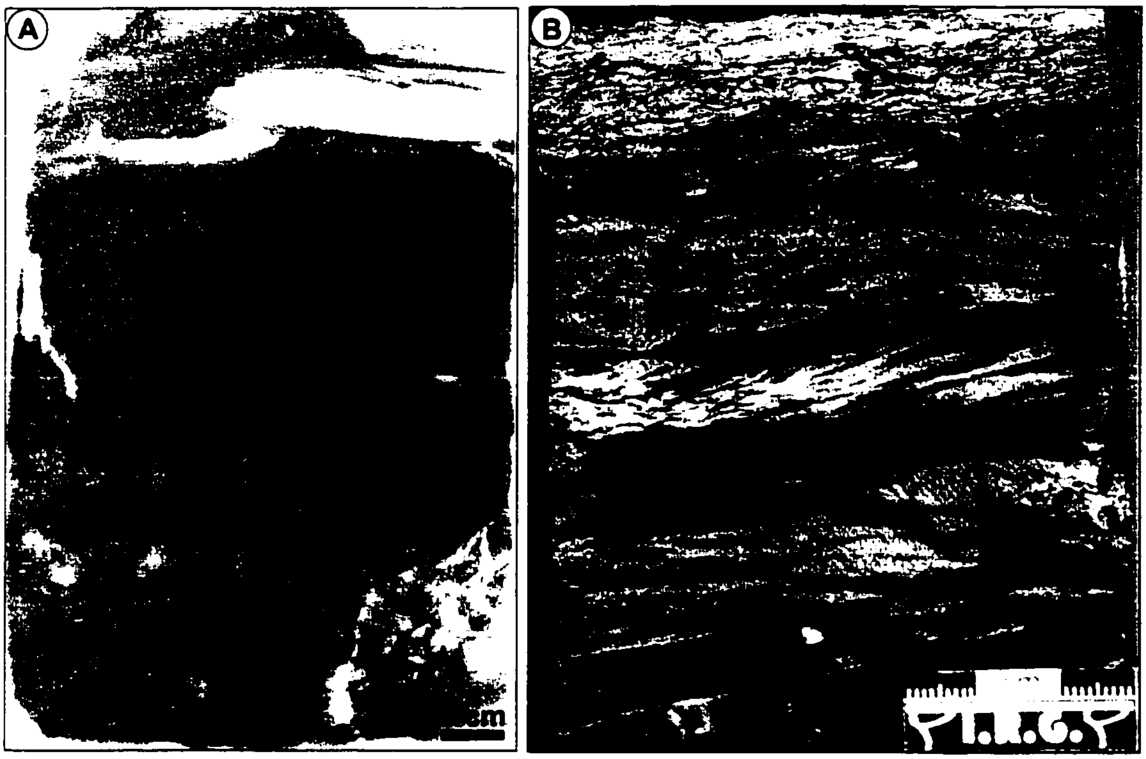

Fig. 3.9. Estuarine channel deposits. **a)** Radiograph of modern subtidal point bar deposit from Willapa Bay. **b)** Facies D - Tidal channel deposit from the Bluesky Formation, 08-20-83-19W5 @ 613.62m.

Middle estuary deposits grade into more sandy units proximal to sandstones of the upper and lower estuary. The cumulative thickness of these deposits reaches up to 9m. Pyrite, carbonaceous mud laminae and bioclastic debris are present locally.

Individual beds within middle estuary deposits at Peace River, with the exception of supratidal flat deposits, are characterized by a low diversity of trace fossils consisting of 5 or 6 individual ichnogenera. Discrete trace fossils are often indiscernable within the mottled texture of tidal flat deposits. The entire assemblage of burrows observed consists of *Planolites, Palaeophycus, Arenicolites, Skolithos, Cylindrichnus, Thalassinoides, Subphyllochorda, Teichichnus,* rhizomes and ?*Asterosoma.*

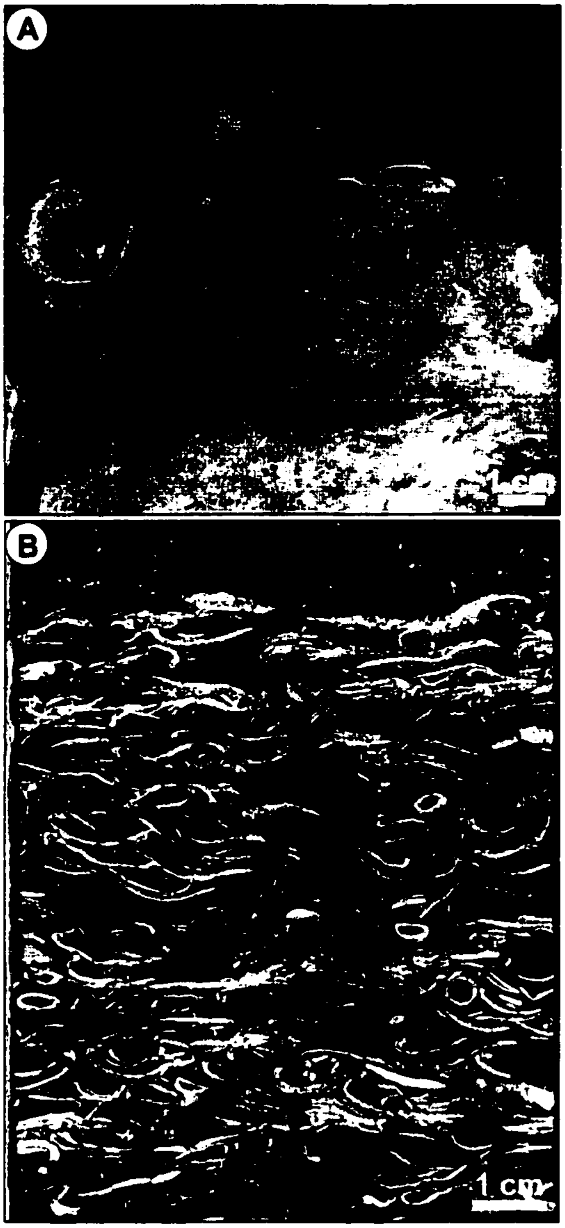

Fig. 3.10. Bioclastic sand deposits from subtidal channels. **a)** Radiograph of modern deposit from Willapa Bay (Palix River). **b)** Bluesky Formation, 16-32-85-16W5 @ 525.3m.

LOWER ESTUARY DEPOSITS

Lower estuarine environments studied at Willapa Bay include sandy intertidal flats and subtidal mid-channel bars (Table 3.1). These deposits, of undetermined thickness consist of well-sorted sands with ripple lamination, low angle cross bedding and inclined stratification common locally. Organic detritus is rare in sediments of the lower estuary. Many depositional environments of the lower estuary present at Willapa Bay have not been studied in detail due to their subtidal location in extremely energetic conditions (eg: tidal inlet, tidal deltas).

Bioturbation intensity ranges from being absent in some channel bars to almost complete within intertidal flat deposits. Biogenic sedimentary structures present include robust *Thalassinoides-*, *Arenicolites-*, *Siphonichnus-*, *Skolithos-*, *Planolites-*, *Palaeophycus-*, *Ophiomorpha-*, and rare *Cylindrichnus-* and *Gyrolithes-* like burrows.

Similar to the modern sediments studied at Willapa Bay, the Pleistocene record of lower estuarine deposition consists mainly of sandy tidal flat and channel bar sandstones, along with tidal delta and tidal inlet deposits (Fig. 3.11c,d) (Table 3.1). These deposits occur in up to 8m thick units, approximately 30m in accumulated thickness locally. Ripple lamination, low angle cross-bedding, inclined stratification, and sigmoidal bedding are present within these units. Abundant organic detritus is typical.

Absent to low intensity bioturbation is characteristic of lower estuarine deposits in the Pleistocene record at Willapa Bay with the exception of some intertidal flat deposits that are thoroughly bioturbated. Where present, *Ophiomorpha*, *Thalassinoides*, *Teichichnus*, *Skolithos*, *Arenicolites*, *Planolites*, *Palaeophycus*, *?Macaronichnus* and *Siphonichnus* are typically robust.

The lower estuary at Peace River is characterized by deposits representing numerous sub-environments including tidal channel (facies D, Fig. 3.9b), lagoon/ quiescent embayment (facies E), tidal delta (facies F, Fig. 3.11a,b), washover fan (facies G) and shoreface (facies H) deposits (Table 3.2). Individual successions of these deposits range from approximately 5 to 20m in cumulative thickness with planar parallel bedding to low angle cross-stratification being the most dominant sedimentary structures present. A strong tidal influence is evident in tidal delta deposits where individual beds range in thickness from 0.4 to 1.2cm within cyclic (spring and neap tidal) bundles.

Trace fossil assemblages vary considerably in deposits of the lower estuary at Peace

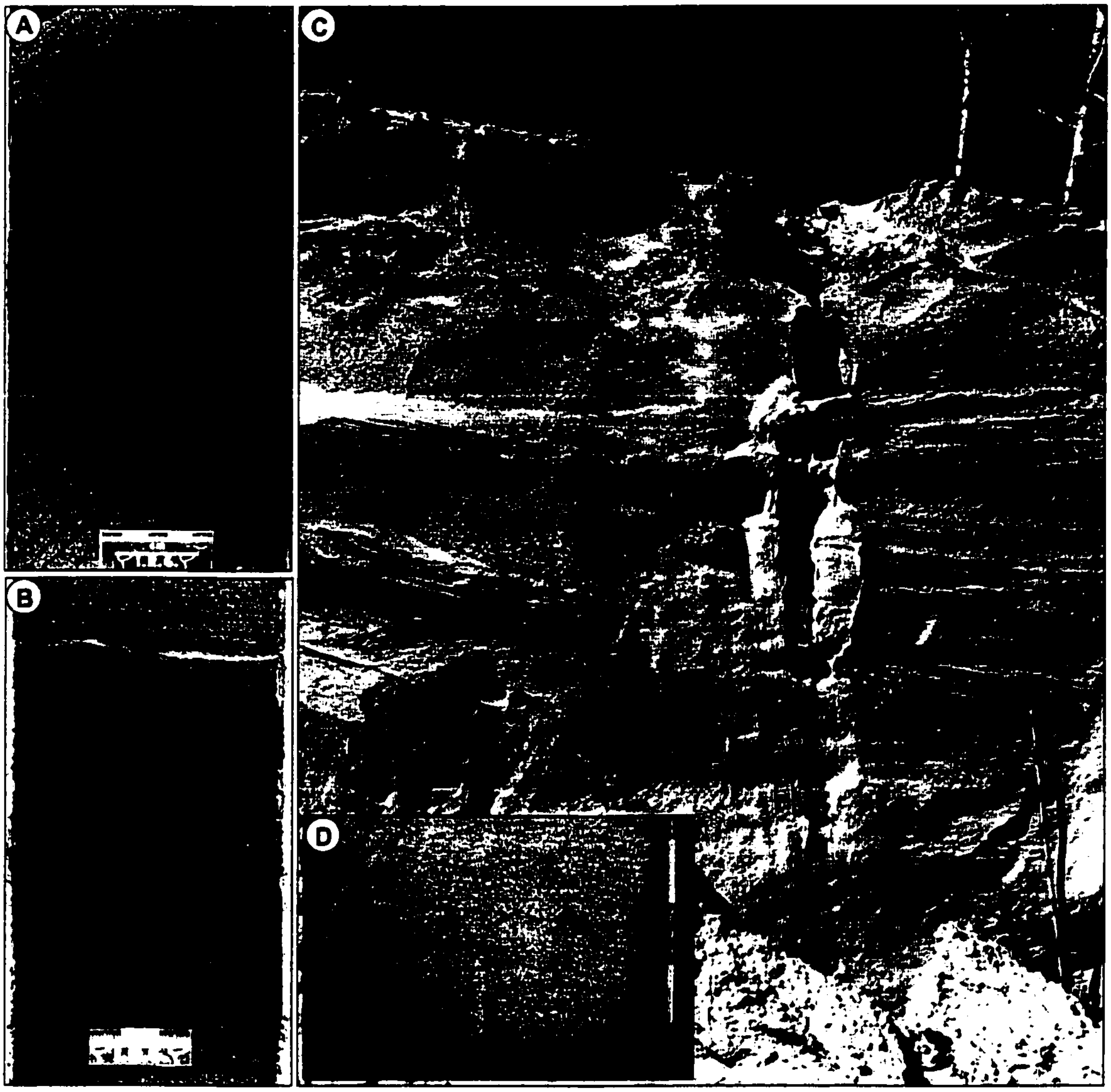

Fig. 3.11. Tidal inlet/delta deposits. **a)** Inclined stratification in tidal delta deposits (facies F) of the Bluesky Formation (09-16-85-18W5 @ 624.1m; note that the well is deviated). **b)** Planar parallel bedding in inlet/delta sandstones (facies F) of the Bluesky Formation (05-33-83-19W5 @ 585.1m). **c, d)** Pleistocene aged tidal inlet/delta deposits from Willapa Bay (North Cove).

River. Generally, the diversity of forms and size of individual trace fossils increases in a westward (basinward) direction. Trace fossil forms present include *Rosselia, Cylindrichnus, Skolithos, Planolites, Palaeophycus, Thalassinoides, Chondrites,* ?*Subphyllochorda, Teredolites,* and *Teichichnus*. Typically, lower estuary deposits contain a diversity of traces consisting of no more than three or four ichnogenera with the exception of lagoonal deposits that can contain up to nine or ten forms. A diverse trace fossil assemblage characterizes shoreface deposits in the westernmost portion of the study area. Oscillation rippled sandstones contain an ichnofossil assemblage consisting of *Macaronichnus, Helminthopsis, Asterosoma, Schaubcylindrichnus, Teichichnus, Chondrites, Planolites, Skolithos, Rosselia* and *Cylindrichnus.*

DISCUSSION: SIMILARITIES AND DIFFERENCES

Many variables lead to the morphology and sediment distribution patterns observed in modern estuaries. In attempting to interpret ancient estuarine deposits through comparisons with modern estuaries, an understanding of these variables and their effects on the passing of deposits into the rock record is crucial. Some of the more obvious variables influencing estuarine sediments include predominant sediment source, tectonic setting, marine processes such as waves and tides, fluvial input, climate, sea-level trends, coastal morphology, and in tectonically active areas, subsidence rates or periods of uplift.

Due to the fact that estuarine deposition is effected by so many variables, no two estuaries are exactly alike. However, the data presented in this paper demonstrate that despite these differences, common sedimentologic/stratigraphic elements persist thematically throughout many different estuarine deposits; hence applicable estuarine facies models have been developed (Reinson, 1992; Dalrymple *et al.*, 1992). In this discussion, similarities in Lower Cretaceous, Pleistocene and modern estuarine deposits are addressed, as are the reasons for some of the major differences observed.

A fundamental difference between Willapa Bay and the Bluesky Formation estuary in the Peace River region are the tectonic settings prevalent during deposition. Willapa Bay is situated on an active margin where base-level has been repeatedly altered due to tectonic activity. Conversely, the Bluesky Formation was deposited in a foreland basin;

further complicating this history is the Peace River Arch, a basement structural feature that was active in the study area throughout the Cretaceous (Williams, 1958). The expression of these fundamental differences between the estuarine deposits in the rock record is uncertain however it is legitimate to postulate that these differences could significantly affect accommodation space, sediment supply, depositional cyclicity, bay orientation, and exposure to oceanic influence during deposition.

Clifton (1983) mapped textural variability across Willapa Bay (Fig. 3.2a). From this study, two estuarine divisions are apparent including the sand-dominated lower estuary, and the mud-dominated middle to upper estuary. The characteristic coarse-grained upper estuarine deposits (i.e. – bayhead delta deposits) are absent at Willapa Bay (although sand bars have been observed within the tidally influenced upper reaches of the North River). This is due to the fact that none of the rivers flowing into the estuary provide a significant coarse-grained sediment load. As previously discussed, the transport mechanism of sand into Willapa Bay is tidal currents. Dalrymple *et al.* (1992) demonstrated that coarse grained upper estuarine deposits are characteristic of wave-dominated estuaries while tide-dominated estuaries are characterized by mud-dominated deposits in the upper reaches of the system. Is Willapa Bay then a tide-dominated estuary? Clifton and Phillips (1980), and Clifton and Gingras (1997) suggested that it is an estuary strongly influenced by both waves and tides (a mixed estuary). Aspects of a wave-dominated estuary evident at Willapa Bay include high wave energies at the mouth of the estuary, a barrier spit, a tidal inlet and associated tidal deltas; aspects of a tidally dominated estuary include high tidal energies at the mouth, a large tidal prism, an extensive tidal range, and the presence of elongate sand bars parallel to the dominant flow directions within the large tidal channels (Clifton and Gingras, 1997).

The Pleistocene record at Willapa Bay is incomplete. Due to the selected preservation of certain facies and the absence of others, this discussion will focus on Pleistocene deposits only where they fill in the holes in the database of modern deposits. One such example is tidal inlet/delta deposits; modern subtidal data in these environments were too difficult to obtain therefore Pleistocene equivalents are used in this discussion.

From the facies study (Hubbard *et al.*, 1999), a generalized depositional model was developed for the Bluesky Formation at Peace River (Fig. 3.2b). The diagnostic tripartite zonation of a wave-dominated estuary is apparent with: 1) fluvial/bayhead delta sandstones in the southwest, 2) quiescent basin mudstones, and mudstone dominated tidal flat deposits of the middle estuary in the central portion of the study area, and 3) lower estuarine sandstones, and interbedded sandstones and mudstones in the western reaches of the study area. Two predominant orientations of sand bodies are present in the lower estuary. Trending northwest-southeast, tidal delta deposits are oriented perpendicular to the paleo-shoreline while normal to this sand body is another dominated by tidal channel deposits (Fig. 3.2b).

UPPER ESTUARY

Due to the differences in upper estuary sediment supply and current energies between Willapa Bay and Peace River, the resulting sedimentary deposits in this environment are very different. Texturally, mud dominates upper estuarine deposits at Willapa Bay (Table 3.1) whereas at Peace River the upper estuary is characterized by moderately well-sorted sandstones (Table 3.2). Despite these differences in sediment character, ichnological trends are evident and thus could be utilized in identifying various upper estuarine deposits. In particular, trends in bioturbation, and trace fossil size and diversity are similar in many of the upper estuarine deposits studied from both Willapa Bay and the Bluesky Formation. Fluctuations in salinity, and the overall lowering of salinity caused by the mixing of fresh and normal marine water affects benthic organisms in deposits of the upper estuary. This results in low diversity trace fossil suites comprised of diminutive forms in the upper estuary relative to deposits lower in the estuary (Wightman *et al.*, 1987; Pemberton and Wightman, 1992; Gingras *et al.*, 1999). At Peace River other stresses on benthic organisms include high sedimentation rates and sediment reworking in the upper flow regime of the bayhead delta. Trace fossils that occur in upper estuarine deposits of both Willapa Bay and Peace River include *Planolites, Skolithos, Thalassinoides* and *Cylindrichnus.*

MIDDLE ESTUARY

Middle estuarine deposits from Willapa Bay and Peace River are dominated by intertidal flat (Figs. 3.5 and 3.8), channel (subtidal point bars) (Fig. 3.9), rare supratidal flat (Fig. 3.6) and quiescent bay deposits (Fig. 3.7) (Tables 3.1 and 3.2). In both locations, muds or mudstones are common, grading into sandier deposits proximal to the lower estuary. At Peace River, where the upper estuary is characteristically sandy, middle estuarine deposits are coarser grained up-estuary as well. In both deposits, bored wood, organic detritus and shelly lags are common (Fig. 3.10). As with deposits of the upper estuary, an analogous characteristic of middle estuarine units are trends in trace fossil character and diversity. Although individual trace fossils present in each estuarine deposit differ, middle estuarine deposits are characterized by a moderate diversity of commonly preserved trace fossils that are diminutive relative to similar forms in open marine environments. This is a reflection of the highly stressed environment of deposition. In the quiescent central basin of the middle estuary, the primary stress on the benthic community is brackish water (MacEachern and Pemberton, 1994), whereas on intertidal flats numerous stresses are present including fluctuating salinity, temperature, variable currents, sporadic deposition and periodic exposure (Weimer *et al.*, 1982; Gingras *et al.*, 1999). Trace fossil forms common in both the modern middle estuary at Willapa Bay and analogous deposits in the Lower Cretaceous Bluesky Formation at

Fig. 3.12. *Rosselia* (**a**) and *Cylindrichnus* (**b**) from facies D of the Bluesky Formation at Peace River and a similar burrow (**c**) from modern tidal flat sediments at Willapa Bay (Bruceport Flats). The inset in (**c**) outlines the detail present. The photographs in (**a**) and (**b**) are from 11-17-83-18W5 @ 625.8 and 627.3m respectively.

Peace River include *Cylindrichnus, Thalassinoides, Palaeophycus, Planolites, Gyrolithes, Skolithos, Rosselia, Teredolites* and *Arenicolites* (Figs. 3.12 and 3.13).

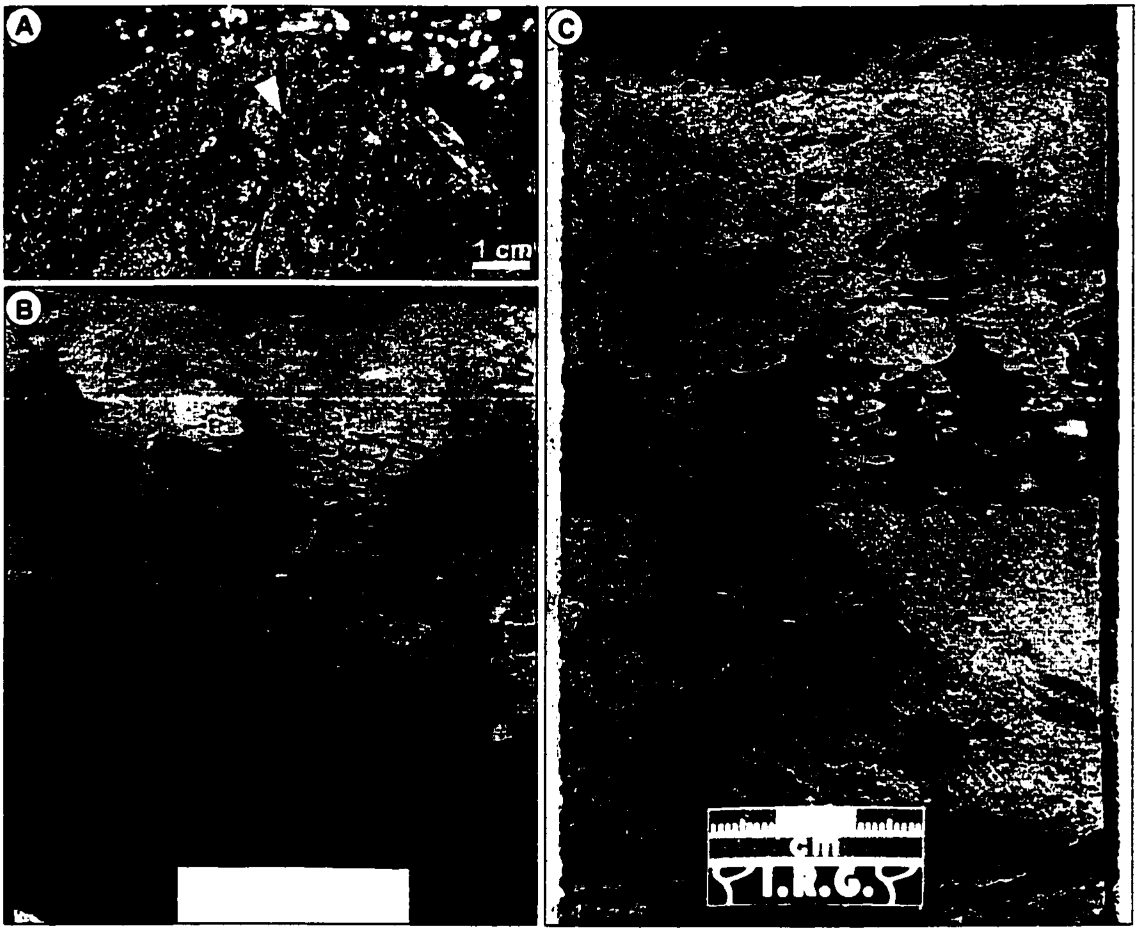

Fig. 3.13. a) *Gyrolithes*-like burrow in modern sediments at Willapa Bay. **b,c)** *Gyrolithes* from facies C of the Bluesky Formation at Peace River (**b** – 04-13-83-19W5 @ 639m, **c** – 05-33-83-19W5 @ 606.5m).

LOWER ESTUARY

Lower estuarine deposits from Willapa Bay and the Bluesky Formation at Peace River are difficult to compare due to: a) poor preservation of numerous deposits from the lower estuary at Peace River reworked during the transgressive event that marked the end of estuarine deposition, b) poor core control through the Bluesky Formation in the western portion of the study area, c) the masking of features as a result of extensive bitumen staining in sandstone units of the lower estuary at Peace River, and d) the inaccessibility of many deposits in the lower estuary at Willapa Bay. Despite these problems, some similarities are apparent. Lower estuarine deposits from Willapa Bay and Peace River include those deposited on sandy intertidal flats, sandy channels, tidal deltas, and tidal inlets (Tables 3.1 and 3.2). The deposits are comprised predominantly of well-sorted, fine to medium grained sand with rare wood and shelly debris. Overall, bioturbation is rare to moderate as a result of high sedimentation, brackish water and the reworking of the sediment column by physical processes. Trace fossils common to both the modern lower estuary at Willapa Bay and Peace River include *Thalassinoides*, *Planolites*, *Palaeophycus*, *Skolithos*, and rare *Cylindrichnus* and *Teredolites*.

The Pleistocene record at Willapa Bay contains tidal inlet/delta deposits similar to those found in the Lower Cretaceous Bluesky Formation (Fig. 3.11). In both deposits, sandstones are characterized by cross-bedding, a subtly fining-upwards grain-size profile throughout the section, and an overall lack of bioturbation. Thin clay drapes are present locally and help to define the bedding planes in the bitumen stained sand of the Peace River deposit. Evidence of tidally influenced deposition is present in both deposits as well (Fig. 3.14). Individual units within the deposits at Willapa Bay and Peace River average 5m in thickness, however in both locations the total thickness of the deposits is almost 30m (Fig. 3.15).

IMPLICATIONS

The interpretation of ancient estuarine deposits, especially in core-based subsurface examples, is difficult due to the fact that they do not easily fit into an idealized facies model. Willapa Bay is an example of a modern estuary that is not easily categorized through the use of the idealized estuarine facies models as proposed by Dalrymple *et al.* (1992). Instead, it falls somewhere between the end members; wave- and tide-dominated. This complication in classifying a modern estuary is obviously magnified when poor preservation of specific facies, or poor core control in some subsurface examples is considered when trying to interpret ancient estuarine deposits.

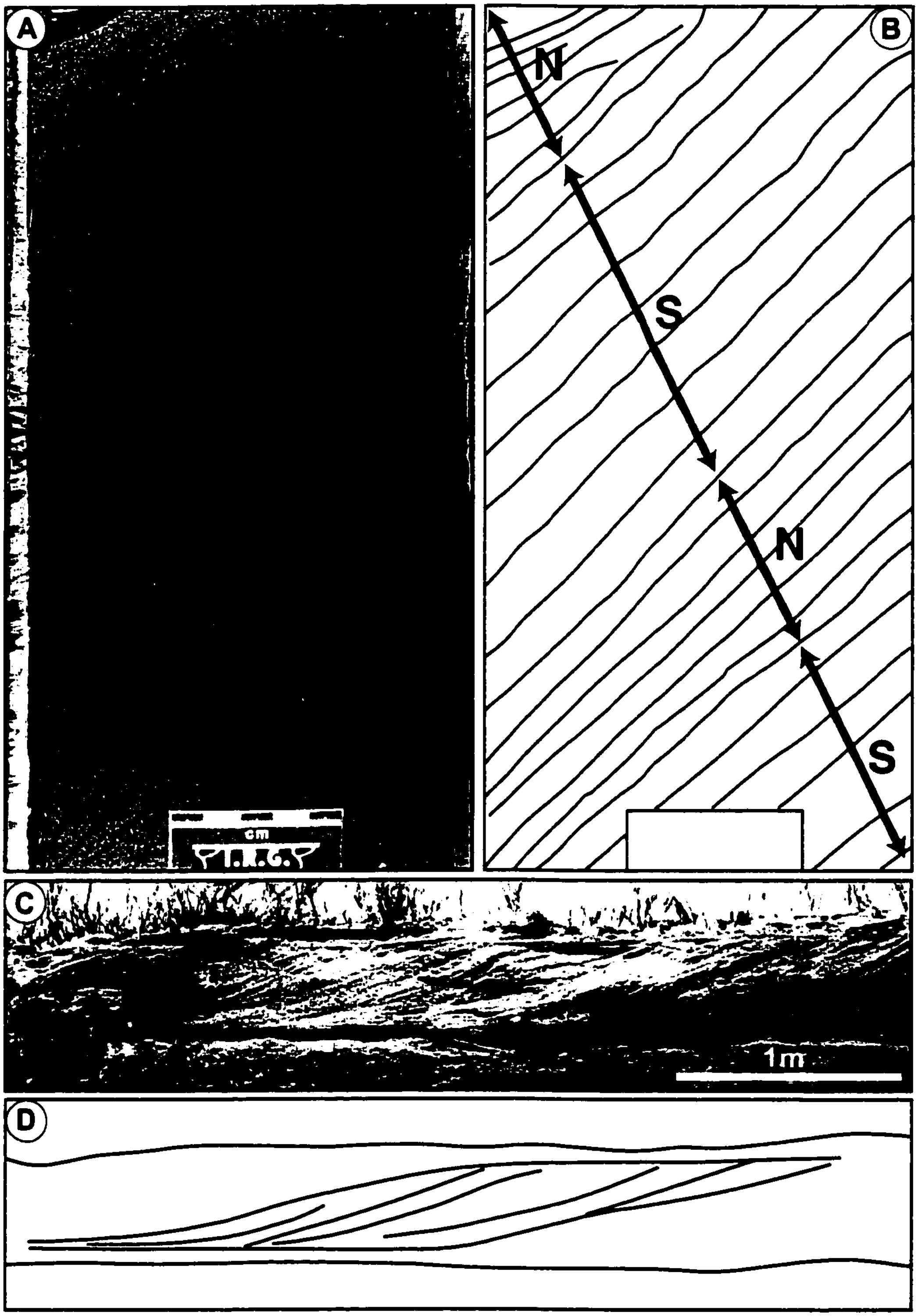

Fig. 3.14. Tidally influenced bedforms in tidal delta deposits. **a)** Neap-spring tidal bundles (outlined in **b**) in facies F of the Bluesky Formation (09-16-85-18W5 @ 624.1m). **c)** Sigmoidal bedding (outlined in **d**) in Pleistocene deposits at Willapa Bay (North Cove section).

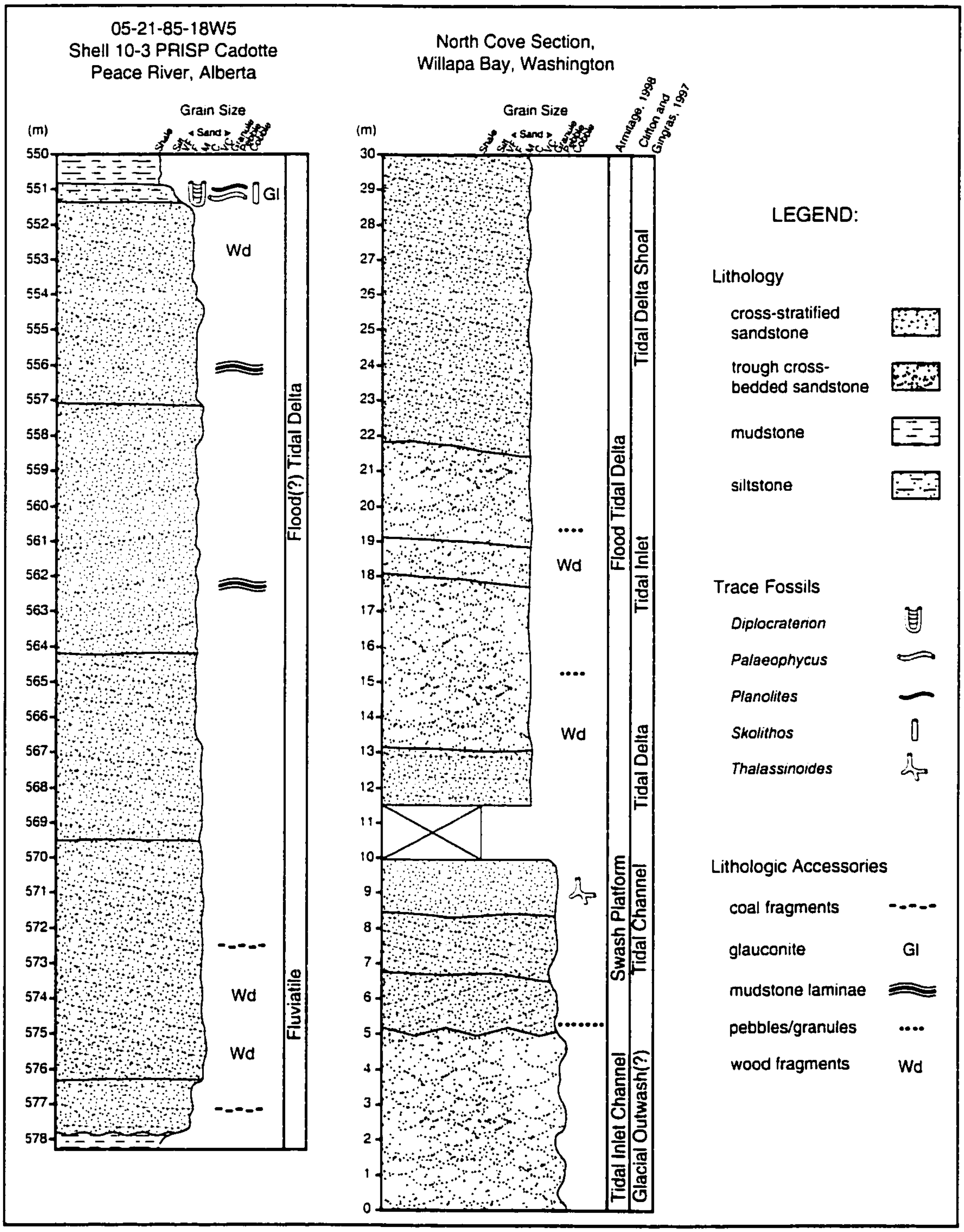

Fig. 3.15. Strip-logs through tidal inlet/delta deposits at (**a**) Peace River (facies F) and (**b**) Willapa Bay. Note the overall lack of bioturbation, similar overall thickness and the subtly fining-upwards profiles in both sandy sections.

An important aspect regarding the understanding of facies variation and distribution in estuarine deposits is recognized when exploring for, or exploiting, estuarine reservoirs in the subsurface. Numerous examples of such reservoirs throughout the Western Canada Sedimentary Basin, including the Peace River Oil Sands Deposit have been recognized (Reinson *et al.*, 1988, Zaitlin and Shultz, 1990, Broger *et al.*, 1997). Estuarine deposits are extremely variable and hence reservoirs in such deposits are difficult to predict. Along the Palix River, one of the five rivers discharging into Willapa Bay, extreme changes in sediment texture over distances of less than 500m demonstrate the variability common within estuarine deposits (Fig. 3.16). Consequently, this is a reflection of what could eventually be the subsequent variability in reservoir quality within these units. The inherent difficulty in producing hydrocarbons from estuarine reservoirs is apparent if it is considered that average well-spacing is 500m or greater.

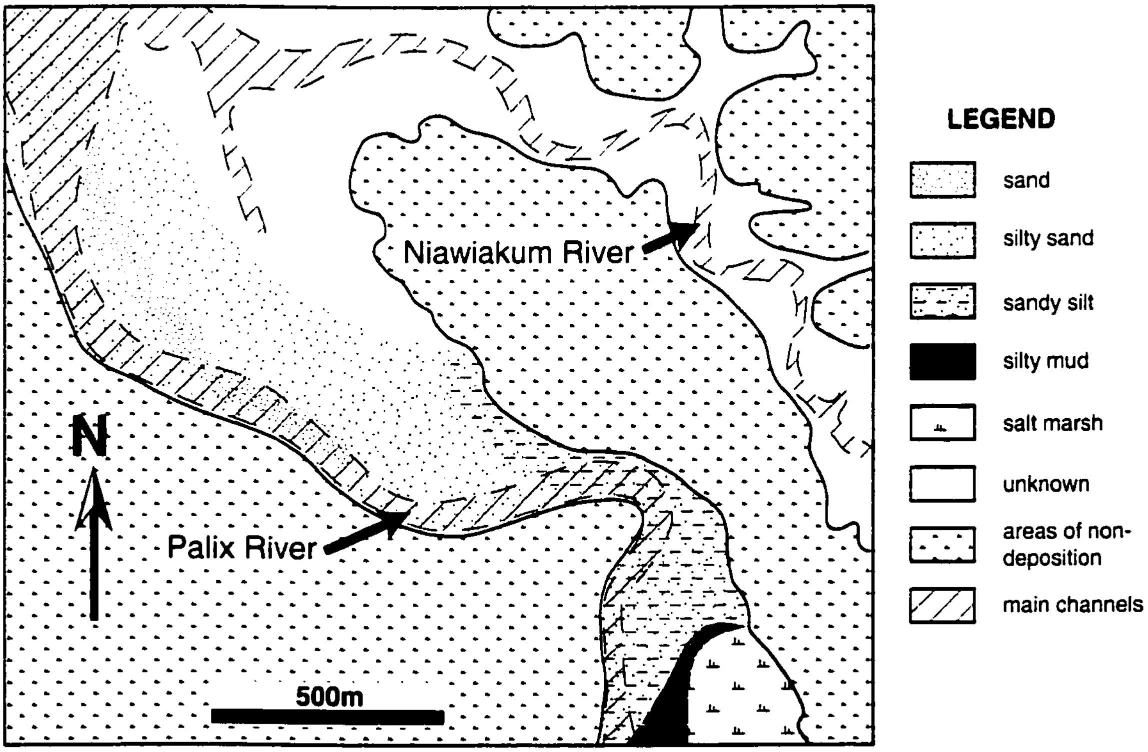

Fig. 3.16. Sediment texture variation in the upper estuary at Willapa Bay, Washington. Subsequent reservoir quality in similar subsurface deposits is effected by the extreme lateral variability in grain-size typical of these deposits.

CONCLUSIONS/SUMMARY

1) Despite the differences amongst estuaries, both ancient and modern, many aspects are similar allowing for recognition of estuarine deposits in the rock record. Although numerous fundamental differences between deposits of Willapa Bay and the Bluesky Formation at Peace River are apparent, many sedimentological similarities are recognizable.

2) An understanding of depositional setting, tectonic setting, and preservational biases should be attained in order to understand, or account for, the differences observed in various estuarine deposits.

3) Ichnology, and in specific the brackish water model (Wightman *et al.*, 1987; Pemberton and Wightman, 1992; Gingras *et al.*, 1999), can be a valuable tool in recognizing an estuarine deposit. Generally, the diversity and abundance of trace fossils decreases with increasing brackish water towards the upper estuary; similar forms which are robust in normal salinity become more diminutive up-estuary.

4) Estuarine facies models as proposed by Dalrymple *et al.* (1992) have proven to be very helpful in recognizing estuarine deposits in the rock record (Pattison, 1992; Broger *et al.*, 1997; Lessa *et al.*, 1998; Hubbard *et al.*, 1999). Recognition of variations on the idealized situations can be difficult, and is critical in identifying many estuarine deposits, especially in core-based studies.

5) Estuarine deposits are extremely variable and thus exploring for, and exploiting ancient deposits can be extremely difficult. Recognizing lateral variation and delineating sub-environments is crucial in resolving geometric problems, predicting compartmentalization of hydrocarbons within estuarine reservoirs, and identifying pool-edge indicators in core-based studies.

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CHAPTER 4 – SUMMARY AND CONCLUSIONS

The Peace River Oil Sands deposit, as part of the colossal accumulation of heavy oils in Alberta, represents a significant portion of the future of the hydrocarbon industry in western Canada. As conventional oil field discoveries become fewer and further between in western Canada, industry will continue to rely more heavily on bitumen production. The development of oil sand relies on the investment of millions of dollars for the implementation of cutting edge production and analytical techniques such as Steam Assisted Gravity Drainage and 4-D seismic surveying. Crucial to the efficient and effective implementation of such development strategies is a thorough geological understanding. The primary goal of the research herein was therefore to compile sedimentologic and stratigraphic data to be used to enhance and expand the development of the Peace River Oil Sands.

Lower Cretaceous subsurface stratigraphy of the Peace River (townsite) region is documented in the literature however many fundamental discrepancies are apparent (Alberta Study Group, 1954; Rottenfusser, 1982; Marion and Rottenfusser, 1992; Smith, 1994). Different studies have indicated that the thick sands comprising the Peace River Oil Sands reservoir are either part of the Gething or Bluesky Formations. Also in question was the presence of the Ostracode Zone in the region. Through detailed sedimentological and geophysical well-log analysis it has been established that: 1) the Gething Formation rests on the sub-Cretaceous unconformity in the southern part of the study area, pinching out to the north. The maximum thickness of the formation at Peace River is approximately 65m. 2) The Ostracode Zone is a 10 to 15m thick interval present over most of the study area, again pinching out to the north. 3) The Bluesky Formation is typically 15 to 25m thick except where it overlies the sub-Cretaceous unconformity, also zeroing out in the northern part of the study area. Exploitable bitumen is contained predominantly within sandstone units of the Bluesky Formation, however where combined with underlying sandstones of the Ostracode Zone, net sand can reach up to 30m. An illustration of the stratigraphy in the area using geophysical well-logs is shown in Fig. 4.1.

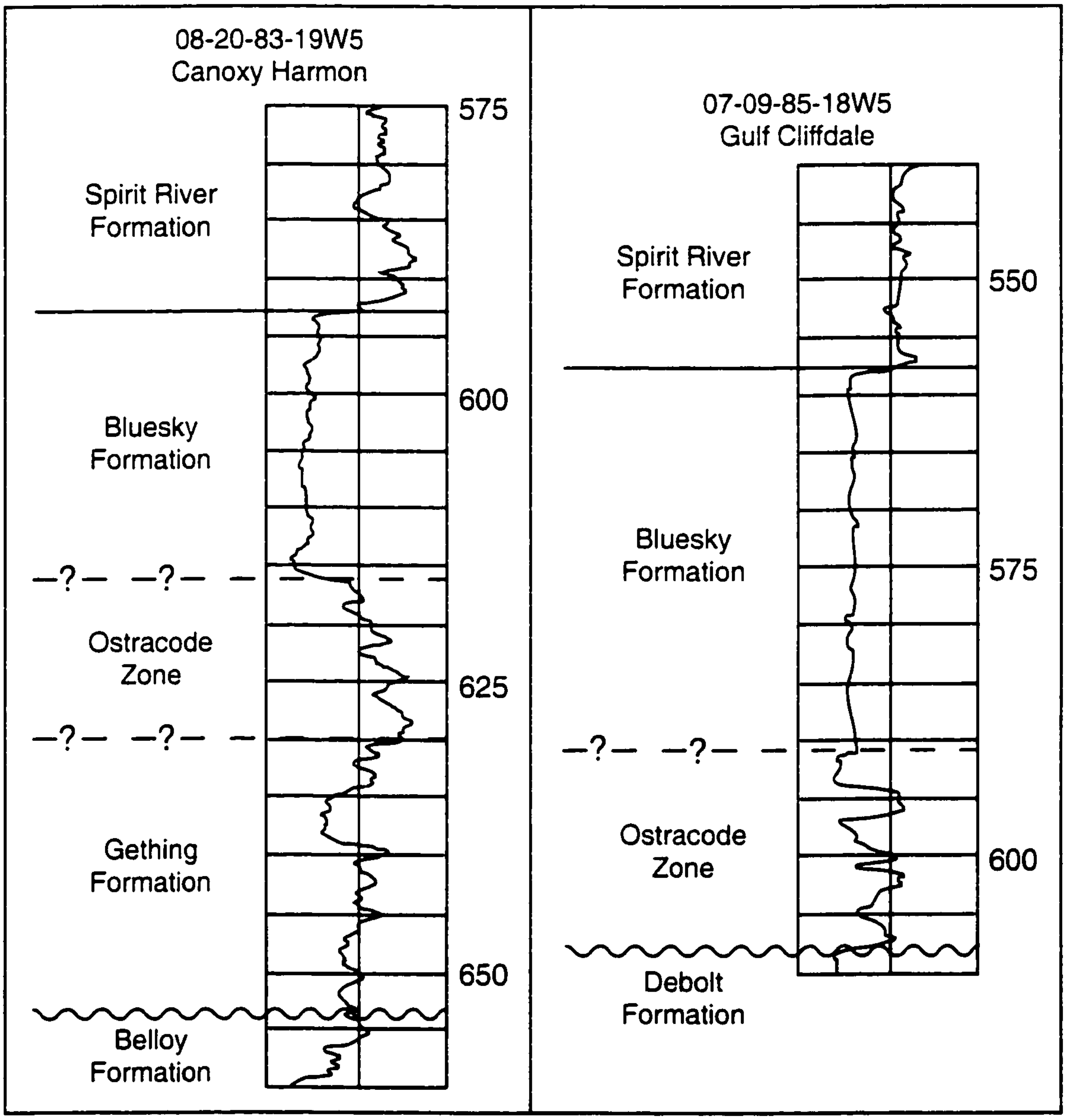

Fig. 4.1. Gamma-ray log signatures and stratigraphy through the basal Cretaceous section from two locations in the study area. Stratigraphic boundaries are often difficult to discern due to the gradational relationship between units.

Although sedimentological studies have previously been undertaken on the deposit, years of newly accumulated data from the deposit have assisted in refining previous interpretations. The regional geological study (Chapter 2) led to the interpretation of the depositional framework and the establishment of a facies model for the reservoir units in the study area. This study was further refined through the comparison of estuarine deposits of the Bluesky Formation with analogous deposits from Willapa Bay in southwestern Washington (Chapter 3).

At Peace River, the Lower Cretaceous sedimentary package represents transgressive deposition in non-marine through to open marine conditions. Coastal plain/non-marine deposits are characteristic of the Gething Formation in the Peace River region. Ichnological evidence indicates proximity to a marine influence throughout deposition of units associated with this interval however. As fluvial input into the basin waned, sediments of the Ostracode Zone were deposited. The regional paleogeographic interpretation of the Ostracode Zone shows a large brackish-water basin present across southern and central Alberta (MacLean and Wall, 1981). This is consistent with sedimentological observations taken at Peace River where fine-grained deposits are characterized by a stressed trace fossil assemblage attributed to deposition in a quiescent, brackish water setting. Locally, sandstones were deposited in fluvial channels sourced from the Mississippian Highlands to the north and east of the study area. As the Western Intracontinental Seaway inundated central Alberta from the north, the shoreline transgressed southward across the basin. Deposition of the Bluesky Formation in the Peace River region took place in a large wave-dominated estuary, sheltered from open marine conditions to the north by the Red Earth Highlands. Estuarine deposition ceased in uppermost Bluesky time as a transgressive shoreline crossed the area. Maximum transgression is represented by the overlying Wilrich Member shales of the Spirit River Formation (Cant and Abrahamson, 1996).

Estuarine deposits of the Bluesky Formation are highly variable across the study area.

In order to gain a better understanding of facies distribution within this interval, a comparison of these deposits with modern and Pleistocene estuarine deposits from Willapa Bay, Washington was undertaken. Through this comparison, many similarities and differences were observed leading to some general conclusions focused on the modelling of estuaries. Although the variability in estuarine deposits makes them difficult to model, sedimentological similarities are often recognizable. Specifically, trends in trace fossil diversity, size and abundance can be used as key indicators in identifying and classifying both ancient and modern estuarine deposits. Generally, all of these parameters show a decrease with lowered salinity up-estuary.

Sedimentological observations are limited in core-based studies, and can make interpretations especially difficult in deposits which vary from the idealized estuarine situations as proposed by Dalrymple *et al.* (1992). Detailed sedimentological analysis, as well as an understanding of depositional setting, tectonic setting and preservational biases are critical towards recognizing estuarine deposits in the rock record.

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APPENDIX 1 - THE ROLE OF HYDROCARBONS AND HOST-ROCK LITHOLOGY IN THE EXCEPTIONAL PRESERVATION OF LOWER CRETACEOUS (APTIAN/ALBIAN) SKELETAL ARAGONITE FROM ALBERTA, CANADA

INTRODUCTION

At Peace River, Alberta, bioclastic accumulations in siliciclastic units from the Lower Cretaceous Gething Formation, Ostracode Zone, and Bluesky Formation are characterized by a diverse assemblage of exceptionally well-preserved bivalves and gastropods. Many shells are composed of aragonite, having never undergone inversion to calcite. This unusual preservation provides a rare opportunity for the detailed analysis of original shell microstructures in Mesozoic fossils. The exceptional preservation is controlled by numerous factors including: the lithology and permeability of the sediment encasing the fossils; reservoir formation and the associated paleo-hydrogeologic environment in the stratigraphic interval; reduced effects of compaction; and the quick burial of organisms following death.

The factors that influence the process whereby aragonite inverts to calcite is poorly understood despite numerous studies (e.g., Friedman, 1964; Bathurst, 1964; Folk, 1965; Dodd, 1966; James, 1974; Wardlaw *et al.*, 1978; Martin et al., 1986; Maliva and Dickson, 1992; Rehman *et al.*, 1994; Hendrey *et al.*, 1995). Although fossilized skeletal aragonite is rare in the geological record, examples are known (e.g., Stehli, 1956; Hallam and O'Hara, 1962; Füchtbauer and Goldschmidt, 1964; Hudson and Palframan, 1969; Bruni and Wenk, 1985). Examples of originally aragonitic fossils subsequently having undergone inversion to calcite are common from Mesozoic and Paleozoic deposits (e.g., Dodd, 1966; Sandberg and Hudson, 1983; Maliva and Dickson, 1992; Hendry *et al.*, 1995).

Part of the problem in understanding the inversion of aragonite to calcite stems from the fact that the process, in a natural setting, is independent of time (Rehman *et al.*, 1994). Some aragonite inverts to calcite in <100,000 years (e.g., Halley and Harris, 1979) whereas other aragonite in Mesozoic and Paleozoic shells, as outlined above, has not yet inverted to calcite. An improved understanding of why aragonite has not inverted to calcite in fossils from lowermost Cretaceous strata of Peace River, Alberta may help us understand the diagenetic processes that govern this complex inversion process.

GEOLOGIC SETTING

The study area is located near the town of Peace River in northwest Alberta (Fig. A.1). The shells come from the Lower Cretaceous (Aptian/Albian) Gething Formation, Ostracode Zone, and Bluesky Formation (Fig. A.2), which average 30 to 40m in cumulative thickness across the study area. These stratigraphic units have been extensively studied in the Peace River area because they contain >14 billion cubic meters (~88 billion barrels) of heavy oil (Alberta Energy and Utilities Board, 1997).

During lowermost Cretaceous time, sediments accumulated in the evolving Alberta Foreland Basin. The Gething Formation, Ostracode Zone, and Bluesky Formation are comprised predominantly of freshwater and marginal marine, brackish water deposits. Most of the fossils examined in this study came from the Ostracode Zone. Detailed facies mapping of this unit in the study area shows fine-grained brackish bay deposits are the predominant facies and are locally associated with fluvial and deltaic deposits (Fig. A.3; Hubbard *et al.*, 1999).

METHODOLOGY

Fossils were collected from 19 drill cores with the permission of the Alberta Energy and Utilities Board (Table A.1, Fig. A.1). Where held in consolidated units, the core slabs were broken down so that the well-preserved fossils could be identified, and their shell

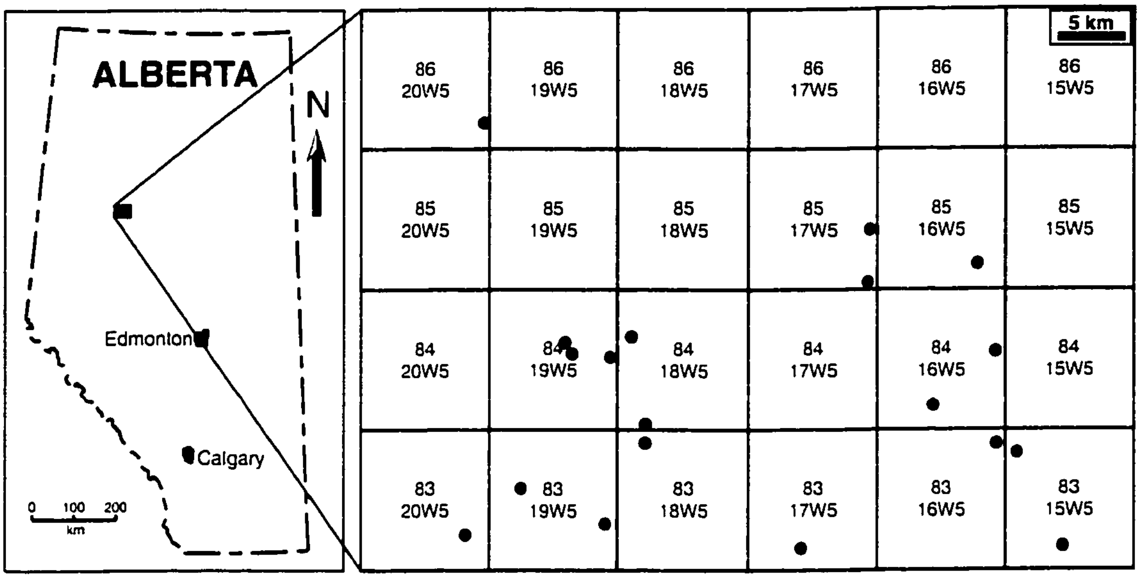

Fig. A.1. Index map showing the Peace River study area and the drill core localities (solid black circles) from which fossils were sampled.

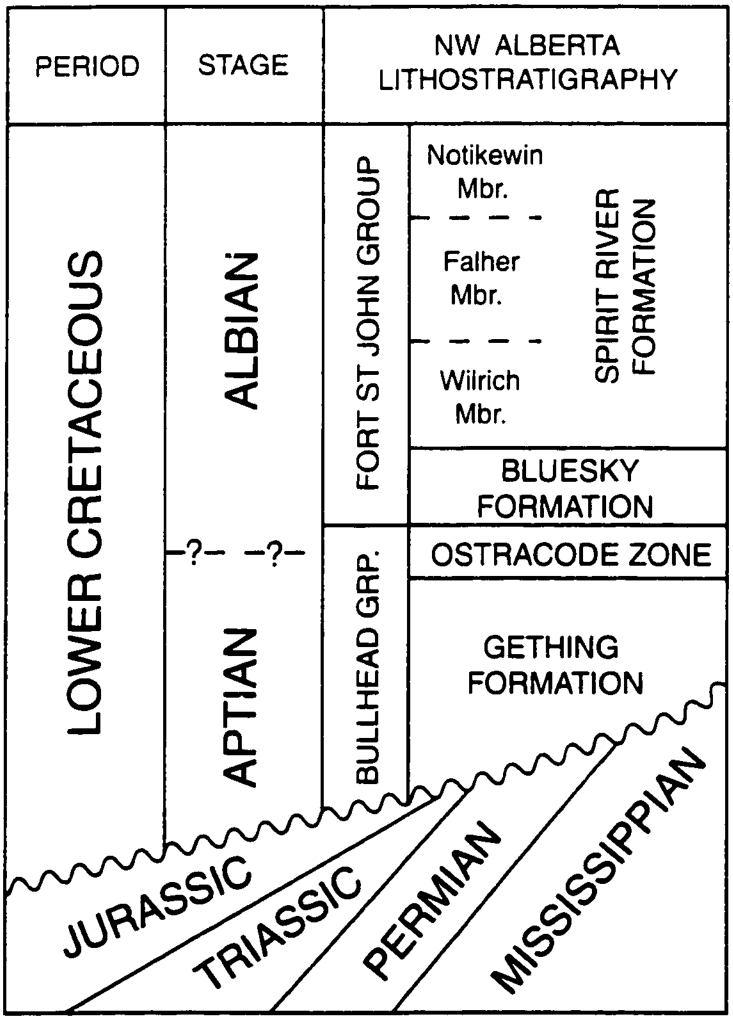

Fig. A.2. Subsurface Lower Cretaceous stratigraphic nomenclature for the Peace River Plains region of Alberta. Not to scale.

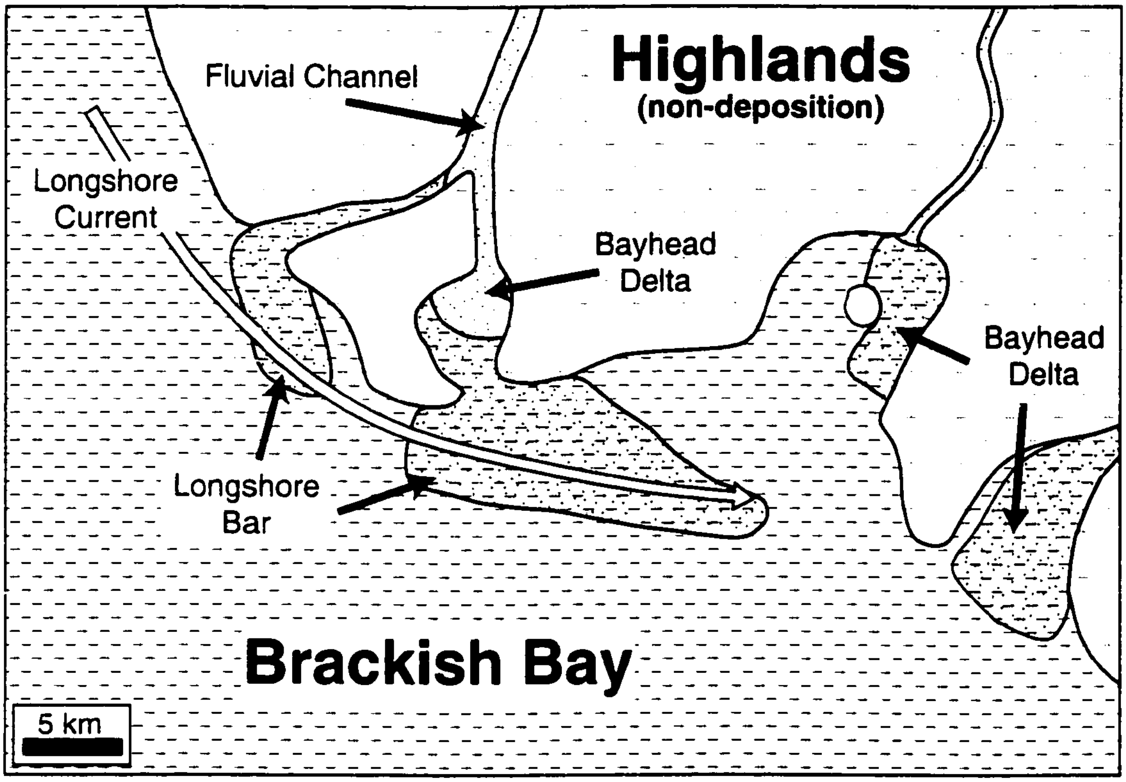

Fig. A.3. Facies map showing environments of deposition prevalent during Upper Gething Formation and Ostracode Zone time. Modified from Hubbard *et al.*, (1999). Fossils are predominantly located in quiet water facies associated with the large brackish bay that was present over most of the study area.

microstructure determined. Thin section analysis, using standard petrographic techniques, yielded estimates of the density of microborings in the shells. Four fossils were powdered for X-Ray diffraction (XRD) analysis. Extreme care was taken to avoid sampling of interstitial material which is comprised of shale, sandy silt, and locally calcite cement. Fractured samples of the shells and thin sections were mounted on stubs, sputter-coated with a thin layer of gold and then examined on a JEOL 630IFE field emission scanning electron microscope (SEM) at an accelerating voltage of 1.5 – 5.0kV. The thin sections were etched in 5% acetic acid for 10 - 12 seconds prior to examination on the SEM.

Location	Depth
02-09-83-15w5	647.5; 650.6; 651.5; 652.8
07-30-83-15w5	652.2
06-36-83-16w5	628.9; 643.2
01-09-83-17w5	694.3
06-32-83-18w5	634.8; 640.12
04-13-83-19w5	632.35; 632.75
08-20-83-19w5	610.8; 611.34
14-11-83-20w5	602.94
07-09-84-16w5	644
04-24-84-16w5	639.8
01-05-84-18w5	636
07-29-84-16w5	607.75
13-22-84-19w5	597.4
16-22-84-19w5	673
02-24-84-19w5	592.55; 600.5
16-10-85-16w5	569.2; 572.4; 573.4; 576.7
09-01-85-17w5	615.15; 618.9
07-13-85-17w5	611.45; 615.0; 617.55; 618.5
01-13-86-20w5	512.35

Table A.1. Fossil localities for samples analyzed in the study. Depths are in meters (m).

FOSSIL SPECIMENS AND PRESERVATION

The assemblage of macrofossils in the Ostracode Zone at Peace River is composed of a broad diversity of fresh and brackish water mollusks. Most of the bivalves and gastropods (Fig. A.4) in this biota have already been described (Stanton, 1893; McLearn, 1929; 1932; Russell, 1932). Individual bivalve shells are disarticulated although rarely fragmented or abraded. Shells in individual layers are generally exclusively convex upward, or concave upward. They are typically found in shaly deposits, and more rarely in siltstones or sandstones (Fig. A.5). Calcite cement is restricted to the coarser grained deposits. Due to the extreme delicacy of the shells, it is assumed they were probably subjected to minimal transportation and then buried soon after death of the organism. Aragonitic nacre forms the innermost layers of many of these fossils (Figs. A.4d,f),

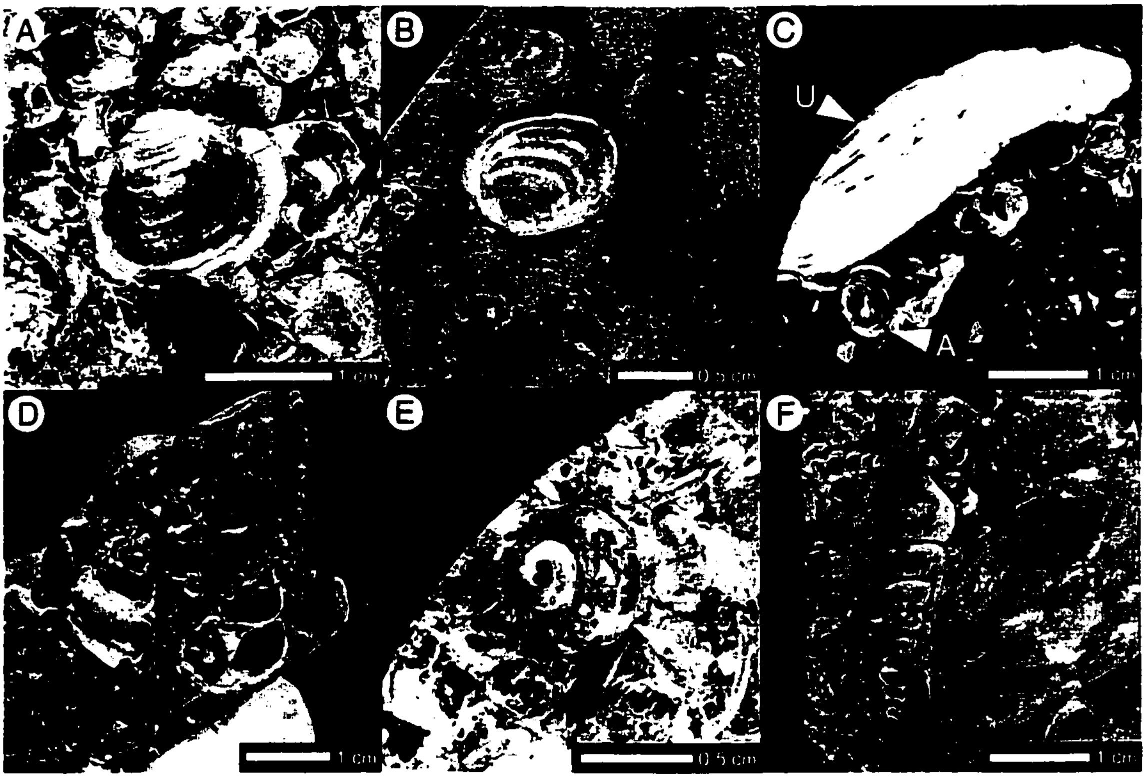

Fig. A.4. Examples of fossils from the Gething Formation, Ostracode Zone and Bluesky Formation at Peace River, Alberta. **a)** *Astarte*? sp. from 08-20-83-19W5 (610.95m); **b)** *Corbula*? sp. from 04-13-83-19W5 (632.75m); **c)** *Unio biornatus* and *Astarte*? sp. from 08-20-83-19W5 (611.34m); **d)** *Lioplacodes bituminis* from 02-09-83-15W5 (651.85m); **e)** unidentified gastropod from 08-20-83-19W5 (610.95m); **f)** *Melania multorbis* from 07-30-83-15W5 (652.91m). Note the nacreous luster of the large bivalve to the right of *M. multorbis*.

however, in coarser-grained deposits many shells have been chalkified (Figs. A.4a,b,e). Both nacreous and chalkified specimens are aragonitic as shown from XRD and SEM analyses (Fig. A.6).

SHELL MICROSTRUCTURES

Shell microstructures are exceptionally well preserved in some of the bivalve specimens examined. These shells are formed of three layers that are separated by distinct boundaries (Figs. A.7a,b). The outermost layer, 10 to 200μm thick, is formed of an aragonitic prismatic structure (Figs. A.7c,d). The middle layer, 250 - 300μm thick, is

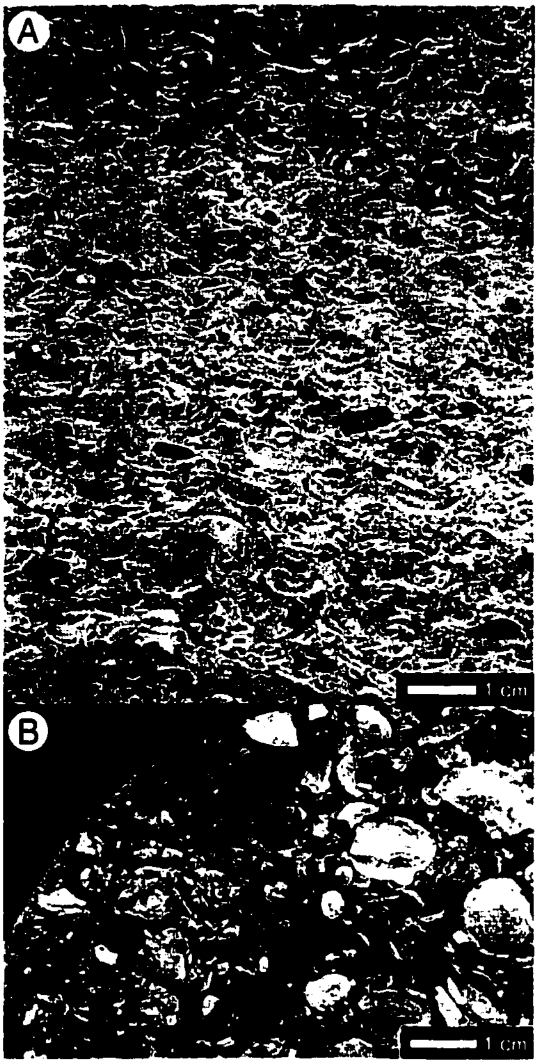

Fig. A.5. Photographs of typical samples from Peace River. **a)** Well-cemented coquinite with coarse grained argillite and chert granule matrix. **b)** Well-preserved bivalves and gastropods in black shale matrix.

formed of aragonitic cone complex crossed lamellar structure (Figs. A.7e,f). The innermost layer, <100μm thick, is characterized by nacreous aragonite (Figs. A.7a,b). Similar structures have been noted in bivalves from other Mesozoic deposits (Carter, 1980; Sandberg and Husdon, 1983).

MICROBORINGS

Three types (I-III) of endolithic microborings are present in many of the fossils. Type I are curved, unbranched borings with tubes less than 5μm in diameter and 100μm long, and are the most common form present (Figs. A.8a-d). These borings, with densities up to 200 borings/100μm^2, are filled with secondary calcite precipitate (Fig. A.8b). Type II

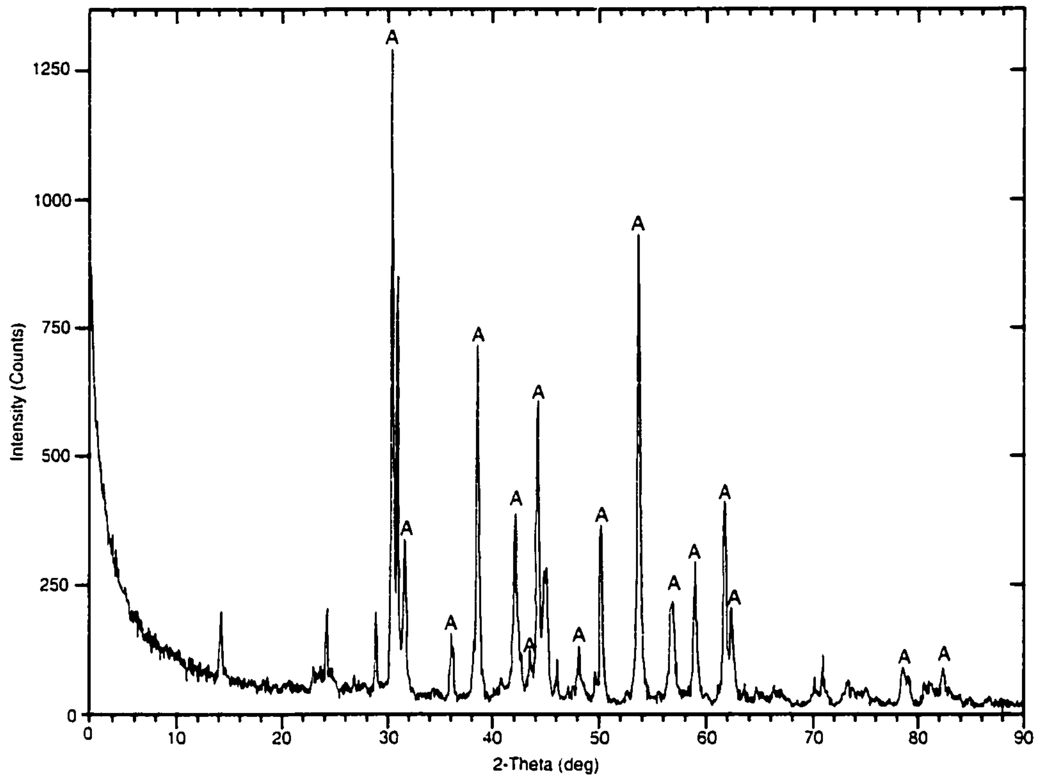

Fig. A.6. X-ray diffraction analysis of bivalve shell from 8-20-83-19W5 (610.73m; Fig. A.4A). Peaks associated with aragonite mineralogy are identified (A). Other major mineralogical constituents of the sample (not identified for clarity) include quartz and kaolinite, derived from the matrix of the sample.

borings are branching (Fig. A.8e), 1-2μm in diameter and < 25μm long. The density of these borings is up to 150 borings/100μm^2. Type III borings are slightly arcuate, unbranched, 20-25μm in diameter, and up to 300μm long (Fig. A.8f). Densities of this boring type reach 6/100μm^2.

There is no preferred orientation of the borings; however, they are typically located close to the outer surface of the shells. In some bivalves the borings radiate from the inner surface of the valve. The predominance of borings on the outer shell surface suggests they were formed while the bivalves were still living.

The size and simple morphology of these borings indicate that they were probably formed by algae or fungi. Types I and II are characterized by slightly curved, unbranched to branched borings, <10μm in diameter which suggest algal boring

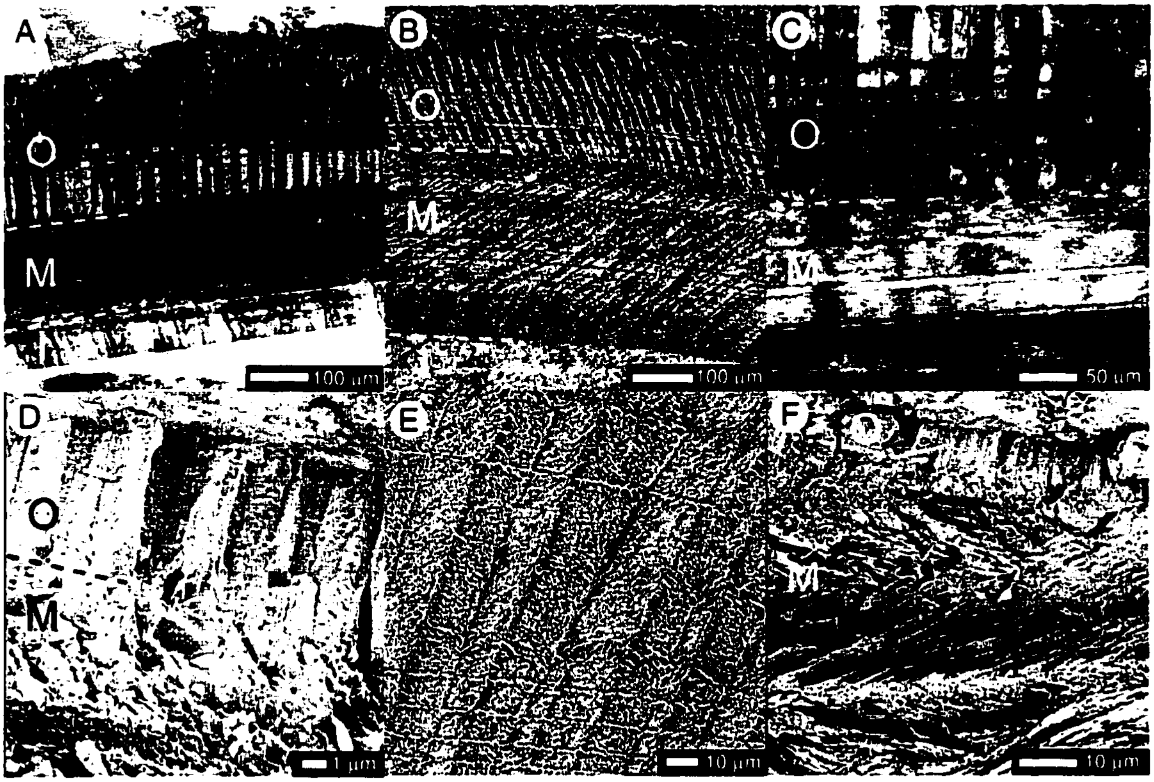

Fig. A.7. Thin section (**a,c**), etched thin section SEM (**b,e**) and rock fragment SEM (**d,f**) photomicrographs showing well preserved shell microstructures. **a**) and **b**) show three distinct shell layers including: [O] outermost aragonitic prismatic structure layer, [M] middle aragonitic cone complex crossed lamellar structure layer, and [I] inner nacreous aragonite layer. **b**) and **c**) show the boundary between layers [O] and [M]. **e**) and **f**) focus on the aragonitic cone complex crossed lamellar structure of [M]. **a**),**c**),**d**), and **f**) from 08-20-83-19W5 @ 610.73m; **b**), and **e**) from 02-09-83-15W5 @ 650.6m.

activity (cf. Kobluk and Risk, 1977). In modern skeletal sediments, Perkins and Halsey (1971) described green algae borings, 15-20 µm in diameter, with simple, gently curved morphologies similar to Type III from the Peace River study area.

FACTORS CONTROLLING THE PRESERVATION OF ANCIENT SKELETAL ARAGONITE

LITHOLOGY OF THE HOST ROCK

The most important parameter regarding the preservation of ancient skeletal aragonite is the lithology and related permeability of the rock unit in which the fossils are encased. An impermeable host rock isolates fossils from circulating groundwater thereby inhibiting the rate of inversion of aragonite to calcite (Füchtbauer and Goldschmidt, 1964; Feazel and Schatzinger, 1985; Bruni and Wenk, 1985). Most

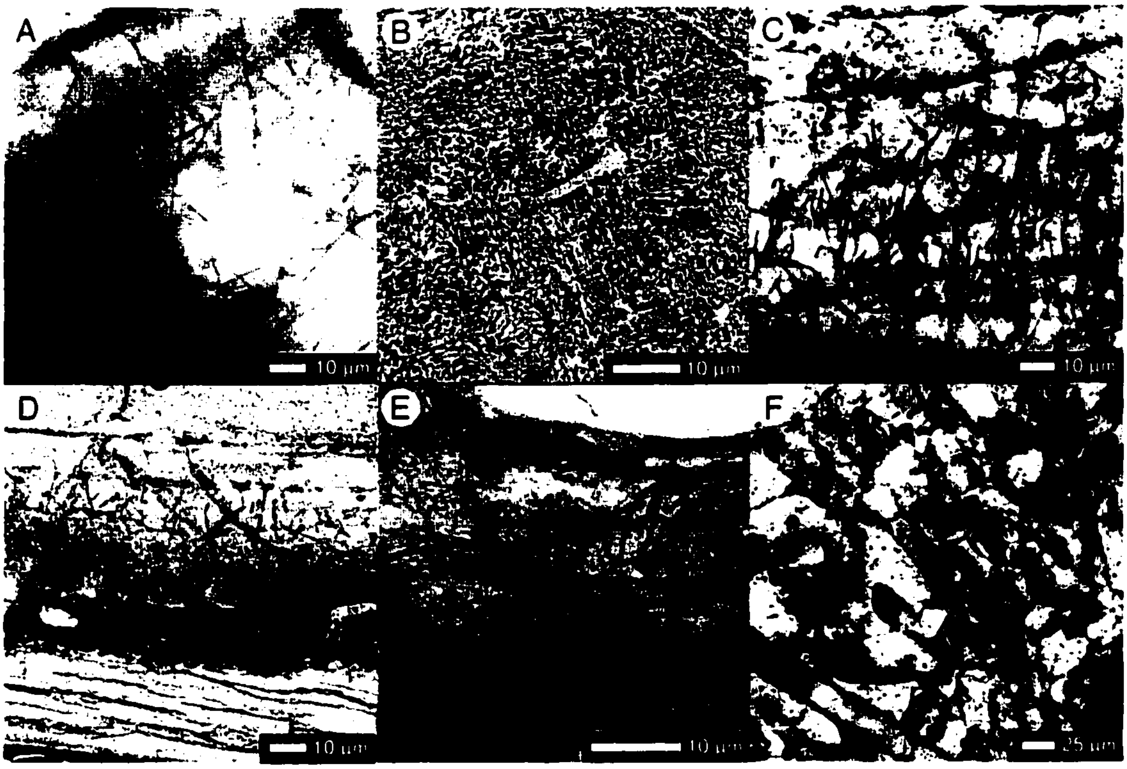

Fig. A.8. Examples of micro-borings in shells from Peace River in thin section with the exception of **b** which is an SEM photomicrograph of an etched thin section (same grain as in part **a**). **a)**, **b)**, and **c)** from 02-09-83-15W5 @ 650.6m; **d)** from 07-13-85-17W5 @ 611.45m; **e)** from 08-20-83-19W5 @ 610.73m; **f)** from 8-20-83-19W5 @ 609.15m.

aragonitic fossils from Paleozoic and Mesozoic rocks are found in low-permeability shaly deposits (Stehli, 1956; Füchtbauer and Goldschmidt, 1964; Hudson and Palframan, 1969).

Most of the aragonitic fossils from the study area are enclosed in impermeable, black shale matrices. Locally, however, coquinites formed of a diverse assemblage of chalky aragonitic mollusks are found in a coarse grained matrix of chert-granules and argillites (Fig. 5a). Preservation of original skeletal aragonite has, in some examples, been shown to be related to early cementation (Meyers, 1980; Bruni and Wenk, 1985; Rehman *et al.*, 1994). An early phase of calcite cementation sealed pores in the coquinites in the Peace River area, preventing passage of later diagenetic fluids.

RESERVOIR FORMATION

In much the same way that an impermeable host rock can prevent diagenetic fluids from reaching bioclasts in the rock, hydrocarbon saturation of a host rock can have the same effect (Friedman and Sanders, 1978; Feazel and Schatzinger, 1985; Choquette and James, 1990). Furthermore, the displacement of pore water by oil and gas shuts-down diagenetic processes because most minerals are insoluble in hydrocarbons. Füchtbauer and Goldschmidt (1964) and Squires (1972), for example, attributed original aragonite preservation of macrofossils to their location in oil-saturated units.

Where the impermeability of the host rock may initially retard diagenetic fluids from altering fossils, hydrocarbons may provide a "geochemical barrier" to diffusion over geological time (Feazel and Schatzinger, 1985). In the Peace River area, oil migration into porous units may have contributed to the buffering of shells from physical fluid flow and diffusion. Examples of preserved aragonitic fossils in bitumen saturated sandstones are common in the study area (Fig. A.9a).

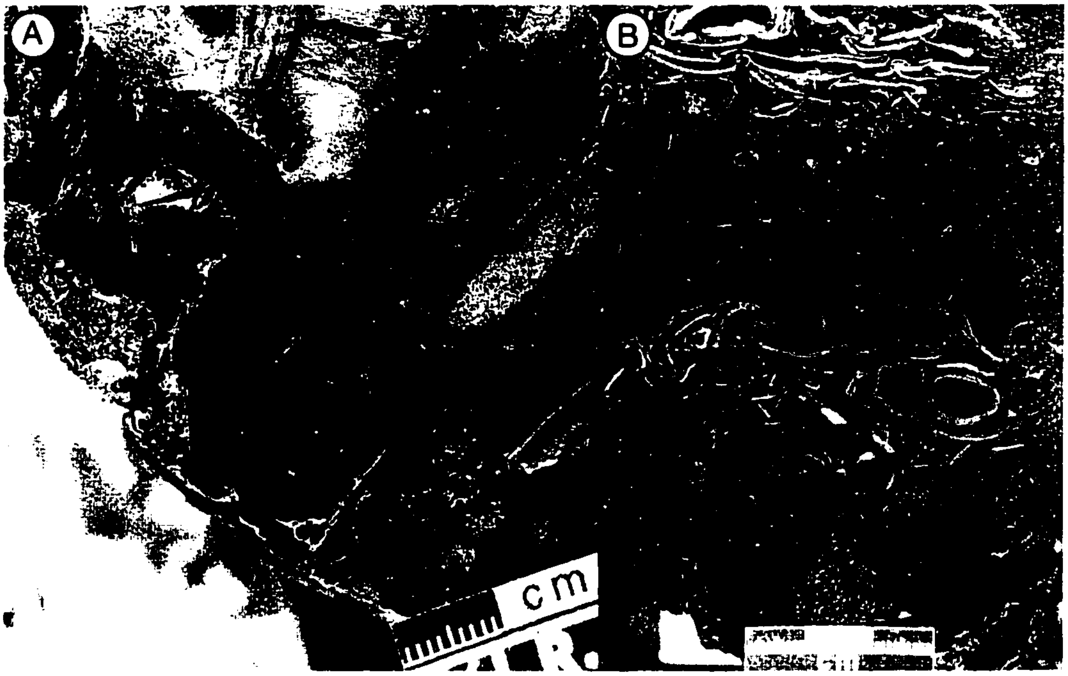

Fig. A.9. Examples of aragonitic shells in bitumen saturated sandstones. **a)** from 01-13-86-20W5 @ 512.4M; **b)** from 16-22-84-16W5 @ 673.5m.

REDUCED COMPACTIONAL EFFECTS

The deposits studied lie approximately 600m below the surface. Although their maximum burial depth is unknown, it has been demonstrated that 1000 to 3000m of overburden has been removed in south-central Alberta (Nurkowski, 1984; Bustin, 1991). These depths are in the range where significant compactional effects should be expected (Meyers, 1980; Feazel and Schatzinger, 1985). Physical crushing, plastic deformation and fragmentation of grains, fracturing (of individual particles as well as the host rock), and pressure solution are common results from the compaction of shelly material (Meyers, 1980; Walker and Diehl, 1985). In Lower Cretaceous deposits at Peace River however, these features are strikingly absent in most cases.

Early diagenetic processes can reduce the effects of compaction in some deposits (Walker and Diehl, 1985). Choquette and James (1990) suggested that one such early diagenetic process is the filling of pore space with hydrocarbons. In the Peace River area, migration of hydrocarbons into Lower Cretaceous deposits contributed to the generation of the pore-fluid pressure necessary to counteract the lithostatic pressure created by the overlying strata. As a result, the effective overburden pressure was more similar to the pressure created in a shallow burial setting (Feazel and Schatzinger, 1985). Thus, the only evidence of compaction in the specimens examined are rare crushed fossils.

In another subsurface study from the Western Canada Sedimentary Basin, Kendall (1975) noted that fracturing associated with compaction can create freshwater conduits into otherwise impermeable deposits. The introduction of freshwater into a system would probably be conducive to skeletal aragonite inversion. There is, however, no evidence of significant fractures in shelly deposits at Peace River, probably because of the lowered effective overburden pressure.

Dunnington (1967) suggested that early migration of hydrocarbons into a deposit would also significantly reduce or inhibit the effects of chemical compaction. Resultant pore fluid overpressure minimizes the effects of solution transfer of carbonate through reduction of stress between grains (Feazel and Schatzinger, 1985). Evidence of pressure-dissolution such as grain suturing and stylolites are notably absent from bioclastic deposits in the Gething Formation, Ostracode Zone, and Bluesky Formation in the Peace River area.

SEDIMENTATION

Several factors related to the life and death of mollusks effect their overall preservation as fossils. Of these factors, the most critical with respect to preserving original mineralogy is rapid burial in the substrate of the organisms following their death. Deep burial improves the potential for preservation because it may retard dissolution of skeletal aragonite, as deposits closer to the sediment-water interface are typically stabilized under oxic conditions (Hendrey *et al.*, 1995). Rapid burial most commonly takes place through event deposition, commonly related to storms. A single storm event may kill an organism and subsequently bury it, preventing the typical exposure subjected to bioclasts in a siliciclastic setting (Driscoll, 1970; Kreisa and Bambach, 1982).

Preservation of original aragonite in shells can be encouraged by abrupt sediment chemistry alteration that is closely linked with rapid deposition (Sepkoski, 1978; Kreisa and Bambach, 1982). In some settings, local carbonate enrichment buffers pore waters, preventing the dissolution or neomorphism of aragonitic shell material. Dissolution of aragonitic shell debris is typically extensive near the sediment-water interface due to undersaturation of aragonite and calcite in the pore waters (Aller, 1982). The effects of dissolution are commonly enhanced in areas of flourishing benthic communities. Deep-burrowing worms and crustaceans lower the redox boundary, thus circulating water and associated bacteria deeper into the sediment column. Therefore, shells have better preservation potential in biologically impoverished deposits (Aller, 1982). Not surprisingly, well-preserved fossils from Peace River are found exclusively in deposits absent of bioturbation.

MICROBORINGS AND SHELL STRUCTURE

On a micro-scale, numerous factors can have a significant affect on the preferential destruction, or replacement, of original skeletal aragonite. Influences on the neomorphism of skeletal aragonite include microborings in shells, shell microstructure, mineralogy, and crystal habit (Rehman *et al.*, 1994). These controls are mainly linked to the reactive surface area of the aragonite skeleton (Martin *et al.*, 1986). In Pleistocene *Strombus gigas*, for example, sponge borings provided a pathway for water to reach the internal part of the shell, thus altering shells from the inside-out (Rehman et al., 1994).

Borings attributed to the work of fungi or algae in fossils from Peace River appear to have had little effect on diagenesis as original aragonite mineralogy persists. Although micro-scale features conducive to the replacement of aragonite with calcite are present in the examined fossils (Fig. 8), other processes such as deep burial in the sediment column and reservoir formation apparently overshadowed their effects.

SUMMARY

The exceptional preservation of fossils from Lower Cretaceous deposits at Peace River, and in particular original skeletal aragonite, is controlled by numerous factors including:

1) the entombment of fossils in impermeable shales and cemented sandstones;
2) migration of hydrocarbons into bioclastic deposits and surrounding sediments;
3) the reduction of compactional effects resulting from deep burial due in part to reservoir formation;
4) rapid burial of organisms upon their death on the seafloor, isolating shells from early diagenetic processes; and
5) the overshadowing of the effects of micro-scale features such as microborings which can enhance the neomorphism of aragonite.

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