University of Alberta

Stratigraphy, Sedimentology and Ichnology of the McMurray Formation; Northeastern Alberta, Canada

by

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ABSTRACT

The Athabasca Oil Sands Deposit is hosted by the Cretaceous (Aptian/Albian) McMurray Formation and Wabiskaw Member of the Clearwater Formation. This study focuses on the Albian Sands Muskeg River Mine and Husky Sunrise Thermal Project. Bitumen migrated into these reservoirs prior to lithification, therefore hydrocarbon occurrence is directly related to the distribution of primary facies.

Core-based sedimentologic and ichnologic analysis, supported by wireline logs, delineates six stratigraphic successions comprised of fifteen facies. This synergistic approach provides the geological interpretation required for the challenging task of modeling this substantial and complex reservoir in order to improve exploration and exploitation strategies.

As a consequence, three previously poorly understood units are examined in detail, including the coal-bearing unit's stratigraphic significance in relation to 'lower' McMurray classification. In addition, oil sand karst reservoirs are identified as potentially economically viable in the future. The formation and economic significance of bank collapse breccia is also assessed.

ACKNOWLEDGMENTS

This thesis began with the encouragement of Murray Gingras, who initially suggested that I begin an M.Sc. with George Pemberton. About a week later, I shakily climbed the stairs in the Earth Sciences building with a pounding heart. I stood outside the door for a couple of minutes building courage; I finally knocked. The voice of the "Jedi" responded, "come in." Courage failed me. I tiptoed into the office, hoping not to make a sound. I sat across the desk from George, head down, asking in a quavering voice if he would accept me as a new student. I peeked up to see the reaction to the request. He asked me if I was the girl who sat in the front row for every class, contorted in some strange yoga position and slept through his lectures. I admitted the truth, yes, it was I.

He accepted me as a student even with my prior indiscretions, and as rumor has it, he turned the event into lunchtime lore. I am indebted to George for his encouragement, enthusiasm, and moral, financial and intellectual support, but most importantly his belief that I would finish. I would like to express gratitude to Susan Fleming for all her help through the years, especially for knowing how to fill out the forms correctly the first time. In addition, she kept the Ichnology Research Group in line with repeated threats to call our parents.

There are many people I appreciate in the IRG, both past and present. The first is Murray Gingras for his mentorship during my undergraduate thesis, his ability to foster the passion of geology, and for advising the thesis route, even after it was discovered that my father taught him junior high math. Having both a January start and using an extended thesis completion time, I witnessed the passing of many IRG generations. When I began, the IRG was composed of an intimidating group of enthusiastic, animated, and rowdy young men, including Jason Lavigne, Eric Hanson, Steve Hubbard, Glenn Schmitt, Ian Armitage, and Jason Frank. There are no limits to the stories that surround this wild bunch. These folks necessitated a mandatory retreat of my shyness.

I would like to thank the IRG of my generation. Michelle Spila assisted me through periods of duress and acted as a confidante. Demian Robbins, initially my

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At Husky Energy I would like to thank my first industry mentor, Jack Livingston, who recommended that I use available Sunrise data to aid in the completion of my thesis. I value his thought-provoking stories. More recently, Ken Weaving taught me that excessive cursing has an enormous element of humor and therapeutic benefits. He has been an exceptional mentor in our many discussions. We disagreed on almost everything, which allowed me to hone my debate skills and broaden my views. I admit that I may occasionally be wrong. I applaud his recognition of when I am "fragile". Carol Fisher taught me more efficient ways to do things. From Shaurat Sayani, I learned the value of asking questions. At Albian Sands I would like to thank Alex Paul, through whom the project was initially generated.

I am indebted to Mike Ranger, the "oil sand guru", who was invaluable as a mentor. On my first field trip to Fort McMurray he served as field guide and taught me how to rappel. When my hard drive died, Mike lent me a computer. His advice has helped to author several posters and talks for CSPG and AAPG.

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LIST OF ABBREVIATIONS

API	American Petroleum Institute
FA	Facies association
FS	Flooding surface
HCS	Hummocky cross-stratification
HST	High stand systems tract
IHS	Inclined heterolithic stratification
LST	Low stand systems tract
SAGD........	Steam-assisted gravity-drainage
SB..............	Sequence boundary
SCS	Swaley cross-stratification
TR	Tidal ravinement
TSE	Transgressive surface of erosion
TST	Transgressive systems tract
WR............	Wave ravinement

CHAPTER 1
OVERVIEW

INTRODUCTION

There are three major oil sand deposits hosted in Lower Cretaceous strata of northern Alberta: the Athabasca, Cold Lake, and Peace River deposits (Figure 1). The Athabasca Oil Sands Deposit is the most extensive in terms of area and bitumen reserves. Additionally, the Athabasca deposit is considered the single largest hydrocarbon reservoir in the world (DeMaison, 1977), with an estimated resource of over 1.3 trillion barrels (209 billion cubic metres) of bitumen in place (ERCB, 1990). The Athabasca deposit pinches out to the northeast against the Canadian Shield and to the west against the Nisku Grosmont High (Stewart, 1963). In the east and southeast it is apparently trapped by a structural rollover caused by underlying salt solution collapse. To the northwest, McMurray reservoir sands grade into marine shales and in the north and northeast, the oil sands are limited by glacial erosion (Stewart, 1963). The southern limit of the deposit is poorly defined (Carrigy, 1959a).

Compared to values of 25° to 40° API (American Petroleum Institute) for conventional oils (North, 1985), Athabasca bitumen has a measured gravity of 8° to 10° API (Rennie, 1987) corresponding to the rank of heavy oil. Due to this high viscosity, unconventional recovery methods such as mining or one of various in situ recovery schemes are required. Current and proposed in situ recovery technology includes steam-assisted gravity-drainage (SAGD), steam assisted gravity-push (SAGP), vapor extraction (VAPEX), and cyclic steam stimulation (CSS). High-resolution determination of oil sand distribution (reservoir versus non-reservoir) is of particular importance in terms of maximizing recovery efficiency and lowering production costs. For this reason, exploration and delineation drilling of oil sands deposits are typically undertaken with exceptionally closely-spaced core control, in order to ensure that high-grade reservoir bodies are mapped to a very precise degree. Delineation wells for an oil sands project may be as closely spaced as 300 m apart, making the Athabasca deposit one of the most densely drilled areas in the world (Mattison, 1987).

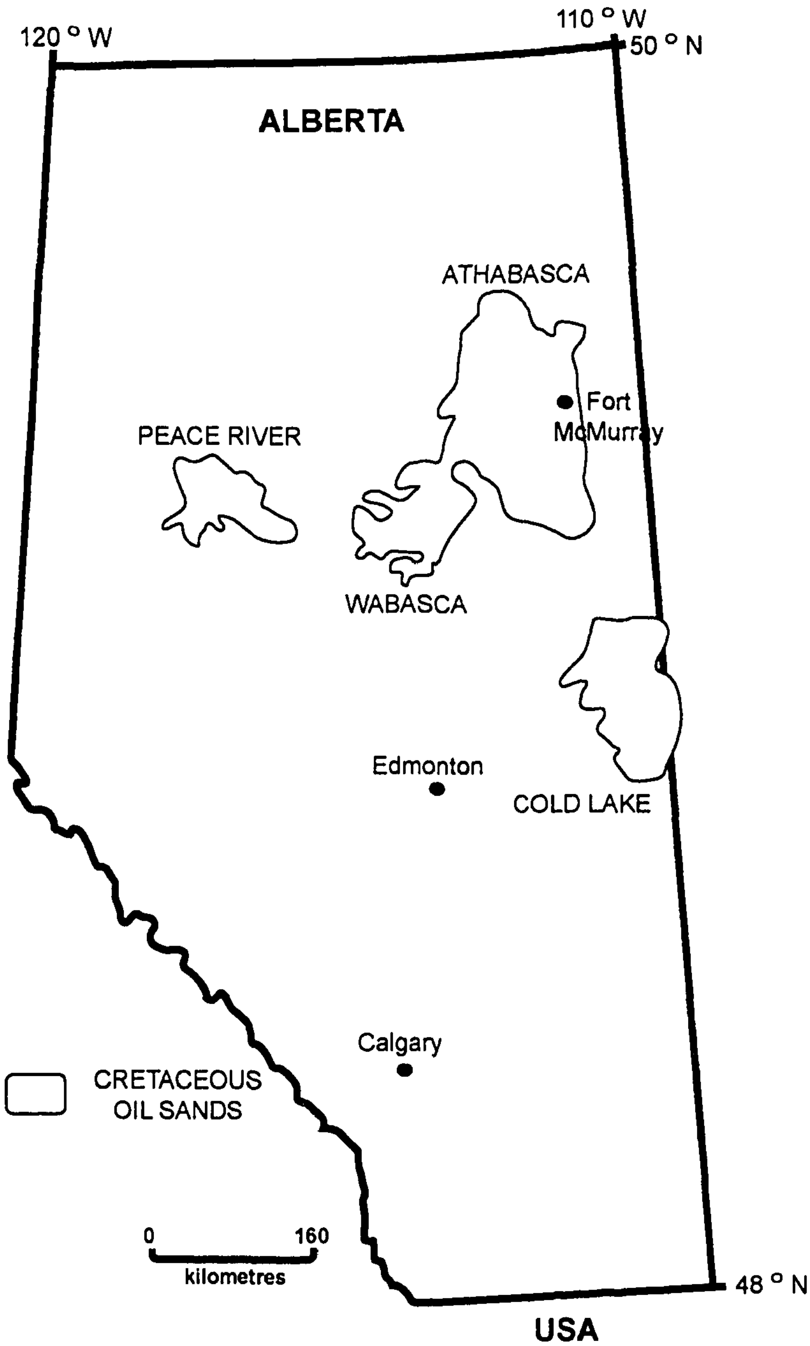


Figure 1
Athabasca (and Wabasca), Cold Lake, and Peace River Cretaceous oil sand deposits in Alberta (modified from Mossop *et al.*, 1982).

Kidd (1951) observed that bitumen distribution in the McMurray Formation is controlled by lithology, wherein cleaner, well-sorted, quartzose sands with high porosity and permeability have the highest degree of bitumen saturation. This simple observation is a salient feature as the McMurray Formation has undergone little post-depositional diagenetic modification such as cementation, quartz diagenesis, clay authigenesis, etc. As a result, bitumen content is primarily dependent upon facies distribution, and therefore, ultimately controlled by depositional environments (Mossop, 1980). Description and interpretation of sedimentological features, the key to understanding the physical and biological processes responsible for the distribution of facies, is therefore of prime economic importance.

STUDY AREA

Two discrete project areas were examined for this study: the Sunrise Thermal Project and the Muskeg River Mine Project (Figure 2). The two study areas are in close proximity, yet positioned between them lays an economic boundary separating the mineable portion of the oil sands to the west from the in situ recoverable portion of the oil sands to the east. For the purposes of this study, this boundary is defined as 50 m of overburden (Figure 3). Open pit mining is not economic where more than about 50 m of overburden must be removed. Areas with greater than 50 m of overburden are amenable to in situ recovery methods. This boundary may change with time based on factors such as available technology and oil price.

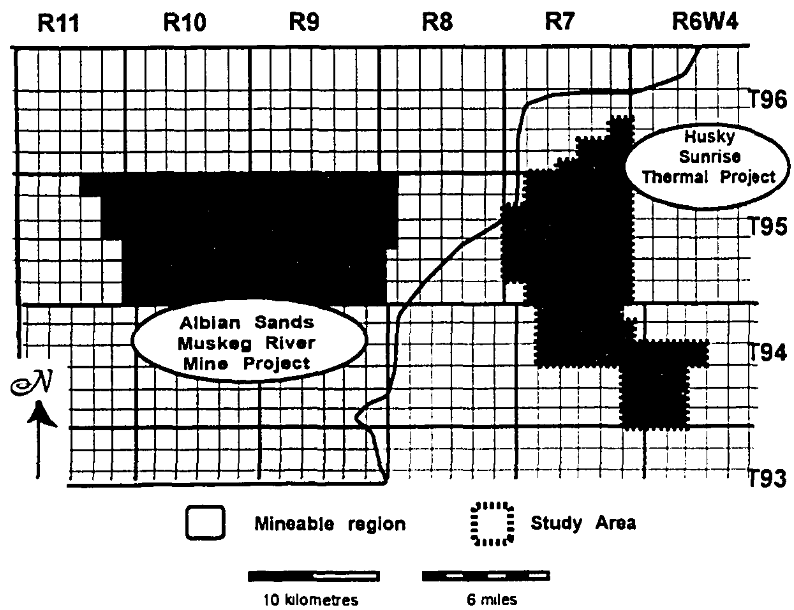


Figure 2
Spatial relationship of the study areas for Husky Sunrise Lake Thermal Project and the Albian Sands Muskeg River Mine Project. The depicted area of the surface mineable area of the Athabasca Oil Sands Deposit is modified from Govier (1974).

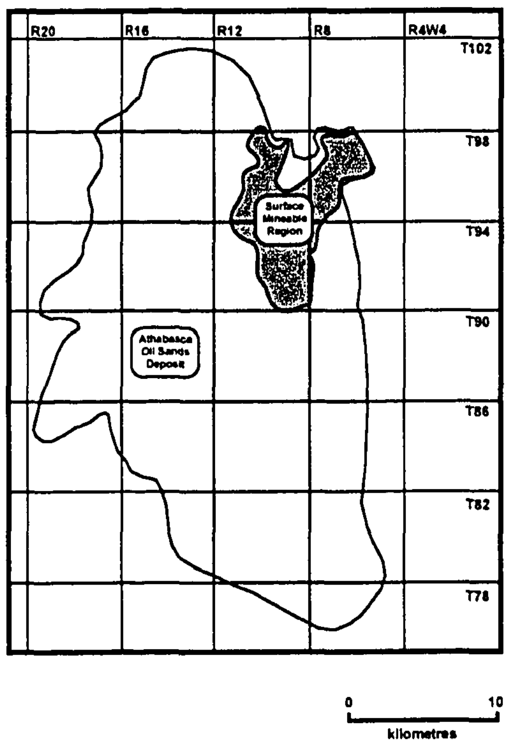


Figure 3
Surface mineable area of the Athabasca Oil Sands Deposit (modified from Govier, 1974).

The Muskeg River Mine Project study area encompasses an area of about 10 km^2 (4 mi^2) in Township 95, Range 10 west of the Fourth Meridian comprising sections 23, 24, 25 and 26 (Figure 4), which is only a small portion of the entire lease. This area outlines the first two years of projected mining within the Muskeg River Mine, with initial ore extraction beginning in December 2003. This study area has exceptional core control. Thirty-five cores were examined to determine facies associations, depositional environments and hydrocarbon distribution in the McMurray Formation. From a regional perspective, the study area is a portion of the central axis of the McMurray Valley System. Thus, the McMurray Formation is thicker in this region (averages 85 m) as compared to areas such as the Grosmont High where the McMurray is thinner (less than 10 m) to absent (Figure 5).

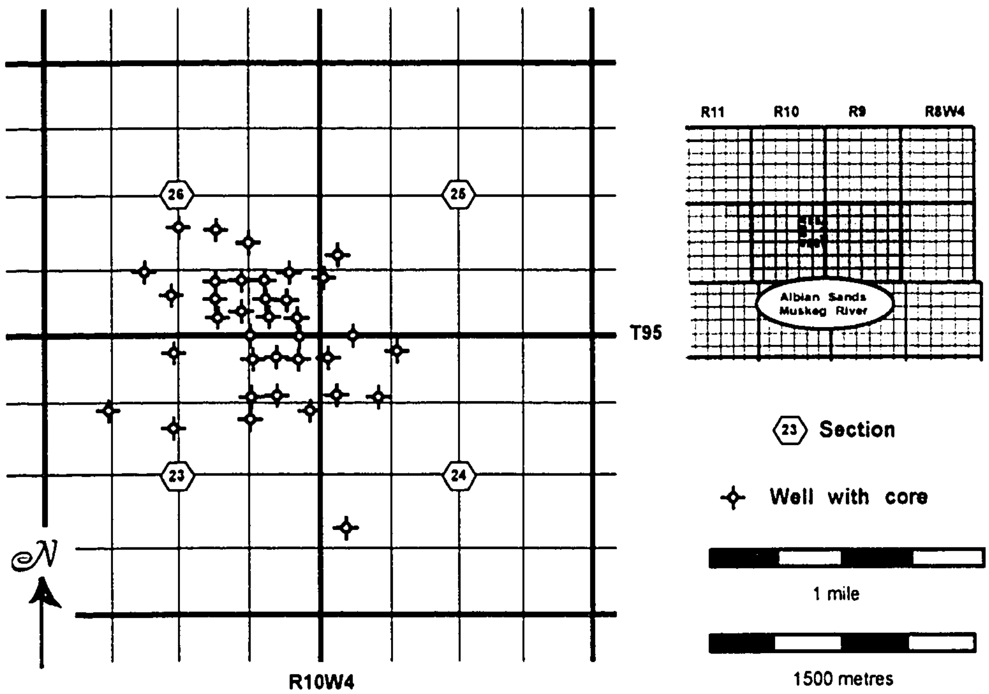


Figure 4

Albian Sand Muskeg River Mine study area and locations of core examined.

The Sunrise Thermal Project study area encompasses the entire project lease. It constitutes a major portion of Township 95 Range 7 and portions of Township 96

Range 7, Township 94 Range 7 and Township 94 Range 6 west of the Fourth Meridian (Figure 6). A SAGD (Steam-Assisted Gravity-Drainage) project is planned for future development of the lease. Ninety-seven cores from the 2002 drilling season and 212 cores from the 2003 drilling season (assisted by Shaurat Sayani and Cheryl Hanson) were examined to determine facies association, depositional environments and hydrocarbon distribution in the McMurray Formation. From a regional perspective, this study area is adjacent to the central axis of the McMurray Valley System and is similar in thickness to the Muskeg River Mine Project study area with an average thickness of 65 m.

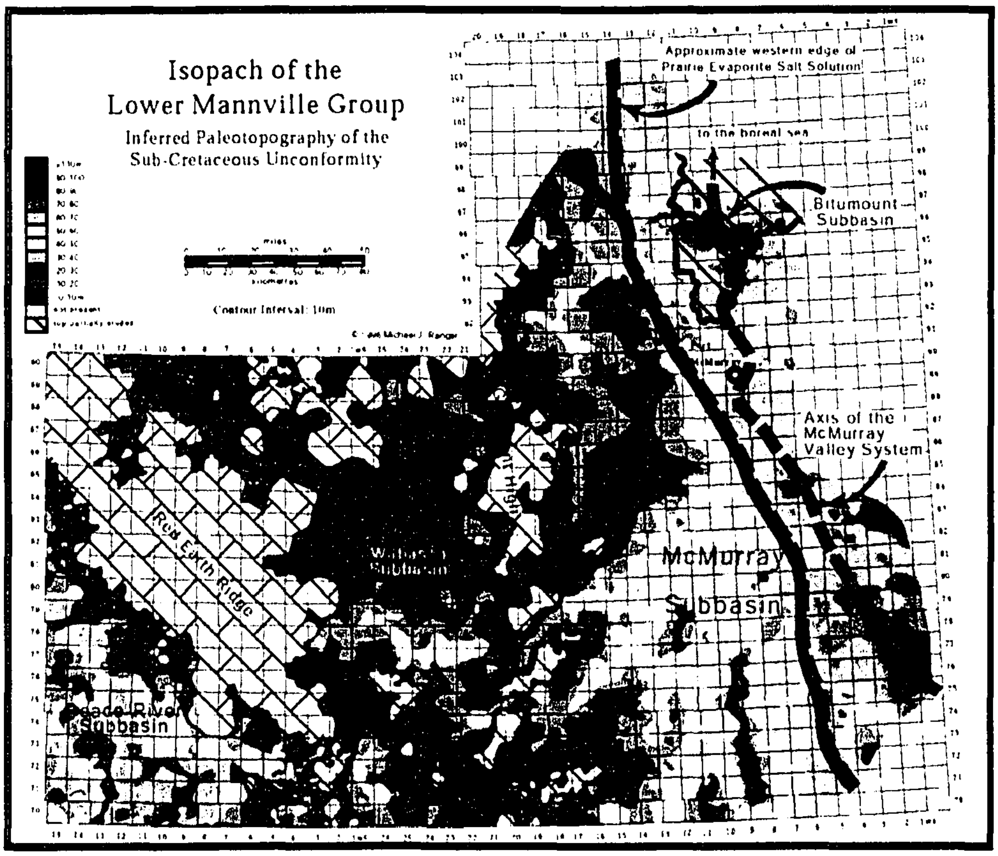


Figure 5
Paleotopography in earliest Mannville time in northeastern Alberta, inferred from the isopach of the Lower Mannville Group (Ranger and Pemberton, 1992).

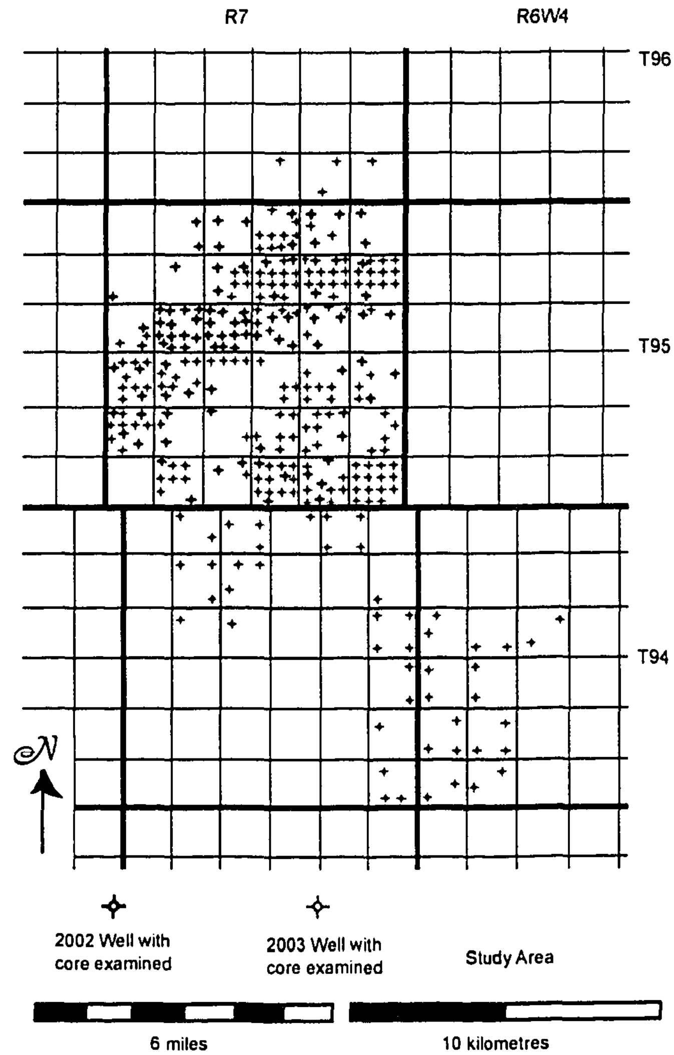


Figure 6
Sunrise Thermal Project study area and location of cores examined from 2002 and 2003 drilling seasons.

METHODS

Thirty-five drill cores from the Muskeg River Mine Project were examined at Pearce Leahy Archives in Calgary. The Sunrise Thermal Project cores from the 2002 and 2003 drilling seasons were viewed at AGAT Laboratories and Norwest Laboratory in Calgary. Logging was completed with the aid of APPLECORE software created by M. J. Ranger. Features such as lithology, grain size, sorting, biogenic structures, relative degree of bioturbation, sedimentary structures, nature of bedding contacts, bedding styles, bed thickness, lithologic accessories, and the relative degree of bitumen saturation were examined.

At the Muskeg River Mine Project coring was initiated from the surface in Pleistocene glacial sediments that unconformably overlie the McMurray Formation, and penetrated the entire McMurray Formation to approximately 5 m below the sub-Cretaceous Unconformity into the underlying Devonian Waterways Formation. At the Sunrise Thermal Project coring was initiated in the Clearwater shales, penetrated the entire McMurray Formation and approximately 15 m into the underlying Devonian Waterways Formation below the sub-Cretaceous Unconformity.

In cores with heavy bitumen saturation, sedimentary structures are commonly obscured, producing a massive appearance. X-radiography may be useful to reveal stratification in these apparently massive sands (Fox, 1988), but this technique was not used in the present study. Alternatively, variations in grain size and imbricated mud clasts often reveal the nature of the stratification. In addition, cutting tools may smear the slabbed face and sections of core may rotate in the tube due to drilling, making it difficult to determine if the orientation of inclined bedding is strictly due to sedimentary processes or was mechanically induced. The presence of bitumen normally binds the otherwise unlithified sediment together. In water-saturated and low saturation zones the absence of bitumen allows the sand to disaggregate, resulting in poor core recovery and preservation structure.

PREVIOUS WORK

Discovery and Delineation Phase

The first recorded mention of the Athabasca oil sands is attributed to the English explorer Henry Kelsey. In 1719, while serving as manager of the Hudson's Bay Company trading post, Kelsey noted in his journal that a Cree aboriginal named Wa-Pa-Su had given him a sample "of that Gum or pitch that flows out of the Banks of the River". Exploration of the oil sands began in 1778 by the fur trader Peter Pond, whose notes make reference to the deposit. In the early 1790's, Sir Alexander

Mackenzie documented the oil sands as "bituminous fountains". Further expeditions by explorers in the early to middle 1800's generated surveys of the rivers and noted their features (Carrigy, 1959a).

Detailed geologic study of the area was first undertaken in the late nineteenth century by researchers such as Dr. R. Bell, Dr. R.G. McConnell and Dr. George M. Dawson from the Geological Survey of Canada. A reconnaissance survey of the strata along the Athabasca and Clearwater Rivers was conducted by Bell (1885) who noted the great economic significance of the bitumen. McConnell (1893) published a detailed study of outcrop exposures along the Athabasca River, its tributaries and other rivers in the area. These early studies were concerned mainly with local stratigraphy of the Athabasca deposits and correlation to other Lower Cretaceous exposures in the Western Canadian Sedimentary Basin.

McLearn (1917) proposed the term "McMurray" for the strata containing the tar sands. He deemed that "tar sands" was a lithological term, and therefore not appropriate as a formation name. McLearn (1917) did not attempt to establish an age for the McMurray Formation.

Numerous studies in the early part of the twentieth century stressed the extent and volume of the oil sand deposits, with emphasis on possible commercial applications such as paving material and bitumen recovery (Ells, 1914; 1926; Clark and Blair, 1927). From 1913 to 1915, Sydney C. Ells (funded by the Federal Mines Branch of Canada) conducted paving tests using Athabasca oil sands. K.A. Clark and S.M. Blair were the first to attempt extraction of oil from the oil sands in 1923, using an experimental hot water extraction plant in the basement of the power plant at the University of Alberta (Carrigy, 1973b).

In the middle of the twentieth century, researchers studying the Athabasca Deposit focused on the origin of the bitumen in the oil sands (Ball, 1935; Sproule; 1951; Link, 1951; Hume, 1951). They also proposed possible depositional environments for the sand, but utilized little to no collaborating evidence to support their interpretations.

Modeling Phase

A new stage in the study of the McMurray Formation was initiated with an article published by Kidd (1951). He used detailed stratigraphy, mineralogy, paleocurrent analysis, and sedimentary structures to develop a floodplain to coastal lowland depositional model. This research was continued and expanded upon by Carrigy, who in numerous papers spanning approximately fifteen years (Carrigy, 1959a, 1973b), developed much of the foundation for the modern understanding of the McMurray Formation.

Carrigy's deltaic complex depositional model for the McMurray Formation (Carrigy 1966, 1971) dominated McMurray research until the mid 1970's. It is not surprising that Carrigy proposed the deltaic model for the McMurray Formation, as it was the most studied and published depositional model available to the clastic sedimentologists at the time. In addition, the inclined heterolithic stratification (IHS) beds were interpreted as delta foresets, in opposition to the point bar stratification interpretation common today.

As an increasing number of different depositional models were developed in detail and applied to ancient sediments during the mid sixties to early seventies, it became evident that the deltaic depositional model for the McMurray Formation would require further scrutiny. Despite new discoveries and advances, this model has persisted to more recent publications such as that by Leckie and Smith, (1992). Due to the "energy crisis" of the early seventies, interest in the Athabasca Oil Sands increased substantially. During this time, researchers began to concentrate on local detailed studies of the McMurray Formation (Flach, 1977; Nelson and Glaister, 1978; Mossop, 1980), a shift from the previous regional studies. Studies from this period produced two main depositional models for the McMurray Formation: the estuarine model (Stewart and MacCallum, 1978; Pemberton *et al.*, 1982; Ranger and Pemberton, 1992) and the fluvial model (Flach, 1977; Mossop and Flach 1983). Smith (1987) suggested a merger of these two models when he proposed a threefold lithofacies classification for meandering channel point bar deposits. The three point bar styles represent the transition from fluvial through middle estuarine environments in an estuarine system (Figure 7).

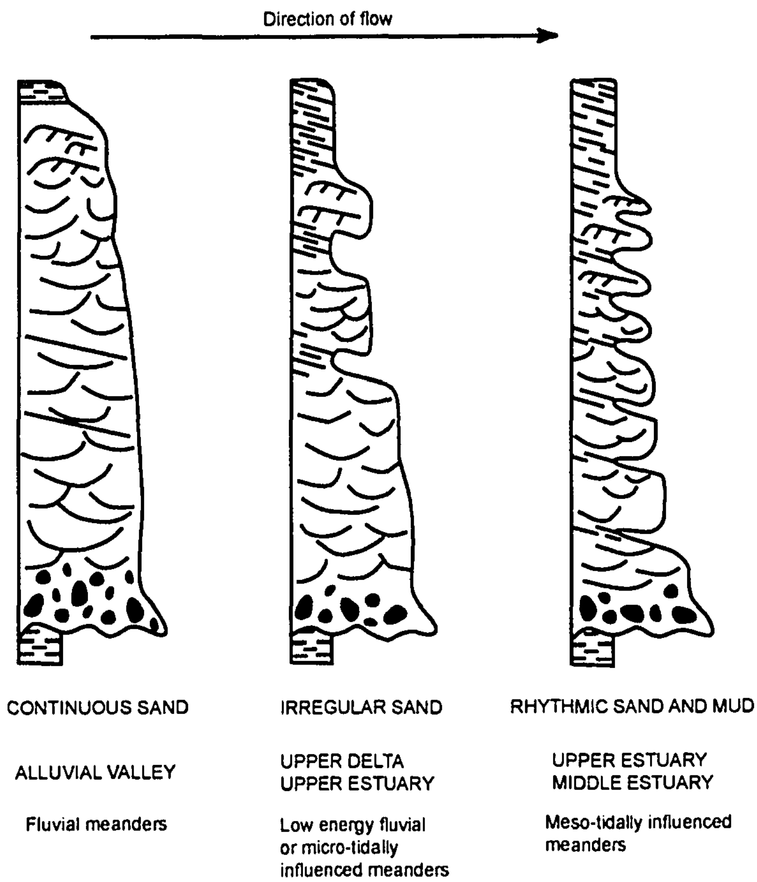


Figure 7
Lithofacies models for meandering river-estuarine point bar deposits (modified from Smith, 1987).

Incorporation of the relatively youthful discipline of ichnology (beginning in the early 1980's) has typically supported the estuarine model (Pemberton *et al.*, 1982; Bechtel *et al.*, 1994; Yuill, 1995). Estuarine deposition was one of the first genetic interpretations of the formation (Russell, 1932) and has been revived from time to time (Falconer, 1951; Jardine, 1974). On a regional scale, evidence has been presented for estuarine deposition in coeval strata for the McMurray in the central plains of Alberta, and in northwestern and southern Alberta (Williams, 1963; Acham, 1971; Finger, 1983; Wanklyn, 1985). The present study also favors a brackish water interpretation for the majority of the McMurray Formation sediments.

SOURCE OF SEDIMENTATION

McMurray oil sands in the Athabasca area have a grain and matrix composition significantly different from those of the Cold Lake and Peace River heavy oil areas as revealed by petrographic and X-ray analyses (Nelson and Glaister, 1978). Specifically, the clay/silt ratio in the matrix fines of the quartzose McMurray sands is about one fifth of that found in the lithic-feldspathic Cold Lake deposit and chert-rich sands of the Peace River deposit (Nelson and Glaister, 1978). McMurray Formation sediments within the area of the Athabasca Oil Sands Deposit are generally thought to have been derived from an eastern source, most likely from the erosion of the Proterozoic Athabasca Sandstone of the Precambrian Shield (Stewart and MacCallum, 1978).

The general consensus is that the initial and intermediate stages of sedimentation were derived from reworking of the Athabasca Sandstone and later sediments from the erosion of the underlying igneous and basement rocks of the Precambrian Shield (Sproule, 1951; Mellon and Wall, 1956; James, 1977). A few authors (Carrigy, 1959a; Bayliss and Levinson, 1976; Wach 1984) have raised the possibility that another source may have been the Western Cordillera, at least during the latter stages of deposition during McMurray time.

STRATIGRAPHY

Pre-Cretaceous Succession

In the Athabasca Oil Sands area, the Precambrian basement is overlain unconformably by a succession of Devonian evaporites and carbonates. A second major unconformity separates the Devonian strata from the overlying McMurray Formation (Carrigy, 1973a). The Devonian strata pinch out against the Canadian Shield to the east and thicken westward to about 350 m near Fort McMurray (Norris, 1973). The Devonian rocks dip to the west-southwest and the strata that subcrop at the sub-Cretaceous Unconformity become successively younger toward the west (Martin and Jamin, 1963).

The Devonian succession in the Fort McMurray area comprises the Lower to Middle Devonian Elk Point Supergroup and the Upper Devonian Beaverhill Lake Group (Norris, 1973). In the Athabasca area, the Elk Point Supergroup is comprised of the McLean River Formation, Methy Formation, Prairie Evaporite, Muskeg Formation, Watt Mountain Formation and the Fort Vermilion Formation. The Prairie Evaporite Formation has immense consequence for the area as its dissolution caused the major collapse feature near Bitumont (northeast of Fort McMurray) where strata are offset by as much as 60 m (Coneybeare, 1966; Gallup, 1974) and the eastern edge of the bitumen in south Athabasca producing the structural trap (Ranger, 1994).

The Beaverhill Lake Group overlies the Elk Point Super Group, and is separated from it by a paraconformity. The Beaverhill Lake Group is comprised of the Waterways and the Slave Point formations. The Waterways Formation is divided into four members: the Firebag, Calumet, Christina, and Moberly members, which are comprised of argillaceous limestone, calcareous shale and clastic limestone. The McMurray Formation is in direct, unconformable contact with the underlying Waterways Formation in the study areas. A subcrop map (Figure 8) shows the regional distribution of Devonian strata at the sub-Cretaceous unconformity.

Sub-Cretaceous Unconformity

Bell (1885) and McConnell (1893) first noted that Cretaceous sediments unconformably overlie Devonian carbonates in the Athabasca oil sands area. During this extended hiatus, it is probable that the Devonian strata were subjected to several periods of subaerial exposure. The presence of locally observed calcareous shales directly beneath the McMurray Formation (Carrigy, 1959a; Stewart, 1963) is consistent with this interpretation. These green shales are also identified in the study area (Plate 1, Photo A). In central and southeastern Alberta, the basal calcareous shales are identified as the Deville Member. Although the Deville is similar to the basal claystone beds of the lower member of the McMurray, it is unclear whether the two members are indeed correlative in either a genetic or time-stratigraphic sense. Williams (1963) suggested that the Deville might represent deposits of Jurassic age. However, this remains speculative, as conclusive evidence of deposition between Devonian and Early Cretaceous time has remained elusive in northeastern Alberta (Carrigy, 1959a; Park and Jones, 1985).

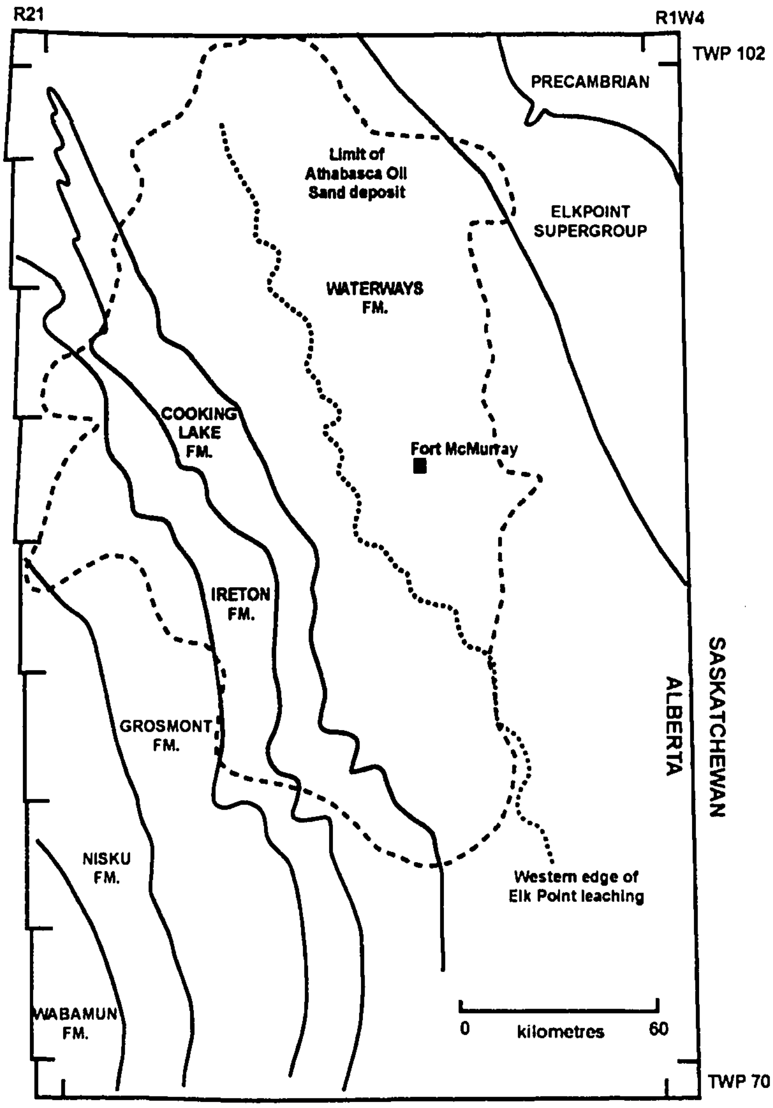


Figure 8
Subcrop map of Devonian strata at the sub-Cretaceous unconformity with outline of Athabasca oil sand deposit and western edge of Elk Point leaching (modified from Stewart, 1963; Norris 1973).

Cretaceous Succession

The Cretaceous succession in the Fort McMurray area of the Athabasca oil sands comprises the McMurray, including Clearwater, Grand Rapids, Joli Fou, Pelican, and, La Biche Formations of the Mannville Group (Carrigy, 1959a). Only the McMurray Formation and a portion of the Clearwater Formation (Wabiskaw Member) were examined in the present study.

The McMurray Formation is correlated to the lower part of the Mannville Group: the Dina Formation in the Lloydminster area (Nauss, 1945), Ellerslie or Basal Quartz and Ostracode in central Alberta (McLean and Wall, 1981), the Sunburst Sandstone in southern Alberta (Mellon, 1967), the Gething Formation of the Bullhead Group in the Peace River and northwestern Alberta and the Gladstone Formation of the Blairmore Group of the Alberta Foothills (McLean and Wall, 1981). Figure 9 is the stratigraphic correlation chart of the Lower Cretaceous in Alberta.

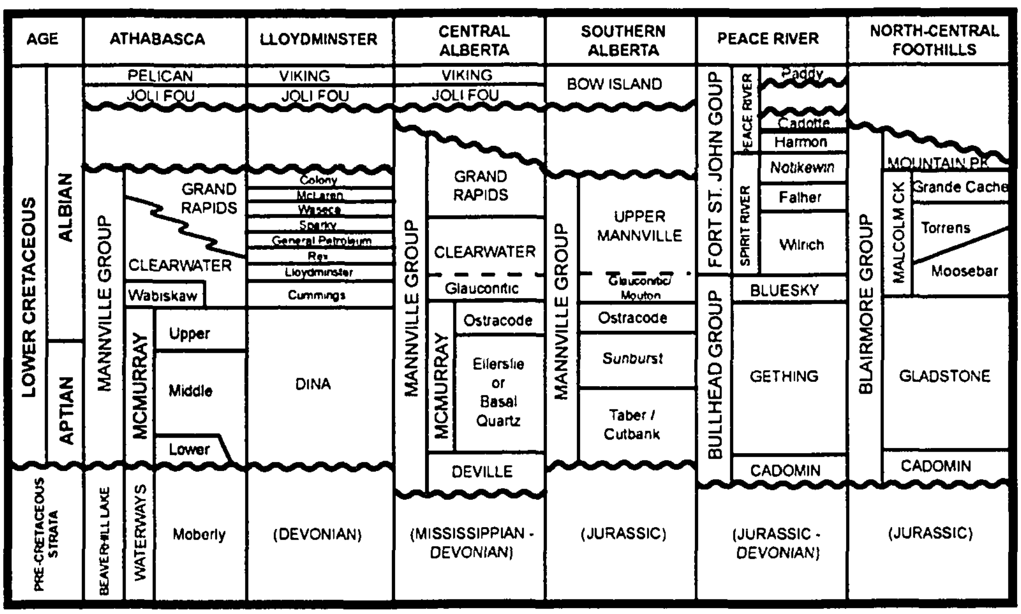


Figure 9
Stratigraphic correlation chart of the Lower Cretaceous in Alberta (from McLean and Wall, 1981; Williams, 1963). Parentheses indicate ages, not formation names.

Carrigy (1959a) further divided the McMurray Formation into three informal members; the lower, middle, and upper McMurray. These members remain informal because their regional correlation is problematic. The lower member of the McMurray Formation was deposited in deep valleys on the sub-Cretaceous Unconformity surface and is consequently of limited areal extent. Clays and coals are commonly interpreted to separate the lower and middle members, but they are not ubiquitous, for example, where the Devonian is structurally high or where incised by a subsequent channel they may not be present. Distinguishing between the lower and middle members is locally problematic where middle McMurray sands rest on lower McMurray sands. The middle McMurray is widespread throughout the Athabasca Deposit. The upper McMurray is also regionally extensive except where removed by subsequent Pleistocene erosion. A fourth unit, the "limey unit" identified by Fox (1988), incises the middle member but is of limited areal extent. This unit was not encountered in the Muskeg River Mine study area but is locally present in the Sunrise Thermal Project study area.

With the exception of locally occurring gastropods within the calcareous unit, a lack of body fossils in the McMurray makes it difficult to determine an exact age for the formation. The present consensus places the McMurray in the Aptian, possibly up to early Albian stages (Burden, 1984; Hein *et al.*, 2000, Appendix 4)

The Clearwater Formation (McConnell, 1893) conformably overlies the McMurray Formation. The base of the Clearwater is placed at the bottom of a well-defined regional glauconitic sand bed (McLearn, 1917; Carrigy, 1959a), designated as the Wabiskaw Member (Badgley, 1952). Common practice places the McMurray-Clearwater contact at the first appearance of glauconitic sediments. Following this practice, the McMurray-Clearwater contact has been identified by other researchers as a distinct color change in shales from brownish gray in the McMurray to a glauconite-induced, dark bluish-gray in the Wabiskaw member of the Clearwater Formation (Plate 1, Photo B). However, petrographic analysis has found this practice to be false. The mineral responsible for the blue-gray color is chlorite. A distinct increase in the ichnofossil size in the Wabiskaw member relative to the McMurray has also been used to help identify the contact (Plate 1, Photo C). In addition, the large-bodied trace fossils have a low diversity indicative of stressed biota. The established age of the Clearwater Formation is early Albian (Carrigy, 1959a; Stelck *et al.*, 1956; Casey,1961; Stelk and Kramers, 1980).

The Cretaceous succession is truncated by Pleistocene glacial till deposits composed of sand, silt, and gravel, which is overlain by muskeg. A summary of the regional stratigraphy is illustrated with representative lithology in Figure 10.

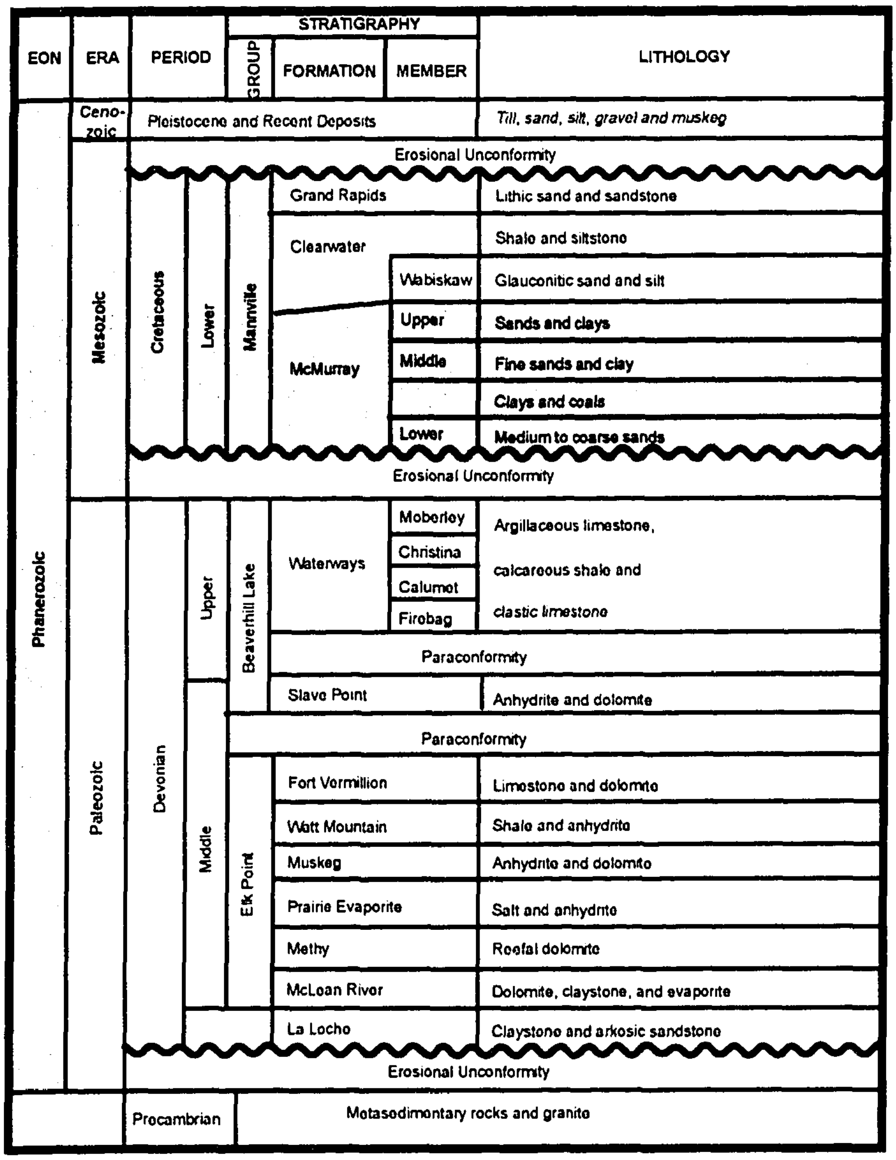


Figure 10
Summary of stratigraphy and representative lithologies within the study area (modified from Carrigy, 1973a; Hackbarth and Nastasa, 1979; Bachu and Underschultz, 1993).

GEOLOGICAL FRAMEWORK

Development of the Foreland Basin

Prior to the Late Jurassic, the Alberta Basin existed as a passive margin on the western edge of North America (Porter *et al.*, 1982). Tectonic activity was initiated in middle to late Jurassic. The consequent lithospheric loading in the fold and thrust belt included flexure or downwarping generating the Western Canadian Foreland Basin (Price, 1973; Beaumont *et al.*, 1993). Erosion of the uplifting Cordillera to the west and the Canadian Shield to the east established the sediment source that inundated the basin with clastic sediments (Price, 1973; Beaumont, 1981) including those of the McMurray and Clearwater Formations (Leckie and Smith, 1992).

Foreland basin morphology exhibits an asymmetric profile with the deepest portion of the basin being adjacent to the fold thrust belt as the result of thrust-belt loading and sediment loading in the basin itself (Leckie and Smith, 1992). The resultant morphology in the Western Canada Foreland Basin is a westward thickening wedge of clastic sediments (Figure 11).

Structural Controls

The deposition of the McMurray Formation in the Athabasca area was influenced by the paleotopography and structure of the underlying Devonian strata and Precambrian basement. The Precambrian basement dips toward the southwest at a gradient of approximately 4 m/km (Carrigy, 1959a; Norris, 1973) and the overlying Devonian strata dip at a low angle roughly parallel to this surface. Post-Cretaceous tilting was approximately 1 m/km to the southwest over most of the Athabasca area (Martin and Jamin, 1963).

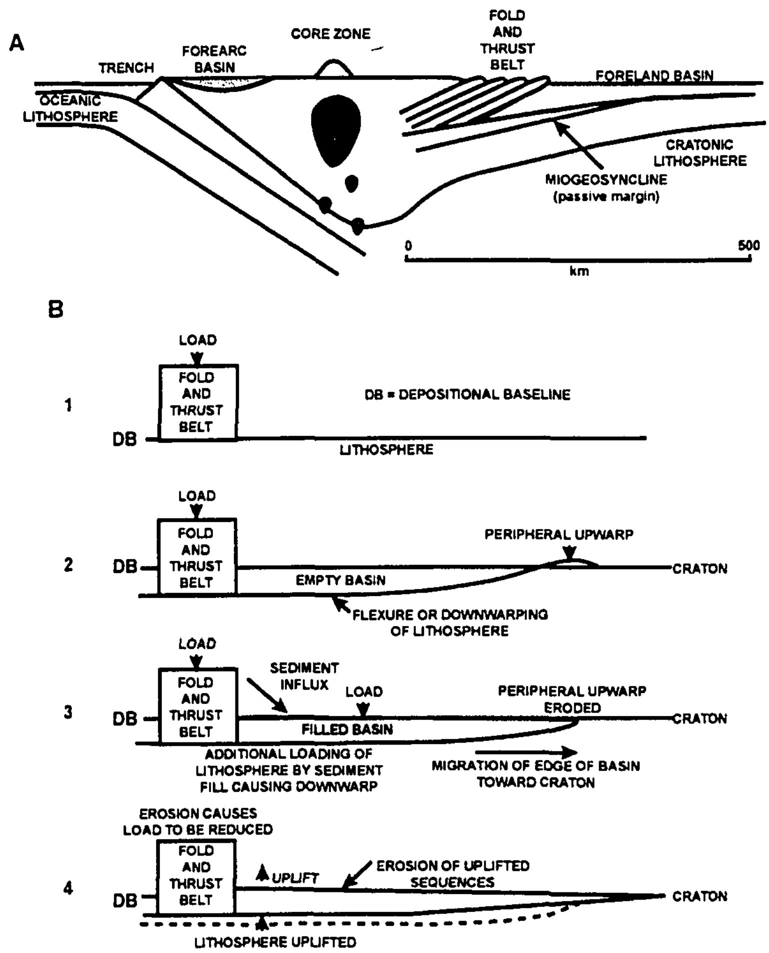


Figure 11
A Destructive plate margin with oceanic crust subduction under continental crust showing development of a fold and thrust belt and adjacent foreland basin (modified from Dickinson, 1976; Beaumont, 1981).
B Four step schematic for the development of a foreland basin as a result of crustal loading in a fold and thrust belt (modified from Price, 1973; Beaumont, 1981).

Topography of the Pre-Cretaceous unconformity surface was the dominant aspect shaping depositional patterns during the initial stages of sedimentation of the McMurray Formation. The two salient structural controls during McMurray time were the Athabasca Anticline and the Salt Collapse Low. Both tectonic features began their evolution during the Devonian.

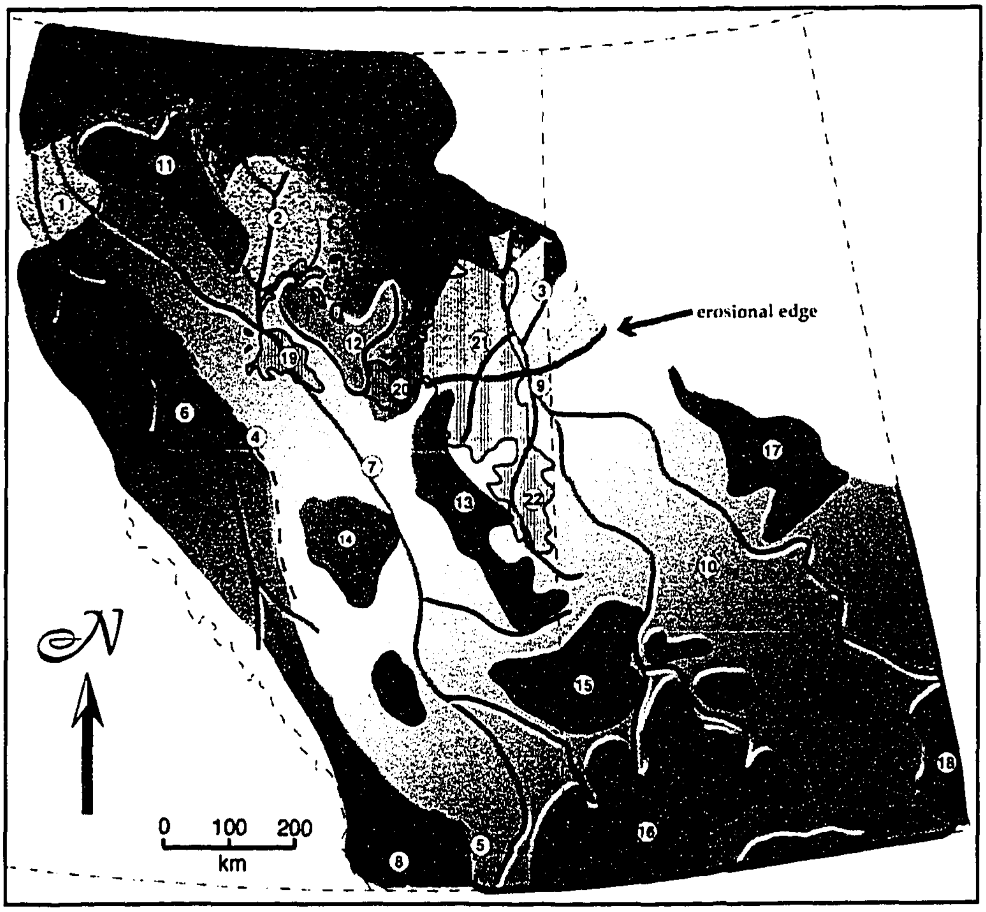
The anticline presently is on the order of 240 km long by 112 km wide and runs in a northwesterly to southeasterly direction with an area of closure that spans over 250 townships. According to Masters (1984), at the time of accumulation of oil in the deposit, the area enclosed by the anticline is estimated to have been 600 townships in extent.

Salt solution is attributed to many of the structural features in the Athabasca Oil Sands area, including the major collapse feature near Bitumont (northeast of Fort McMurray) where strata are offset by as much as 60 m (Coneybeare, 1966; Gallup, 1974). Modern rivers that drain the northeastern corner of Alberta (such as the Athabasca and Clearwater) occupy trends of salt collapse lows for portions of their length (MacCallum, 1977). The thickest McMurray intervals have been documented to occur within the limit of Prairie evaporite solution (Stewart, 1963). Salt solution continues today indicated by saline springs commonly found in the Fort McMurray area (Carrigy, 1959a; Jardine, 1974).

The McMurray Formation occupies the valleys and depressions on the unconformity surface; while its occurrence is thin to absent over hills and ridges (Stewart, 1963). The unconformity surface is very uneven and displays considerable relief (Figure 5), with some slopes as steep as 70 m/ km (Martin and Jamin, 1963). There are numerous north-northwest trending ridges on the unconformity surface that correspond to subcrop edges (Figure 9) of erosion resistant Devonian strata (Martin and Jamin, 1963). The two main ridges are; the Grosmont Ridge, the northern extension of the Wainwright Ridge (Ranger, 1994), which forms the western boundary of the Athabasca Oil Sands Deposit, and the Beaver Hill Lake Ridge, which formed as a result of the salt solution of underlying beds to the east of the ridge (Stewart and MacCallum, 1978). Between the ridges are valleys cut into less resistant lithologies (Martin and Jamin, 1963). There are several valleys that follow a northeasterly trend and seem to be tributaries of the main north-northwesterly trending trunk drainage valley (Ranger and Pemberton, 1988). In addition, fractures or faults on the Pre-Cretaceous surface may have influenced the formation of these tributary valley systems (Martin and Jamin, 1963).

Paleotopography

The erosional continental landscape during the Early Cretaceous (Neocomian/Aptian) was dominated by the incision of three main northwest trending paleovalleys (Figure 12). The orientation of these drainage systems was shaped dominantly by the differential erosion of gently dipping substrate and with lesser effects by other structural elements (Ranger and Pemberton, 1997).



LEGEND

1. Sikanni Chief Delta
2. Keg River Delta
3. Fort McMurray Estuary
4. Fox Creek Escarpment
5. Taber Escarpment
6. Spirit River Channel Valley
7. Edmonton Channel Valley
8. Cutbank Channel Valley
9. St. Paul Channel Valley
10. Assiniboia Channel Valley
11. Keg River Highlands
12. Red Earth Highlands
13. Wainwright Highlands
14. Pembina Highlands
15. Kindersley Highlands
16. Medicine Hat - Swift Current Highlands
17. Molanosa Highlands
18. Moosomin Highlands
19. Peace River Oil Sands
20. Wabasca Oil Sands
21. Athabasca Oil Sands
22. Cold Lake Oil Sands

Figure 12
Inferred paleogeography during earliest Albian time (modified from Smith, 1994).

The three major drainage trunks are the Spirit River valley system, the Edmonton Channel valley system, and the McMurray valley system (Ranger, 1994). The Spirit River valley system was situated along the axis of the incipient foreland trough of the North America Cordillera and drained much of western Alberta (Ranger and Pemberton, 1997). The Edmonton Channel valley trends northward along the western edge of the basin extending through southeastern Alberta and southwestern Saskatchewan. It is believed to have drained much of western Alberta, and at times, the western United States (Ranger, 1994). Along the eastern edge of the basin lies the McMurray valley system (Ranger, 1994), previously referred to as the St. Paul Channel by Williams (1963). Bounded by the Wainwright Ridge-Grosmont High to the west and the Canadian Shield to the east, the McMurray valley system eroded into the Devonian strata and formed the subbasin into which McMurray Formation sediments were deposited.

During early Albian times, the lower Cretaceous Boreal Sea transgressed southward into Alberta and Saskatchewan, flooding these valley systems (Williams, 1963; Christopher, 1980). Eventually, these valley systems constituted arms of the sea (Williams, 1963; McLean and Wall, 1981). Each of the three valley systems reacted independently to transgressions of the Boreal Sea with variations dependent on sediment supply, and topography (Ranger and Pemberton, 1997). Transgression of the McMurray valley system is the result of subsidence of the foreland basin, subsidence due to dissolution of the Devonian strata, and eustatic sea level rise (Leckie and Smith, 1992; Ranger, 1994). The early Albian transgression culminated with the deposition of the Clearwater Formation and is considered to be part of a long-term rise in sea level that peaked during late Albian times with the deposition of the Joli Fou Formation (Caldwell, 1984).

TIMING AND MECHANISM OF OIL MIGRATION AND TRAPPING

Migration Theories

Numerous migration theories for the Athabasca oil sands have been proposed, including but not limited to: the in situ source theory, the leaky reef theory, the Devonian tar theory, and the long distance migration theory, which is most commonly accepted today. The in situ source theory suggests that the bitumen is immature oil that was sourced from organic matter contained in the enclosing reservoir rocks (Ball, 1935; Corbett, 1955). The leaky reef theory was derived from the discovery of Paleozoic down dip reefs. This theory hypothesizes the origin of the Athabasca oils as the result of oil breaching reef reservoirs and accumulating in the overlying Lower Cretaceous sands (Sproule, 1938; 1955). Another theory proposed is the eroded Devonian tar theory whereby bitumen deposits hosted by the Devonian carbonates subcropping at the sub-Cretaceous unconformity were eroded during early Cretaceous times and deposited with the regular sediments (Link, 1951).

The commonly accepted long distance migration theory states that bitumen within the McMurray deposit originated in source beds down dip within the western foreland basin as these beds subsided through oil window conditions (Deroo *et al.*, 1977; Creany and Allen, 1992). Hydrocarbons underwent long distance migration to the east, where they were trapped as conventional oils. Subsequently, these conventional oils were degraded to higher density, high viscosity bitumen through water washing and/or bacterial activity (Deroo *et al.*, 1977; Brooks *et al.*, 1988). This theory is not modern, but rather one of the earlier interpretations, with similar conclusions published by Gussow (1955).

Source Beds

Division of the oils within the Western Canada Sedimentary Basin into distinct families has been accomplished through the work of Allen and Creany (1991) who used biomarkers to fingerprint oils and source beds, according to the geochemical classification of oils by Deroo *et al.* (1977). Correlation of these geochemical families to source rock geochemistry and the recognition of distinct reservoir systems constitute persuasive evidence that the source of the Lower Cretaceous heavy oils is primarily the Jurassic Nordegg Member and the Mississipian Exshaw Shale (Ranger, 1994).

Migration Mechanism

The driving mechanism of fluid migration for the precursor oils of the oil sands is a controversial issue. Two competing theories for the migration mechanism are compaction and expulsion of water and oil in either separate phase or in miscible solution (Gussow, 1955; Vigrass, 1968; DeMaison, 1977) and topographically driven hydrodynamic flow (DeMaison, 1977; Hitchon, 1984; Garven, 1989). The hydrodynamic model depends on the establishment of thrusting and basin uplift (Laramide orogeny) in the west, which established the Rocky Mountains and formed a hydraulic head for the major recharge area in the foreland basin (Ranger, 1994). The timing for hydraulic head formation as discussed in the subsequent section does not support evidence of early generation, trapping and degradation (Ranger, 1994), and thus, migration driven by compaction and buoyancy is the favored theory.

Timing

The timing of hydrocarbon generation and migration within the Athabasca Deposit requires discussion with respect to the timing of the Late Cretaceous-Early Tertiary Laramide orogeny. Commencement of the Laramide orogeny produced the deep burial of potential source beds. Little hydrocarbon generation likely occurred prior to Laramide events, as potential source beds would not have been buried deeply enough to be exposed to sufficient temperatures and pressures to initiate organic diagenesis (Deroo *et al*, 1977). Culmination of the Laramide orogeny in the Paleocene caused uplift in the west that would have facilitated basin wide hydrodynamic flow (Ranger, 1994).

Evidence for early generation, trapping and degradation of bitumen comes from the bitumen water contact. This contact dips to the southwest, parallel to

Laramide foreland basin subsidence, but at a slightly lower angle than the reservoir host strata. Generation, trapping and degradation occurred probably no later than the Cretaceous (Ranger, 1994). At the time of migration, the large-scale, basin groundwater flow of Garven (1989) and Hitchon (1984) could not have been significant.

Trapping Mechanism

The trapping mechanism for bitumen in the Athabasca Deposit has also been a controversial topic for many years. The vast size of the deposit obstructed theorizing on trapping mechanisms until numerous wells had been drilled into the deposit providing a structural database. Current thoughts of the trapping mechanism include a dominant structural trapping component and a stratigraphic trapping component for the northeastern portion of the basin (Ranger, 1994).

Vigrass (1968) recognized the existence of an up dip rollover structure and reversal of dip from the regional southwest dipping reservoir. This rollover is attributed to the dissolution of underlying salt from the Middle Devonian Prairie Evaporite. The existence and proximity of this rollover to the eastern limit of the bitumen suggests that anticlinal structural closure provided a large portion of the trapping mechanism (Figure 13).

A purely structural trapping mechanism cannot account for all hydrocarbon trapping, as bitumen also occurs down dip on the southwestern flank of the anticline. This trapping occurs at least 500 m below the level of a distinct bitumen/water contact that exists on the opposite flank of the anticline. Therefore, there must be a significant stratigraphic component to the mechanism in addition for the northeastern flank of the anticline (DeMaison, 1977). However, the northern edge of the anticline is eroded and its configuration will never truly be known. It is assumed that the McMurray Formation prograded northward into the Boreal Sea, and can also be inferred that it shaled out to the north beyond the present day erosional edge. During the transgression of the Clearwater Sea, shales overstepped the reservoir sand sealing them by onlap against the PreCambrian Shield (Figure 14).

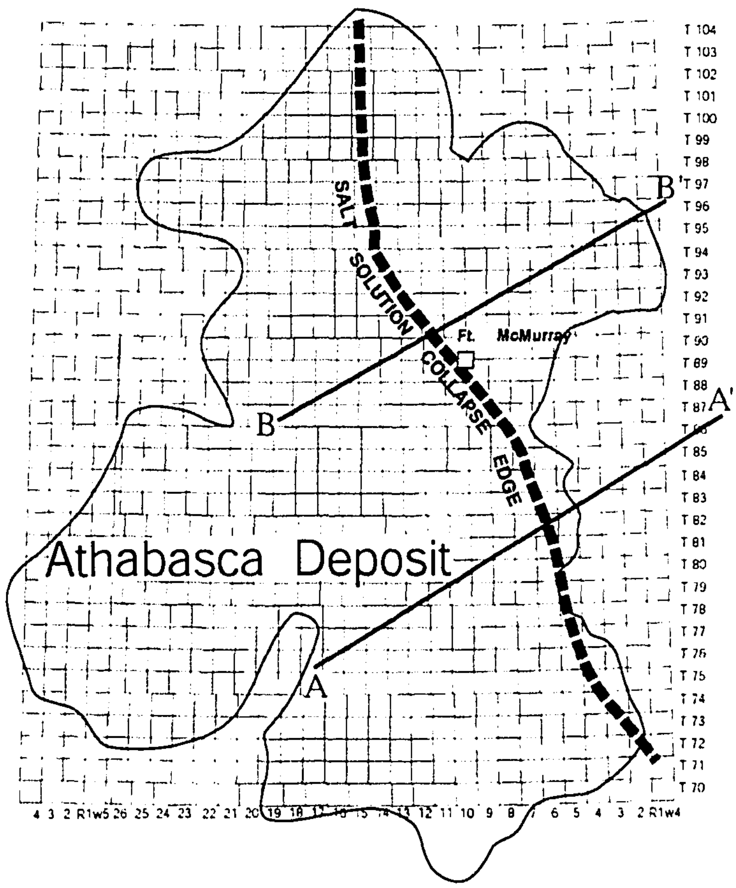


Figure 13
Outline of the Athabasca Oil Sands Deposit. East of the salt solution edge, structural collapse has produced a roll-over structure that forms the trap in the southern portion of the deposit. The northern portion of the deposit extends beyond the salt solution edge and was probably stratigraphically trapped. A-A' and B-B' refer to cross-section figures 14 and 15 respectively (from Ranger, 1994).

This stratigraphic seal is presumed to be "leaky" due to the common observance of bitumen in fractures and porous clastics of the PreCambrian Athabasca Group and in fractures of older basement (Figure 15). Analysis of a sample of this Precambrian oil indicates a composition that approximates the bitumen contained within the McMurray Formation (Wilson, 1985, appendix G) but is heavier and presumably more degraded (Ranger, 1994). Porosity conduits in the PreCambrian regolith and the presence of a coarse detrital transgressive lag from the Clearwater transgression may be responsible for the "leaky" seal (Figure 16). Alone or together, these conditions would provide a pathway for oil (before biodegradation) or gas seeps along the edge of the basin (Ranger, 1994).

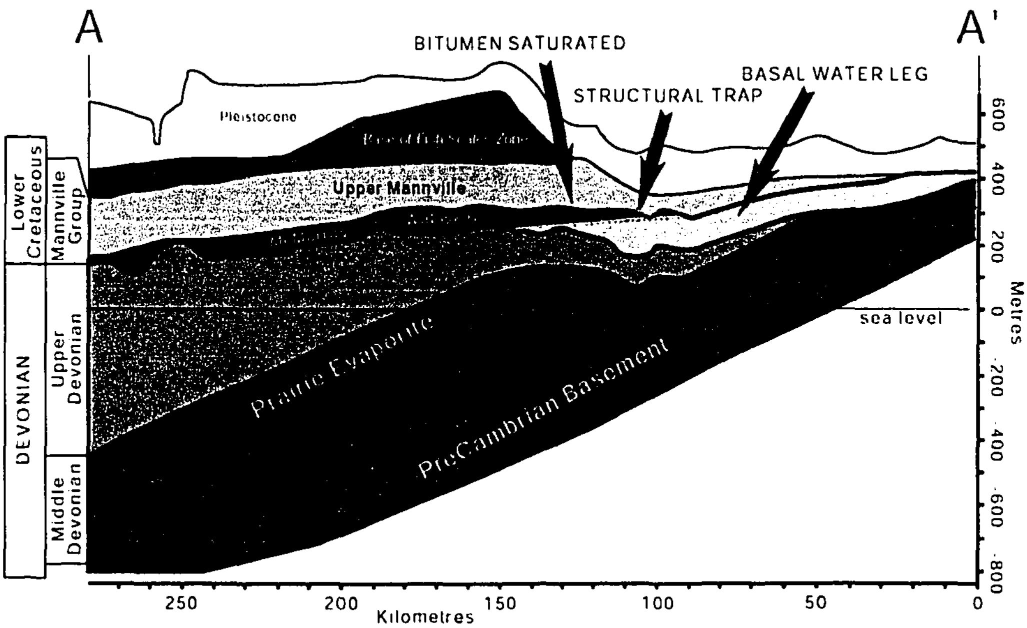


Figure 14
Structural cross-section through the Athabasca reservoir at location A-A' (for location, see figure 13). Trapping mechanism along the southeastern edge of the reservoir is structural, and is caused by collapse due to dissolution of the Prairie Evaporite salt. Structural collapse occurred after deposition of the McMurray-Wabiskaw reservoir rocks, but before migration and trapping (from Ranger, 1994).

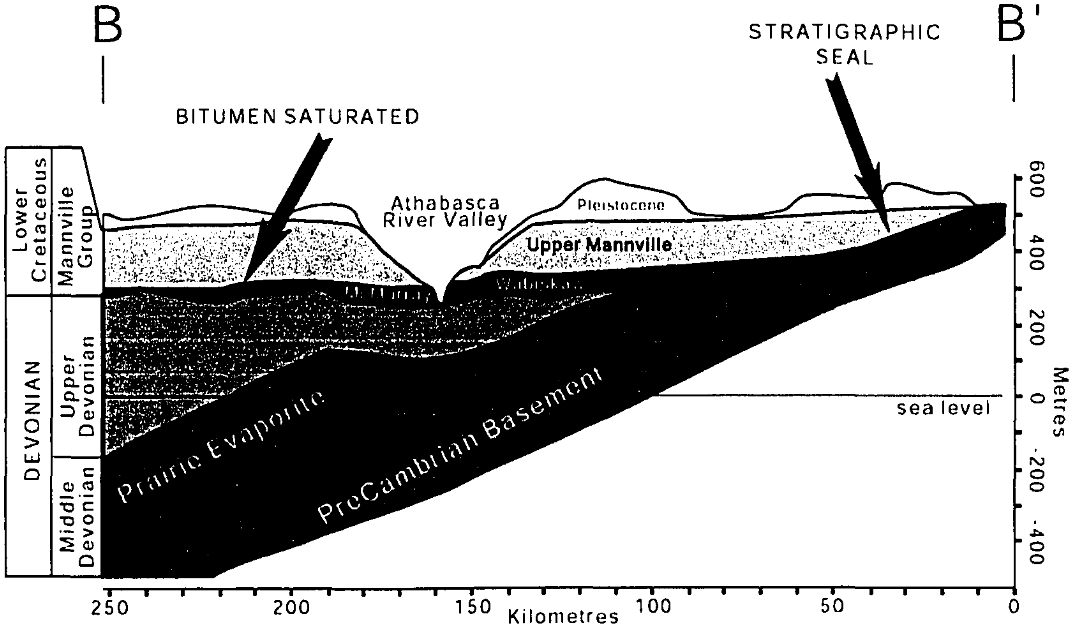


Figure 15
Structural cross-section through the Athabasca reservoir at location B-B' (for location, see figure 13). Trapping mechanism along the northeastern edge of the reservoir was probably stratigraphic. Upper Mannville Clearwater shales onlapped the Precambrian basement, sealing the reservoir. Structural collapse due to salt dissolution of the Prairie Evaporite occurred before deposition of the McMurray-Wabiskaw reservoir rocks, and therefore did not play a role in the trapping mechanism in the northeast (from Ranger, 1994).

Gas

Gas accumulations are common within the Athabasca Deposit. Both large and small gas accumulations share the bitumen reservoirs. Several episodes of gas accumulation charged the reservoir in multiple stages of the structural development of the reservoir. The largest fields are concentrated along the southeastern edge of the deposit, extending beyond the eastern limit of the bitumen (Ranger, 1994).

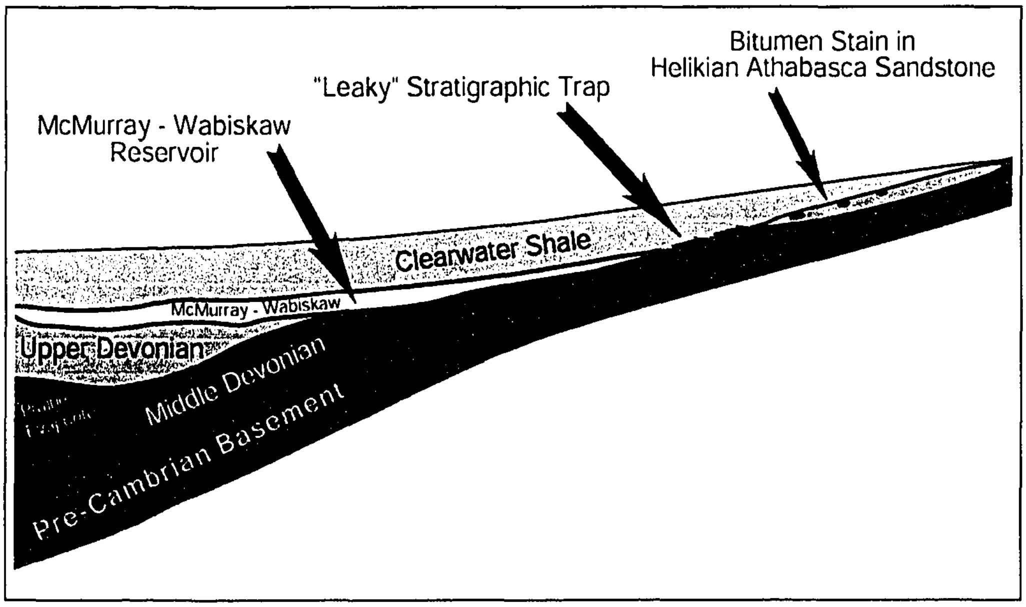


Figure 16
Schematic of the proposed trapping mechanism in the northeast of the Athabasca Oil Sands. The Clearwater shale did not provide a perfect seal against the Precambrian regolith. The presence of bitumen stain in the Helikian Athabasca Sandstone, up dip from the Athabasca Oil Sands, suggests the trap was "leaky". The extent of the Precambrian bitumen reserves is unknown, but has been observed filling fractures and pores in cores recovered during uranium exploration (from Ranger, 1994).

The smaller gas deposits, likely formed biogenically in situ at an early stage (Deroo *et al.*, 1977) and occupy small structural anomalies in the McMurray Formation. The existence of large gas accumulations beyond the eastern limit of the bitumen are evidence for a later phase of gas generation. This area would have been downdip of the structural trap at the time of bitumen accumulation. Subsequent Laramide tilting of the structure created new configurations of structural traps, into which the previously degraded bitumen could not migrate. Late generation gas accumulated in this updip position of the tilted anticlinal structure (Ranger, 1994).

Plate 1

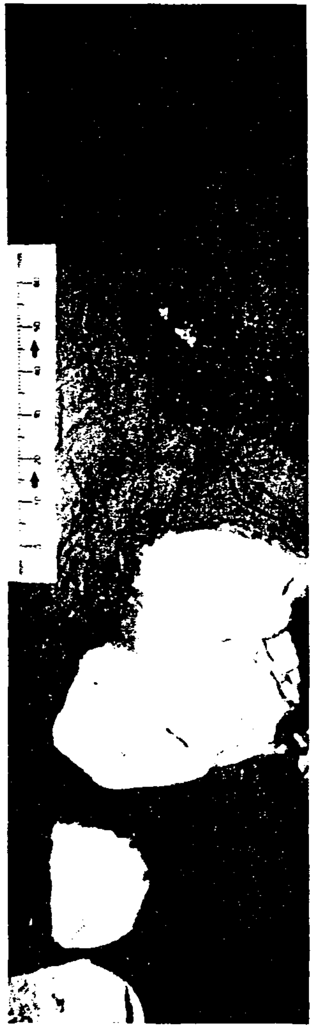
A. Weathered Devonian green shale with limestone clasts and pyrite. AB/03-21-095-07W4 (198.5 m)

B. Shale color change from brownish gray to a chlorite induced dark bluish-gray hue. AA/03-19-095-07W4 (91.5 m)

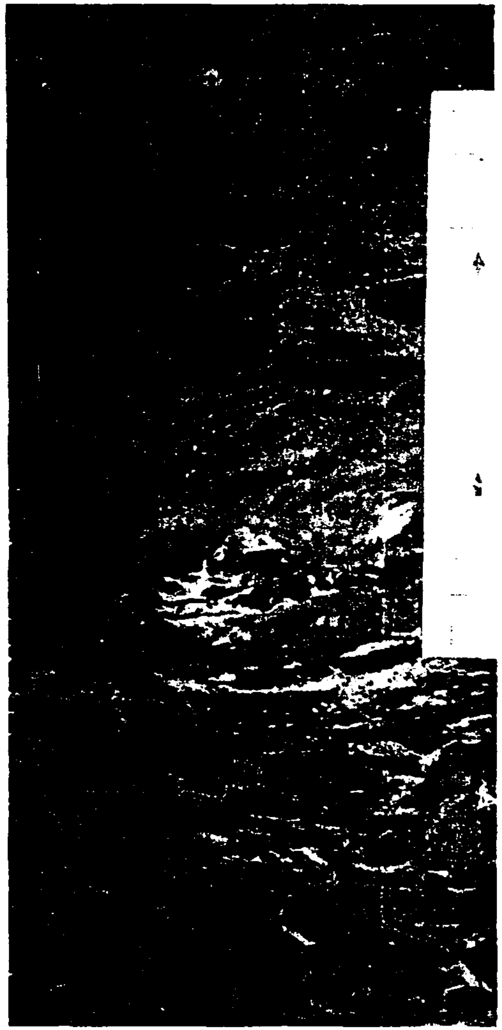
C. Increased burrow size with low diversity of traces. AA/10-20-095-07W4 (105.9 m)

Plate 1

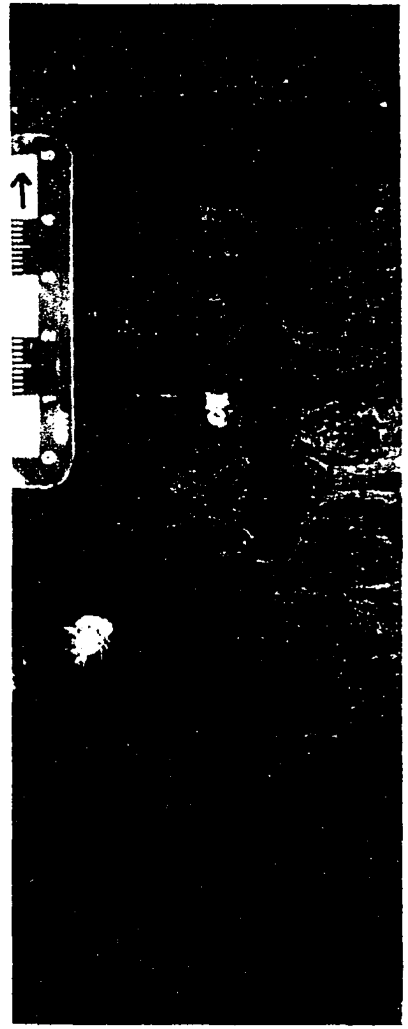
A



B



C



CHAPTER 2
FACIES OF THE MCMURRAY FORMATION

INTRODUCTION

Past researchers have proposed a variety of facies and facies association classifications for the McMurray Formation. These classifications are generally in unpublished thesis format (Fox, 1988; Mattison, 1987; Yuill, 1995; Bechtel, 1996) or government research projects (Hein *et al.*, 2000). From this perspective, the aim of facies delineation is one of building on previous research. This includes asserting that past facies can be extended to other areas, enhancing descriptions, and modifying previous interpretations. Table 1 lists the comparative facies of the current study to those of previous researchers. This study recognizes 15 distinct facies.

As facies descriptions advance through time, some generalities can be made. Initial core-based projects are from mining areas where erosion removed the upper facies. Advances in technology and current high oil prices improve the feasibility of in situ projects where the uppermost facies are not eroded. In general, there is an increase in the number of described facies. Caution must be applied when comparing and contrasting studies, as facies may have the same name, but refer to different features. More subtle changes in facies definitions include the switch from the term "mudstone" to the more appropriate term "mud".

F1 LARGE-SCALE CROSS-STRATIFIED SAND

Description

Large-scale cross-stratified sand is the most common facies within the lower and middle members of the McMurray Formation. The cross-stratification is defined as "large-scale" because inclined strata exceed the width of the core. Bed sets range in thickness from 5 cm to greater than 75 cm, and average 40 to 50 cm. Average apparent dip of the inclined strata is 10 to 15^{o} from horizontal, with a range of 5 to

30° from horizontal. Adjacent sets, which may be tabular or trough cross-stratified, commonly dip in opposite directions with truncation surfaces visible (Plate 2, Photo A and B).

Cross-strata are differentiated by grain size and resultant colour change due to variable bitumen saturations (Plate 2, Photo C). Grain sizes within the cross-strata range from very fine sand to pebbles. Pebbles and granules, where present, tend to occur as dispersed grains in toesets, at the base of co-sets, and most commonly in the lower member. In rare cases, pebbles and granules are so abundant that the lithology may be properly termed a conglomerate (Plate 2, Photo D). Cross-strata thickness ranges from 0.5 to 3 cm, with an average of 1 cm.

Mud laminae drapes are commonly found interbedded with the sand and their occurrence increases upward in a large-scale cross-stratified unit. The boundaries of the mud laminae are typically sharp, but may also be gradational or burrowed. The laminae may be continuous or discontinuous across the width of the core.

Mud clasts, which tend to have a preferred orientation along bedding, are locally common. Clasts are generally small (5 mm) and subrounded, but more rarely are large (greater than core thickness) and angular. As larger clasts exceed the diameter of the core, it is difficult to discern interbedded units of other facies from large imbricated clasts. These clasts are composed of the same material as flat lying, thinly interbedded sand and mud (F6). Mud clasts are most commonly located in the upper portion of large-scale cross-stratified units and in association with sand-dominated, inclined heterolithic stratification (F4).

Carbonaceous debris, coaly laminae, and wood fragments are common. Coal laminae tend to be less than 1 cm thick, are continuous or discontinuous across the width of core, and occur thinly interlaminated with mud beds. Carbonaceous debris may be thinly intercalated with cross-stratified sands. Wood fragments can be quite large (up 15 cm in width, 15 cm long and occupy the entire width of core), but are most commonly 1 cm by 1 cm.

Upper contacts of the lithofacies are commonly gradational, but can be sharp. Large-scale cross-stratified sand generally grades into flat lying, thinly interbedded sand and mud (F6), structureless sand and mud clast breccia (F2), and rarely small-scale cross-stratified sand (F3). The basal contact is always sharp and erosional, and can be found above most other defined facies. It is common to find coal, pebbles, carbonaceous debris, and pyritized mud clasts above this contact.

Ichnology

Bioturbation within the large-scale cross-stratified sand facies is rare to absent. *Cylindrichnus* or *Planolites* is most common, with rare *Palaeophycus* and escape structures. *Cylindrichnus* and *Palaeophycus* are visible in sand due to their mud lining. These subtending traces probably originated in overlying mud laminations, which were subsequently eroded. Escape structures are also located within the sand. *Planolites* are found in mud laminae and are commonly filled with bitumen stained sand. All traces are diminutive (generally less than 1 cm in length or diameter) and morphologically simple forms.

Interpretation

Large-scale cross-stratified sand is interpreted as migrating dune forms in the base of channels. The term "dune" includes both two-dimensional and three-dimensional bedforms previously referred to as megaripples (Reineck and Singh, 1980; Harms *et al.*, 1982). A panel convened to examine bedform nomenclature recommended that the single term "dune" be used for all bedforms larger than ripples (Ashley, 1990).

Dunes have wavelengths ranging between 60 cm and hundreds of metres, whereas height may vary between 0.5 m and 10 m (Leeder, 1982). In order for cross-strata to be preserved, successive dunes cannot erode too deeply and there must be some element of climb. Because the climb is usually low in this facies, only the toesets and lower foresets filling the deepest part of the "lee-scour" are typically preserved.

Dunes are formed in the upper portion of the lower flow regime under unidirectional currents and are similar to ripples in both geometery and movement, but are an order of magnitude larger (Middleton and Southard, 1984). They are stable at moderate energy flow conditions, intermediate between ripples and plane beds (Figure 17). Under weaker flow conditions, dunes are straight-crested (2-D) in plan view, while at higher velocities they become more irregular and linguoid (3-D) (Harms *et al.*, 1982). Dunes can form in sediments with grain sizes ranging from less than 0.1 mm to gravel (Harms *et al.*, 1982).

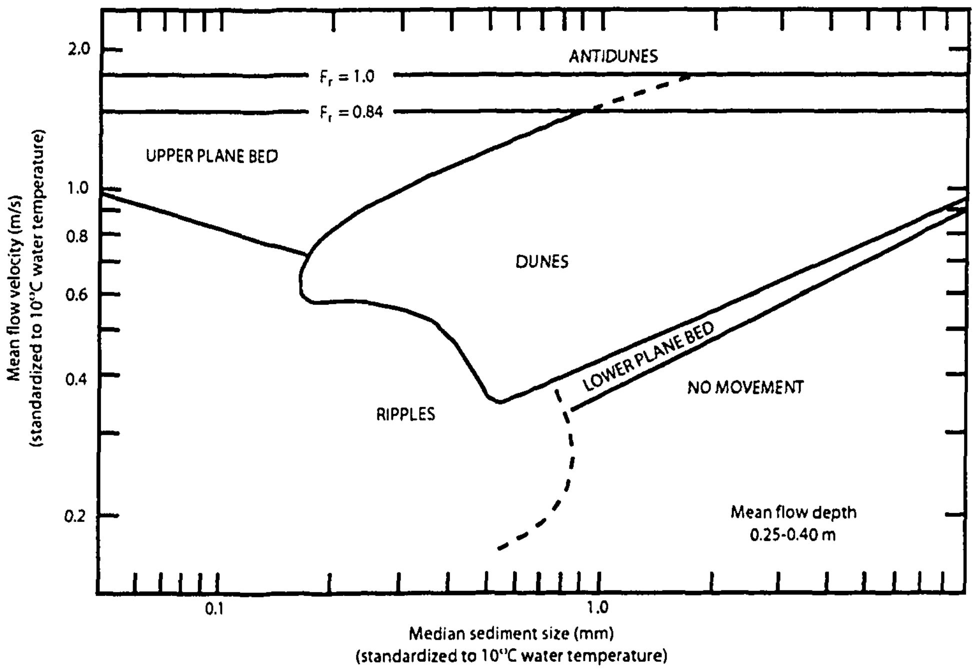


Figure 17
Plot of mean flow velocity against median sediment size showing the stability fields of bed phases. Note that the recommended terminology for bedforms is (1) lower plane bed, (2) ripples, (3) dunes (all large-scale ripples), (4) upper plane bed, and (5) antidunes. Fr = Froude number (modified from Southard and Bouguchwal, 1990).

Tabular cross-stratification is recognized by the angular intersection of cross-strata with the set's lower bounding surface, and that the angle of inclination does not change within the depositional unit (Figure 18A). Straight-crested dunes produce tabular cross-stratification from deposition on the lee face (avalanche face) of the dune (Harms and Fahnestock, 1965; Harms *et al.*, 1982).

Trough cross-stratification is recognized where cross-strata are curved and meet the lower bounding surface tangentially. The angle of inclination of cross-strata increases towards the top of the set (Figure 18B), reflecting the preservation of toesets to foresets during bedform migration (Harms *et al.*, 1982). Trough cross-stratification is produced within elongate scours that develop downstream of the linguoid dune parallel to flow. Low-angle curved laminae fill these scours (Harms *et al.*, 1982). The strata are deposited either from suspension or by avalanche down the lee slope of the dune. It may be difficult to differentiate between tabular and trough cross-stratification due to the small diameter of the drill core.

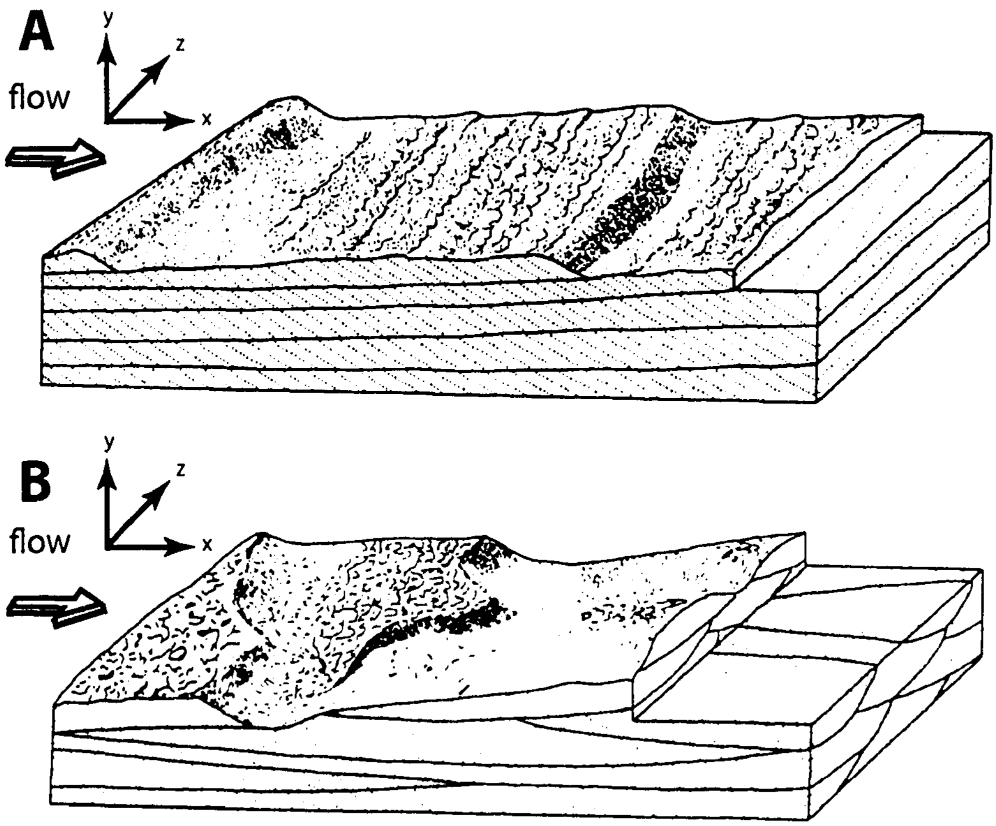


Figure 18
Patterns of cross bedding.
A Tabular cross-bedding generated by the migration of longitudinal dune/ripple forms.
B Trough cross-bedding formed from the migration of higher flow regime linguoid or discontinuous dunes/ripples.
(modified from Harms *et al.*, 1982).

The granule and pebble layers mark the base of dune troughs. Pebbles and granules are first transported during upper flow regime conditions, and rolled into dune scours during the lower flow regime (Harms and Fahnestock, 1965).

Mud laminae indicate that flow velocities decreased enough to allow mud deposition from suspension. Composite sand and mud interlaminations indicate fluctuating current strength, alternating between energies high enough to deposit sand and lower energies where mud is deposited from suspension. Additionally, small-scale cross-stratified sands, found at the top of large-scale cross-stratified sets, represent a decrease in energy flow conditions. It is also possible that these small-scale cross-stratified sets represent increased climb of the dune, as the migration of the subsequent dune did not plane off the uppermost portion of the previous dune.

Small and rounded mud clasts indicate transport from their point of origin. Their preferred orientation suggests that they were probably deposited on the avalanche face or within the scours, along with sand. Larger clasts reflect the erosive nature of this environment, and are likely associated with fluctuating flow regimes.

Carbonaceous debris and woody fragments accumulated within scours at the toesets of subaqueous dunes. Flow velocities were periodically slow to allow the deposition of material with low specific gravity over deposition of sand. This flow was probably directed up the avalanche face of the dune as reverse eddies (Harms and Fahnestock, 1965).

Lack of bioturbation indicates an environment inhospitable for benthic organisms. Migration of large-scale bedforms in this high energy environment, were likely too energetic for organisms. The constantly shifting nature of the substrate and persistent avalanching prevented significant colonization. In addition, high energy is not conducive to the preservation of biogenic sedimentary structures. The few trace fossils present indicate a stressed environment as forms are morphologically simple and small with low diversity.

Large-scale cross-stratified sand is deposited as a result of dune migration in channels.

F2 APPARENTLY STRUCTURELESS SAND AND MUD CLAST BRECCIA

Description

Apparently structureless sand is found most commonly in the middle member and more rarely in the lower and upper members of the McMurray Formation. This facies is characterized by an apparently massive, structureless appearance with no visible physical or biological sedimentary structures (Plate 3, Photo A). Sands are typically fine-grained, and well sorted, but coarser grain sizes, such as granules, may be observed.

Mud clasts occur with either a lack of clast orientation, or with a preferred orientation along bedding planes. They have comparable lithologies to flat lying, thinly interbedded sand and mud (F6) and inclined heterolithic stratification (mud-dominated – F4) (Plate 3, Photo B). Clasts are angular to subrounded and have an average length of 3 cm although both smaller and larger clasts are common (Plate 3, Photo C).

Mud clast breccia units vary in thickness, ranging from isolated mud clasts to breccia units exceeding 5 m in thickness. Breccia units are typically matrix-supported and rarely clast-supported. Coal detritus and preserved logs (Plate 3, Photo D) can occur within the sand matrix of the breccias. Mud clasts are rarely replaced by siderite. Breccia units typically have limited lateral extent in outcrop (over a few metres), occurring as thin lenses and less commonly in small cut and fill features (Hein *et al.*, 2000).

Basal contacts with other lithofacies are gradational or sharp (possibly scoured); the upper contact is gradational. Structureless sand and mud clast breccia is most commonly found in association with large-scale cross-stratified sand (F1) and inclined heterolithic stratified units (F4).

Ichnology

Bioturbation in the sand matrix is generally absent. In mud clasts, bioturbation is rare to absent, consisting of *Planolites*, *Paleophycus*, and *Cylindrichnus*.

Interpretation

Sedimentary structures are commonly obscured in cores with heavy bitumen saturation. This imparts a massive appearance and stratified facies are often misclassified to this facies. X-radiography, which was beyond the scope of this study, may be useful to reveal stratification in these apparently massive sands (Fox, 1988). Implementation of this technique would likely place most apparently structureless sands into the large-scale cross-stratified sand lithofacies (F1).

Apparently structureless sand as a primary sedimentary structure can be produced by deposition from highly concentrated sediment-laden flows (Blatt *et al.*, 1980; Collinson and Thompson, 1982). Sediment grains in flows are supported by fluid turbulence, and where this turbulence can no longer overcome gravity acting on the sand grains, deposition occurs (Allen, 1985). Sharp to scoured basal contacts indicate erosion into underlying lithofacies. This erosion may have occurred with the initial mass movement of clasts in sediment-laden flows at the time of collapse.

The most common physical process destroying primary sedimentary structures is liquefaction (Middleton and Hampton, 1973; Blatt *et al.*, 1980; Collinson and Thompson, 1982). Liquefaction occurs when sand grains, which usually support one another, are for an instant supported and dispersed by pore fluid (Allen, 1984; Collinson and Thompson, 1982). This fluid supported sand is easily deformed. A shock produced by earthquakes or very rapid sedimentation, can increase pore pressure to the point of liquefaction (Collinson and Thompson, 1982). The collapse of a channel bank due to natural processes such as undercutting provides both the source of the mud clasts and the required shock for the loss of grain cohesion associated with liquefaction. Liquefaction is interpreted to be the key mechanism producing structureless sand and mud clasts breccia.

The majority of bank collapse occurs on the cutbank incorporating clasts into the highest energy portion of the channel. Some clasts would be transported downstream and deposit in lower energy areas, accounting for the common occurrence of mud clasts within the uppermost portions of large-scale cross-stratified sand (although in lower concentrations and with slightly more rounded character).

A second mechanism of clast conception is described within the inclined heterolithic stratification facies interpretation (F4). A comprehensive analysis of the breccia facies and its resultant economic significance is provided in Chapter 6.

Apparently structureless sand and mud clast breccia resulted from collapse of channel banks along the cut-bank margins of meandering channels. These breccias form part of the normal processes of cutbank-point bar erosion and migration associated with meandering channel flow.

F3 SMALL-SCALE CROSS-STRATIFIED SAND

Description

Small-scale cross-stratified sand is found throughout the McMurray Formation, but is predominant in the middle and upper members. "Small-scale" cross-sets are defined as less than 5 cm in thickness with both bounding surfaces typically clearly visible in core (Plate 4, Photo A). Cross-strata can generally be differentiated into foresets and toesets. Individual cross-laminations are visible due to a minor mud component and differential bitumen saturations. Although similar features are found in other facies, 'small-scale cross-stratification' as defined here, is composed exclusively of small-scale ripple forms.

When mud drapes are present, they may be continuous or discontinuous between individual cross-strata or between sets of small-scale cross-stratified sands. Mud drapes range 1 to 5 mm thick and can be preferentially siderite cemented (Plate 4, Photo B). Associated flaser to wavy bedding may also be present (Plate 4, Photo C). Carbonaceous debris is a common component, while mud clasts are rare.

Two main types of cross-sets include: tabular-shaped and trough-shaped. Tabular-shaped cross-sets have upper and lower bounding horizons that are generally flat and parallel to one another; these surfaces may dip slightly (approximately 10° from horizontal). Tabular-shaped cross-strata are steeply dipping, and in superimposed sets, tend to dip in the same direction. The foresets are steeper, with the toesets flattening out tangentially against the lower bounding surface of the cross-set. Trough-shaped cross-sets have a concave-upward lower bounding surface with a scoured upper surface. In general, cross-strata are gently dipping in opposite directions in superimposed sets. Cross-strata appear to approximately parallel the lower bounding surface of the bed set.

Grain size is very fine to fine. Bitumen saturation is high due to the well-sorted nature of the sand. Visibility of the small-scale cross-stratification is enhanced in areas with moderate bitumen saturation and with higher argillaceous content. If bitumen staining is heavy, portions of this facies appear massive.

Basal contacts with underlying facies are generally sharp and scoured, but may also be gradational. Gradational contacts commonly occur with large-scale cross-stratified sand (F1) and both sand-dominated and mud-dominated inclined heterolithic stratification (F4). Sharp contacts are more common when in contact with other facies.

Ichnology

Although rare, bioturbation occurs most commonly in thin mud drapes in the form of diminutive (1 to 2 mm diameter) round to ovoid *Planolites*. The most common traces in sand are escape structures (fugichnia), 1 to 2 cm in length *Skolithos*. *Cylindrichnus* and *Palaeophycus* are less common, but easily identified by their central sand core and surrounding mud wall.

Interpretation

Small-scale cross-stratification is produced by the migration of ripples. They are produced in the lower part of the lower flow regime, shortly after the initiation of sand-sized particle movement (Harms and Fahnestock, 1965; Simons *et al.*, 1965). Ripples are generally spaced less than 20 to 30 cm apart and are less than 2 to 3 cm high. The ratio of spacing to height is about 10 to 1 (Harms *et al.*, 1982).

Ripples consist of a gentle up-current stoss side and a steep down-current lee side with a crest that is perpendicular to flow direction (Selley, 1988). Transport of sediment involves the movement of sediment up the back (stoss side) of the ripple and an avalanching of the sediment down the face (lee face) of the ripple (Figure 19) (Simons *et al.*, 1965).

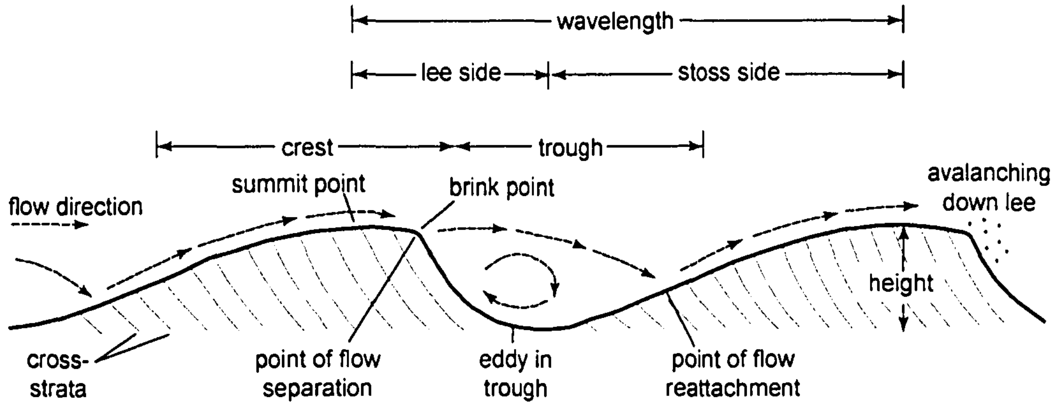


Figure 19
Terminology used to describe asymmetric ripples (modified from Tucker, 1981).

Tabular shaped cross-bed sets are produced by asymmetrical ripples characterized by steep laminae that are parallel with the lee side of the ripple and formed by unidirectional currents (Selley, 1988). If sediment is added from suspension while the ripples are migrating, the ripples will increase in height or "climb" (Harms *et al.*, 1982). In the McMurray sediments, ripple lamination generally exhibits a low element of climb. When climb is zero, thin discontinuous lenticular sets of cross-stratification are produced (Harms *et al.*, 1982). A vertical section transverse to flow shows trough-shaped sets, and the tabular-shaped sets are seen in vertical sections parallel to flow.

Symmetrical ripples (oscillation or wave) form by the back and forth motion of waves (Selley, 1988). The internal laminae of symmetrical ripples are generally concordant with the ripple profile and show superposed crests and troughs (McKee, 1965). However, wave ripples may also show asymmetrical internal laminae due to an uneven oscillatory flow, in which the current in one direction is stronger than in the other (Harms *et al.*, 1982). The ripples formed by these combined processes may produce internal laminations that are very similar to those produced by current ripples. It may be difficult, therefore, to distinguish current ripples from "combined-flow" ripples. Combined-flow ripples are generally good indications that both marine and fluvial processes are active, as in an estuarine setting.

The observed ripple bedding are interpreted as current, or combined flow ripples as the bedforms lack the features of wave ripples. The lower portion of the lower flow regime responsible for small-scale cross-lamination is active within estuarine channels during waning flow conditions. These waning flow conditions are associated with the onset or termination of the slack period of the tidal cycle, or with falling water levels during ebb tide. Small-scale cross-stratification may also form during high tide cycles where the flood tide has inundated the upper portions of a point bar.

Mud drapes were deposited from suspension during slack water conditions resulting from reduction of current velocity. Estuarine conditions in these deposits are evidenced by mud (changing flow conditions), and combined-flow ripples, and the trace fossil assemblage. The trace fossil assemblage is dominated by small and morphologically simple forms of low diversity indicating a stressed environment and the unstable, shifting nature of the substrate.

Small-scale cross-stratification develops as a result of ripple migration under waning flow conditions across larger channel bedforms on the channel floor or on point bar surfaces of channels.

F4 INCLINED HETEROLITHIC STRATIFICATION (IHS)

Description

Inclined heterolithic cross-stratification (IHS) is most common in the middle McMurray Formation. The term 'IHS' adopted from Thomas *et al.* (1987) is used to replace 'epsilon cross-stratification' of Allen (1963). Sand-dominated IHS is an end member of a continuum, which has mud-dominated IHS as its counterpart. Sand-dominated IHS is defined for facies where sand interbeds comprise greater than 50% of the facies; and mud-dominated IHS refers to facies where mud interbeds comprise greater than 50% of the facies.

The dominant aspect of this lithofacies (F4) is the inclined thickly interbedded to finely interlaminated sand and mud. The apparent degree of inclination is dependent on the angle at which the core was slabbed with highest angles associated with sections paralleling the depositional dip. The inclination ranges from 0 to 15° from horizontal for sand-dominated IHS; slightly lower inclinations are associated with mud-dominated IHS.

Interbedding occurs as normally graded couplets, with sharp based sand grading into, or sharply overlain by mud. The contact between underlying sands and overlying muds also tend to be burrowed. Within sand-dominated IHS (Plate 5, Photo A), sand interbeds typically range from 7 to 30 cm, up to or greater than 70 cm thick, while mud interbeds from 1 to 20 cm, up to or greater than 30 cm thick. Within mud-dominated IHS, sand interbeds average 3 to 5 cm and may be as thick as 15 cm (Plate 5, Photo B and C), while mud interbeds range from 1 to 10 cm, but may reach thicknesses up to 20 cm.

The coarse layer is dominated by small to large-scale cross-stratified (trough and tabular cross-stratification) fine to very fine sands. The fine layer is massive gray mud (most common, in but not restricted to, mud-dominated IHS) or mud interlaminated with sand or silt (more common in, but not restricted to, sand-dominated IHS). Interlaminated mud and sand is most commonly wavy and/or lenticular bedded. Upper and lower contacts within the fine layer are typically gradational, but sharp contacts are present locally.

Other sedimentary structures include microfaults (with displacements of less than 2 cm), local synaeresis cracks (infilled with sand from overlying sand beds), and rare flame structures. Sands are variably bitumen saturated, ranging from moderate to high.

Sand-dominated IHS typically overlies large-scale (F1) and small-scale cross-stratified sand (F3) and commonly grades or abruptly switches upwards to mud-dominated IHS. Mud-dominated IHS typically has gradational upper and lower contacts. Locally, mud-dominated IHS directly overlies large-scale cross-stratified sand (F1) and small-scale cross-stratified sand (F3). Commonly, mud-dominated IHS grades into gray mud (F5) or flat-lying, thinly interbedded sand and mud (F6).

Ichnology

The ichnologic signature of IHS varies from rare to common with some monospecific horizons with abundant burrowing. The most intense burrowing usually occurs at interfaces between sand and mud. Traces include: *Cylindrichnus, Planolites, Gyrolithes, Teichichnus, Arenicolites, Skolithos, Palaeophycus,* and escape traces (fugichnia). Alternatively, some IHS may be totally unburrowed.

Characteristic monospecific assemblages comprise *Gyrolithes*, *Cylindrichnus*, or *Planolites*. *Gyrolithes* monospecific assemblages are most common in the Muskeg River Mine lease (Plate 5, Photo B and C), while the monospecific assemblages of *Cylindrichnus* are more common at the Sunrise Thermal Project lease. Both leases exhibit rare occurrences of the *Planolites* monospecific assemblages. *Cylindrichnus* and *Gyrolithes* define a preferred burrow fabric where the long axis of burrows shows a common orientation, typically perpendicular to IHS bedding planes.

In both the Sunrise Thermal Project lease and the Muskeg River Mine lease *Gyrolithes* occurs in two forms differentiated by the radius of spiral to length ratio. *Gyrolithes* Type I exhibits a higher spiral radius to length ratio and greater shaft diameter for a more robust appearance (Plate 6, Photo A). *Gyrolithes* Type II exhibits a smaller spiral radius to length ratio and smaller shaft diameter for a less robust appearance (Plate 5, Photo B and C). Length of the vertical component of the two types is similar. *Gyrolithes* Type II is the dominant form in monospecific assemblages and *Gyrolithes* Type I is the dominant form in mixed ichnologic assemblages.

Interpretation

IHS is interpreted as deposition on the inclined surface of a point bar within a meandering channel (Allen, 1963; Mossop and Flach, 1983; Thomas *et al.*, 1987; Smith, 1987; Rahmani, 1988). The IHS bedforms within the McMurray Formation are interpreted as both estuarine (Smith, 1987; 1988a; Ranger and Pemberton, 1992; Bechtel *et al.*, 1994) and fluvial (Mossop and Flach; 1983; Flach and Mossop, 1985) migration of point bars.

Evidence for tidal influence within IHS beds is contributed to by the disciplines of sedimentology and ichnology. Rhythmic deposition is indicative of tidally influenced environments (Allen, 1991), and this cyclicity is their most characteristic feature (Hawley, 1981a; Nio and Yang, 1991). It has been demonstrated experimentally (Terwindt and Breusers, 1972; Hawley, 1981a; b) and in the field (Reineck, 1960; Reineck and Wunderlich, 1968) that interbedded sand and mud can be produced by current unsteadiness associated with a single tidal cycle.

The distinctive feature of this lithofacies is the cyclic alternation of coarser and finer grained units. The coarse layer is attributed to traction bedload associated with higher flow velocities, while the finer layer is the result of deposition from suspension during periods of lower flow velocities (Thomas *et al.*, 1987). Fluctuations in flow conditions are indicated by the nature of the contacts between layers. Sharp contacts may indicate rapid changes in flow velocities or erosion of the underlying layer while gradational contacts indicate a gradual change in flow velocities typical of waning flow (Thomas *et al.*, 1987).

Each sand-mud couplet represents initially rapid deposition, indicated by escape structures and coarser grain size, followed by lower energy conditions and mud sedimentation. Sand beds are deposited during higher flow conditions associated with ebb and/or flood periods of tidal cycle and the muds are deposited during intervening slack water periods. Sand beds and thin mud laminae may have been deposited during a single tidal cycle. Thinly intercalated sand and mud may be representative of diurnal or semi-diurnal tidal cycles, but where the laminae are greater than 1 cm in thickness they may represent several slack water periods associated with neap tide periods or suspension deposition following a flood event (Thomas *et al.*, 1987).

Deposited muds can often withstand erosion by currents that are capable of transporting sand and gravel (Terwindt *et al.*, 1968; Drake, 1976) (Figure 20). Mud that is deposited during a slack water stage and preserved in the stratigraphic record likely represents the basal remnant of a thicker unit that accumulated during slack water stages (Owen, 1970; Terwindt and Breusers 1972; Hawley, 1981b). Experimental work by Hawley (1981b) demonstrated that an initial thickness of 3 to 10 mm of mud is required to form this resistant basal layer. If this critical thickness of mud is not attained, mud that settles to the bed will not survive erosion by subsequent current activity. The thicker interbeds within the McMurray Formation were probably deposited in response to long term variation in current velocities, possibly related to the neap/spring cycle or storms. Thin intercalations of mud in the sand beds and sand lenses in the mud bed reflect more short term current unsteadiness possibly associated with daily tidal cycles.

Angular rip-up clasts sourced from the fine layers also indicate the fluctuating nature of water levels within the channel. Mud deposited during high water levels (flood or spring tides) are exposed during low water levels (ebb or neap tides) resulting in consolidation and desiccation. Subsequent flood tides may then erode and transport the mud as rip up clasts (Plate 6, Photo B). Their angular nature suggests short transport distances (Smith, 1972).

Synaeresis cracks support the cyclic nature of the depositional environment and provide evidence of variable water salinity. They form in response to fluctuations in salinity (Burst, 1965). Such salinity variations are favored within settings subject to both fluvial and marine influences, such as in an estuary.

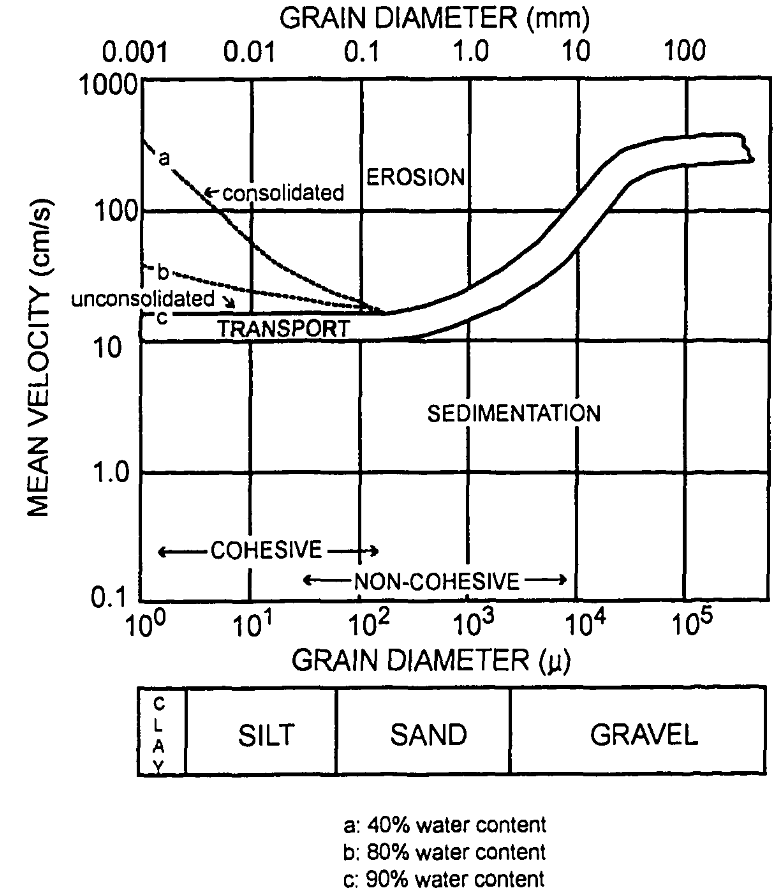


Figure 20
"Hjuslstrom Diagram" velocity versus grain size showing fields of erosion transport and sedimentation. Erosion of muds requires increasing current velocities as the consolidation of a mud bed increases (modified from Nichols and Biggs, 1985).

Ichnologic evidence for tidal influence within the IHS is indisputable. Thomas *et al.*, (1987) suggested that the recognition of trace fossils is the single most significant criteria for distinguishing tidally influenced IHS from fluvial IHS. Brackish water environments produce a trace fossil assemblage with the following distinct characteristics (Wightman *et al.*, 1987; Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; Ranger and Pemberton, 1992):

(1) Smaller than their fully marine counterparts,

(2) Restricted to morphologically simple forms,

(3) Low diversity, including locally monospecific assemblages,

(4) High abundances, and

(5) Fluctuating energy conditions produce substrates of variable consistency and therefore, a combination of traces from both the Skolithos and Cruziana ichnofacies.

The Skolithos ichnofacies is indicative of relatively high levels of wave or current energy and typically develops in slightly muddy to clean, well-sorted loose or shifting particulate substrates (Pemberton *et al.*, 1992a). This assemblage is commonly composed of ***Skolithos, Diplocraterion***, ***Arenicolites***, ***Ophiomorpha***, *Monocraterion*, and ***Palaeophycus.*** Bold-fonted traces are commonly present within McMurray facies. The Cruziana ichnofacies is most characteristic of subtidal, poorly sorted and unconsolidated substrates. Conditions typically range from moderate energy levels in shallow water below fair-weather wave base but above storm wave base, to low energy levels in deeper quieter waters. The ichnofacies is also found in the littoral to sublittoral parts of some estuaries, bays, lagoons and tidal flats (Pemberton *et al.*, 1992a). This assemblage is commonly composed of *Phycodes, Rhizocorallium*, ***Teichichnus***, *Asteriacites*, *Cruziana*, *Aulichnites*, ***Thalassinoides***, *Chondrites*, ***Arenicolites***, ***Rosselia, Planolites***, and ***Gyrolithes*** (Frey and Pemberton, 1984; Frey and Seilacher, 1980). Trace fossils associated with brackish water conditions supporting mixed assemblages include ***Skolithos, Planolites, Palaeophycus, Teichichnus,*** and ***Gyrolithes*** (Pemberton and Wightman, 1992). In addition, fugichnia reflect episodic deposition commonly associated with fluctuating energy conditions.

Monospecific assemblages of *Cylindrichnus*, *Gyrolithes* and *Planolites* represent opportunistic colonization of the substrate following an environmental stress. Stress on a benthic population may result from several possible events including turbidite deposition, oxygen deficiencies, storm deposition, or salinity variations (Pemberton *et al.*, 1992a). Stress associated with McMurray deposition, including salinity fluctuations and/or periodic subaerial exposure, account for the general absence of a competitive equilibrium assemblage.

The occurrence of Type II *Gyrolithes* may represent a response to a more severe depositional environment. *Gyrolithes* represents the organism's attempt to escape salinity fluctuations at the sediment water interface (Benyon and Pemberton, 1992). Lack of tapering and increased depth of penetration (relative to shaft diameter) in *Gyrolithes* II may reflect the trace-makers escape capabilities relative to *Gyrolithes* I.

The abundance and location of mud-dominated portion of IHS may be partially explained as the typical fining-upward progression associated with channel point bar deposition (Jackson, 1976; Smith, 1987). Thomas *et al.*, (1987) identified seven types of fining trends within IHS deposits:

(1) Overall vertical fining-upward,

(2) Lateral fining away from the channel axis into an overbank sequence,

(3) Lateral fining toward the channel as the result of abandonment,

(4) Along strike (down-flow) fining associated with the curvature of the point bar,

(5) Up-dip fining with individual inclined units,

(6) Fining perpendicular to inclined bounding surfaces within individual inclined units, and

(7) Fining-upward rhythms within individual inclined units (Figure 21).

Mud-dominated IHS reflects deposition within low energy environments due to the aforementioned fining-upward traits of lateral accretion deposits of an estuarine channel.

Deposition of mud is a significant component of estuarine systems (Dalyrymple *et al.*, 1992). Dörjes and Howard (1975) identified the middle region of the Ogeechee River/Ossabaw Sound tide-dominated estuary as an area with muddy substrates and higher suspended solid contents than the inner and outer regions. In his review of the modern tide-dominated Gironde estuary, Allen (1991) identified a marked decrease in channel sediment grain size as an indicator of the fluvial to tidal transition. In addition to the fining upward trends, this increase in mud deposition (relation to the turbidity maximum and the salt wedge) is a significant control on the deposition of sand-dominated versus mud-dominated IHS. The majority of examples of this facies in the McMurray Formation, likely form as a result of both mechanisms.

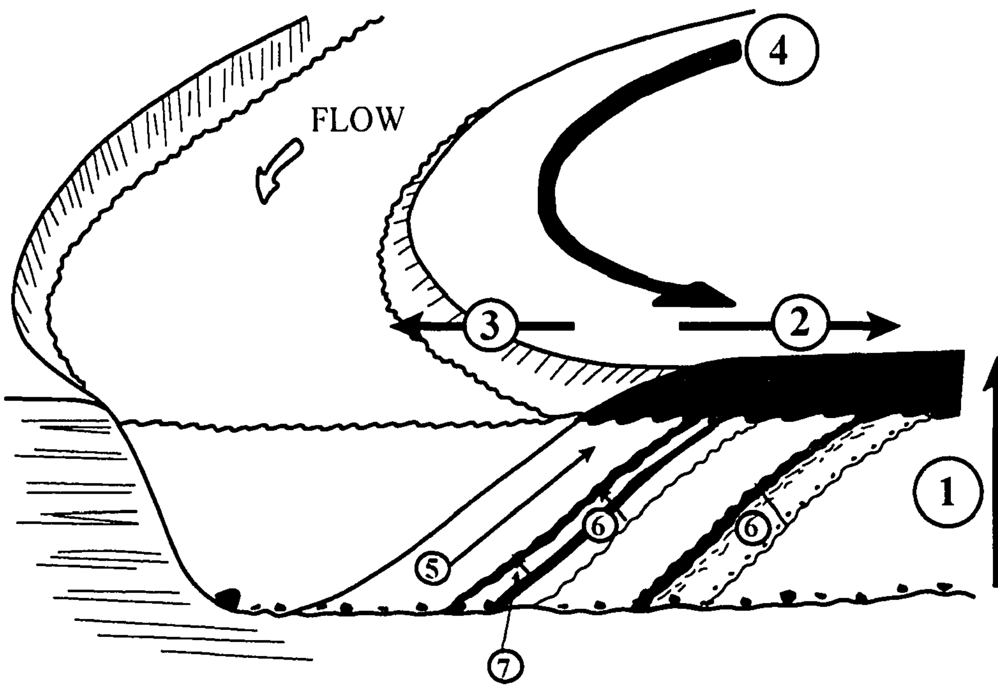


Figure 21
Schematic illustration of a hypothetical point bar showing seven possible grain-size fining trends associated with IHS deposits. 1= overall vertical fining-upward, 2 = lateral fining away from the channel axis into an overbank sequence, 3 = lateral fining toward the channel as the result of abandonment, 4 = along strike (down-flow) fining associated with the curvature of the point bar, 5 = up-dip fining with individual inclined units, 6 = fining perpendicular to inclined bounding surfaces within individual inclined units, and 7 = fining-upward rhythms within individual inclined units (modified from Thomas *et al.*, 1987).

Turbidity Maximum and Saltwedge

The salt wedge is defined as a dense body of saline water which rests on the bottom of the estuary, created by the density differences between salt water and freshwater (Dyer, 1986). The salt wedge may move upstream or downstream depending on the interaction between landward-flowing marine flood-tidal waters and seaward-flowing fluvial and ebb-tidal waters (Dyer, 1986). Mixing of saltwater and freshwater is important in an estuary due to the effects on biogenic activity, sedimentation and flocculation of muds, and water circulation patterns (Ranger and Pemberton, 1992).

The turbidity maximum is a zone within an estuary containing high concentrations of suspended sediment associated with high clay flocculation rates (Kranck, 1981; Dyer, 1986). The location of the turbidity maximum affects the location of maximum mud deposition. The turbidity maximum may be landward of the salt wedge or it can straddle the landward limit of the salt wedge (Allen, 1991).

Density currents (residual circulation) and tidal current asymmetry are the two dominant processes that cause trapping of suspended sediment, and therefore the turbidity maximum (Dyer, 1986; Allen, 1991). Density currents are created by vertical circulation patterns created when landward flow of saltwater converges with seaward flow of freshwater. Where these two flows converge, a suspended sediment trap is created, and the turbidity maximum is formed (Allen, 1991).

Tidal current asymmetry plays a major part in maintenance of the turbidity maximum during periods of low river discharge (Dyer, 1986; Allen, 1991). During spring tides, current velocities are high, causing muddy sediments to be eroded and resuspended, and the turbidity maximum migrates up the estuary. During neap tides, current velocities are low, causing suspended material to be deposited during the slack, and the turbidity maximum decreases in volume (Dyer, 1986; Allen, 1991). This process results in the cyclicity of sand and mud found in tidal estuarine deposits.

The salt wedge and turbidity maximum may be shifted seaward by ebb tidal flow, neap tides, and/or increased fluvial discharge. They may be shifted landward by flood tides, and spring tides (Dyer, 1986). Sand beds are deposited during times of increased fluvial discharge or during high velocity tidal currents. Mud beds are deposited during periods of slack water, and as the turbidity maximum migrates through the area. Sand-dominated IHS is not formed within the turbidity maximum due to the relative lack of mud within the point bar.

Abundance or paucity of burrowing on the point bar is related to the location of the saltwedge. If burrowing is intense, the point bar is located seaward of the turbidity maximum, within the salt wedge. If burrowing is low or absent, the point bar is located landward of the salt wedge, but still within the range of tidal influence.

IHS represents lateral accretion deposits associated with tidally influenced point bars of a meandering estuarine channel.

F5 GRAY MUD

Description

Gray mud is located most commonly in the middle member. Thickness of this lithofacies varies from 0.5 m up to 20 m (Plate 7, Photo A). The distinguishing characteristics are light to dark gray colour and apparent lack of sedimentary or biogenic structures (Plate 7, Photo B), although some planar lamination is identifiable. Siderite and pyrite are common; sideritized muds are discolored yellow or orange, while pyritized muds exhibit greenish-brown alteration halos (Plate 7, Photo C). Infrequently, gray mud contains thinly interlaminated flat to low angle silt or very fine sand. Carbonaceous debris or wood fragments are also rare. Plate 7, Photo D is a unique example of a septarian nodule observed within this facies.

Basal contacts are commonly gradational with mud-dominated IHS (F4) and less commonly, sharp with sand-dominated IHS (F4) and large-scale cross-stratified sand (F1). Upper contacts are erosive with large-scale cross-stratified sand (F1), or intercalated with muddy facies.

Ichnology

Ichnofossils are absent with the exception of rare rooting (phytoturbation) in the uppermost extremities of the facies.

Interpretation

Gray mud is interpreted as abandonment of a channel meander loops or an oxbow lake. This interpretation is based more on the exclusion of features due to the lithofacies' apparent lack of structures. For example, the limited rooting may indicate deposition in a subaqueous environment.

Channel abandonment of cutoff meander loops can result from two processes: chute cut-off and neck cut-off. Chute cut-off occurs when the new channel is cut along the top of a point bar. Neck cut-off occurs when the new channel is cut through the narrow neck between two meander loops (Reineck and Singh, 1980). Chute cut-off results in a thin mud deposit overlying thicker sand, silt and mud of the point bar (Reineck and Singh, 1980). The chute cut-off process best fits examples of this lithofacies as illustrated in Figure 22.

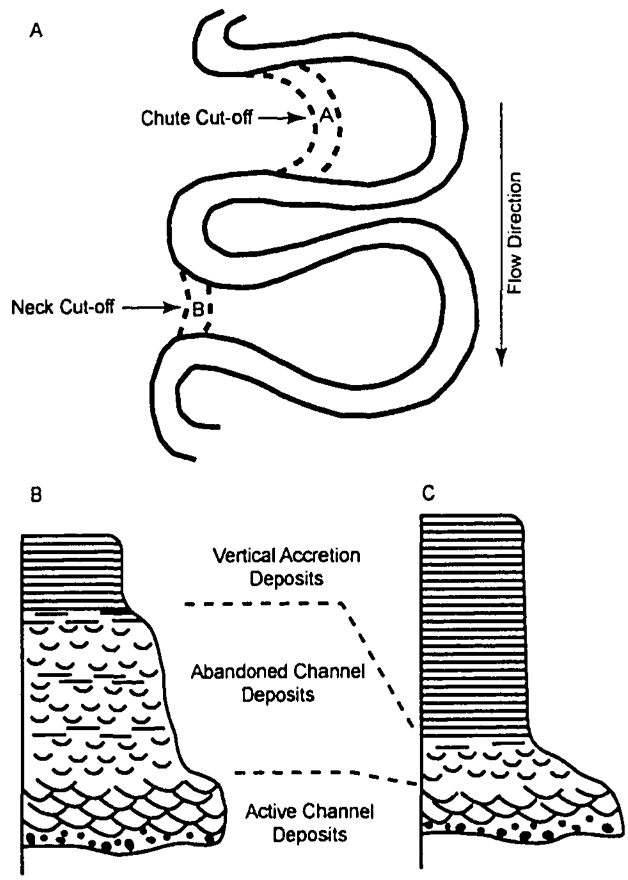


Figure 22
A Meander loops abandoned by chute cut-off or neck cut-off. Dashed lines indicate new channels.
B Idealized vertical succession in a chute cut-off.
C Idealized vertical succession in a neck cut-off.
(modified from Harms *et al.*, 1982).

The distinct absence of macrofaunal bioturbation suggests the restricted nature of the channel abandonment with limited water circulation required by burrowing organisms (Figure 23). These organisms may only receive water during deposition of episodic flooding events. However, deposition from flooding events is not likely as rooting is rare to absent. The apparent paucity of bioturbation may be also due to the lack of lithologic contrast that is beneficial for identifying traces.

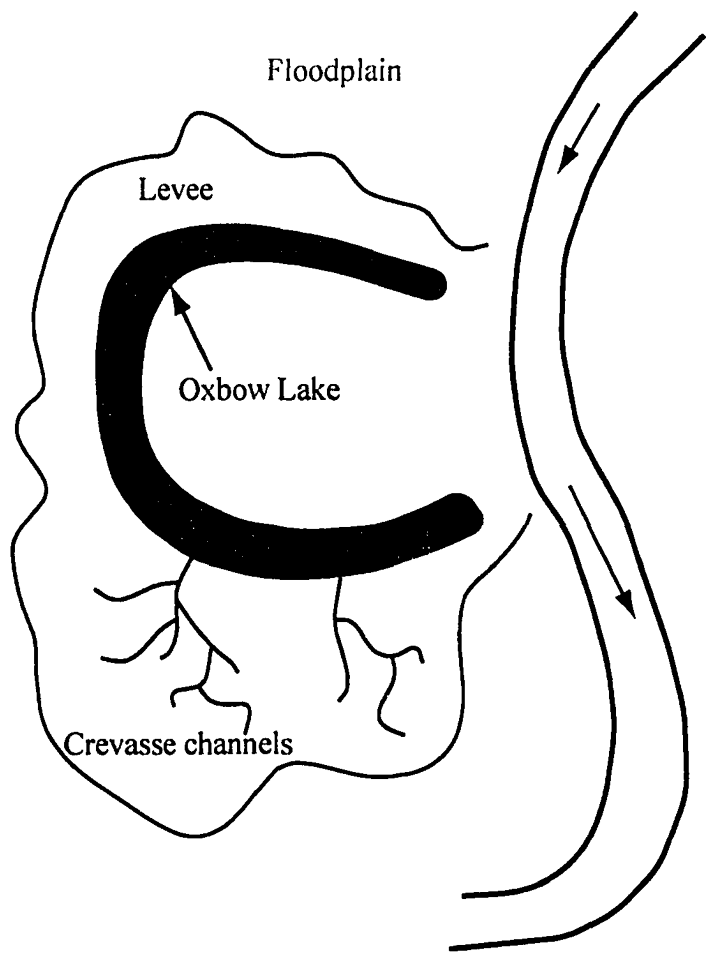


Figure 23
Oxbow Lake formed by neck cut-off of a meander bend, with preserved levee, crevasse channels, and crevasse splay deposits (modified from Collinson, 1986).

Gray mud is interpreted as abandonment of a channel meander loop.

F6 FLAT LYING, THINLY INTERBEDDED SAND AND MUD

Description

Flat lying, thinly interbedded sand and mud occurs in the upper portions of the middle and upper members. This facies is characterized by the regular alternation of thin interbeds of sand and mud with rare to common burrowing (Plate 8, Photo A and B).

This lithofacies may be sand-dominated or mud-dominated, but is typically sand-dominated. Rhythmic interbeds vary in thickness from 0.5 to 5 cm; sand beds rarely attain a thickness up to 30 cm. The thin sand interbeds are horizontal to low angle planar, laminated (1 to 2 mm). Thicker sand beds are current ripple laminated, possible combined flow ripple laminated, climbing ripple laminated, and horizontal to low angle planar laminated. Mud interbeds appear structureless or contain thin (less than 1 mm) sand laminae. Interlaminated sand and mud may also be present as 'pinstripe bedding' or by the genetic term 'tidal bedding' (Plate 8, Photo C). Other common forms of tidal bedding (Reineck and Wunderlich, 1968) such as flaser, wavy, and lenticular bedding are present, although flaser bedding is rare. Contacts between the interbeds, where not disturbed by burrowing, are commonly sharp. Sand interbeds are well sorted with grain sizes varying from lower very fine to lower fine. Coal or wood fragments, and siderite cemented zones are present. Synaeresis cracks are rare.

This facies is associated with gray mud (F5) and mud-dominated IHS (F4) with gradational or distinct contacts. Upper contacts are typically sharp, but may be gradational locally.

Ichnology

Ichnofossils within this facies are rare to churned. The trace fossil assemblage is comprised of diminutive *Planolites, Teichichnus, Cylindrichnus, Palaeophycus, Skolithos*, *Arenicolites*, *Conichnus* (Plate 8, Photo D), and *Ophiomorpha*. Fugichnia are commonly associated with thicker sand beds, which otherwise have little evidence of burrowing activity. Trace fossils within this facies commonly have a thicker mud wall than is typically observed in other facies. *Cylindrichnus* may constitute small *Rosselia* in some instances (Plate 8, Photo E). Phytoturbation is rare.

Interpretation

Flat lying, thinly interbedded sand and mud is interpreted to as tidal flat deposits. Relationships with other facies indicate this lithofacies was deposited fringing estuarine channels and point bar complexes rather than the widespread 'classic' coastline tidal flats of Evans (1965) or Klein (1977). They occur stratigraphically higher than the point bar and represent the vertical accretion deposits of a meandering channel succession.

The combination of horizontal to low angle planar stratification and current ripple cross-laminated sand demonstrates that fluctuating nature flow conditions are responsible for deposition. Horizontal planar stratification is the result of upper flow regime plane beds (Harms and Fahnestock, 1965) and can develop in lower flow velocities in finer grained sand than the flow velocities required for developing plane beds in coarser sands (Figure 17). Current ripple cross-laminations are the result of deposition with the lower flow regime, similar to the small-scale cross-stratified sands. Climbing ripple cross-lamination represents waning flow conditions as abundant sediment, previously held in suspension, is deposited (Reineck and Singh, 1980).

Waning flow energy is the result of three processes, or a combination thereof. First, as sediment laden flow leaves the associated channel, it becomes unconfined on the tidal flat, where energy decreases and deposition occurs. Secondly, a decrease in energy may be the result of cessation of an episodic flooding event, such as a seasonal flood or storm event. Finally, waning energy may be the result of waning tidal energy associated with the cycle. Thicker sand beds (5 to 30 cm) intercalated within this facies represent episodic depositional events. Synaeresis cracks suggest an environment subject to fluctuating salinities.

Interbedded sand and mud indicates that both sand and mud are abundant in the environment. Hawley (1981a) suggested a mechanism that allows for alternating deposition of sand and mud. Sand is deposited when a threshold current velocity is attained, while mud is kept in suspension (Figure 24). Mud is deposited when current velocities are sufficient to allow mud to settle from suspension; consequently, sand transport stops. Under tidal conditions, the sand is deposited during current activity and the mud is deposited during slack water periods (Reineck and Singh, 1980). The contact between individual sand and mud interbeds is typically sharp with little evidence of size grading due to the difference in settling velocity of sand and mud particles, defined as a lag in time when sand transport stops and mud deposition begins (Little-Gadow and Reineck, 1974). Interbedded sand and mud produced by daily tidal current unsteadiness is commonly thinly stratified due to the relatively small volumes of sediment deposited during each current or slack water stage.

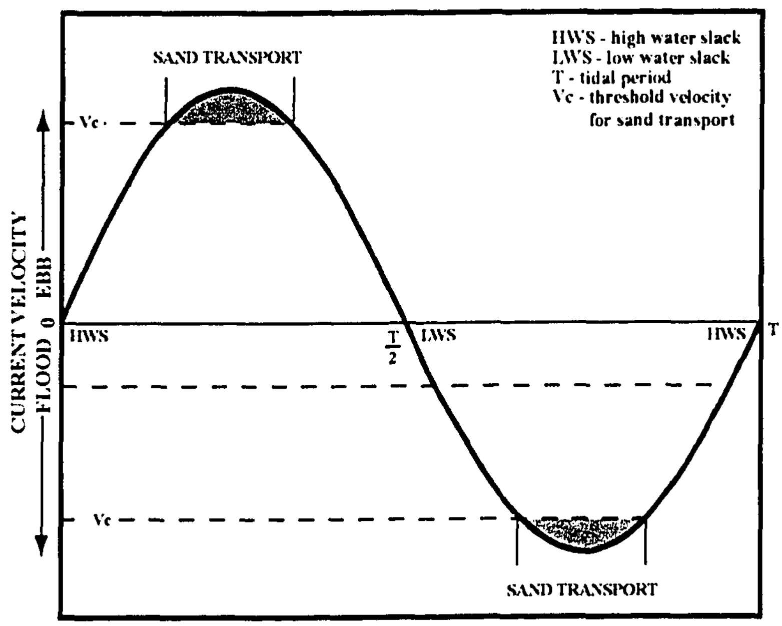


Figure 24
Variation in sand transport over a single tidal cycle (modified from Allen, 1985).

Wavy and lenticular bedding indicate cyclic energy levels with sand deposition during higher flow conditions and mud deposition from suspension during low energy conditions. Flaser, wavy and lenticular bedding are characterized by the proportion of mud to sand and aspect of the bedding. Flaser bedding consists of sand with thin wavy lenses of mud (Reineck, 1960), wavy bedding is characterized by laterally continuous interbedded sand and mud in approximately equal abundance (Reineck and Wunderlich, 1968) and lenticular bedding consists of mud with interbedded lenses of sand (Reineck, 1960). The genesis of flaser, wavy, and lenticular bedding in a tidal environment are depicted in Figure 25A, B, and C. This stratification is not restricted to tidal environments; although, they are a commonly used as an indicator of such environments (Reineck, 1967; Reineck and Wunderlich, 1968; Klein, 1977; Reineck and Singh, 1980).

Clifton (1983) identified a number of distinguishing criteria for modern and Pleistocene intertidal and subtidal deposits in Willipa Bay, Washington. With respect to these criterion this facies exhibits an overall lack of medium and large-scale cross-bedding, directionally inconsistent (not unidirectional) ripple lamination, local rooting, and localized abundance of thin, regular alternations of clay, silt and fine sand. All of which indicate that the facies is intertidal as opposed to subtidal. Other criteria listed by Clifton (1983) require examination of fossil material, paleocurrent data and the associated runoff channel facies, which was not undertaken in this study.

Tidal flat models, such as those by Klein (1977) and Reineck and Singh, (1980), are typically separated into sand flat, mixed flat and mud flat facies. This additional subdivision was not undertaken in this study. Many examples of the flat lying, thinly interbedded sand and mud grade from approximately equal amounts of sand and mud to mud-dominated, which is consistent with the fining upward nature of prograding tidal flat deposits (Evans, 1965; Klein, 1977).

Modern tidal flat deposits are typically abundantly bioturbated (Reineck and Singh, 1980; Clifton, 1983). The trace fossil assemblage demonstrates a higher diversity of traces than other facies, which is likely the result of more saline conditions. The Ogeechee River - Ossabaw Sound estuary demonstrates an increase in species diversity towards the fully marine environment (Dörjes and Howard, 1975; Howard *et al.*, 1975). Trace fossils are small relative to their fully marine counterparts, and contains traces common to both the Skolithos and Cruziana ichnofacies. Paucity of bioturbated sediments evokes episodic rather than tidal processes (periodic) or may be attributed to rapid deposition or sporadic larval distribution. Relative abundance of escape traces support this interpretation.

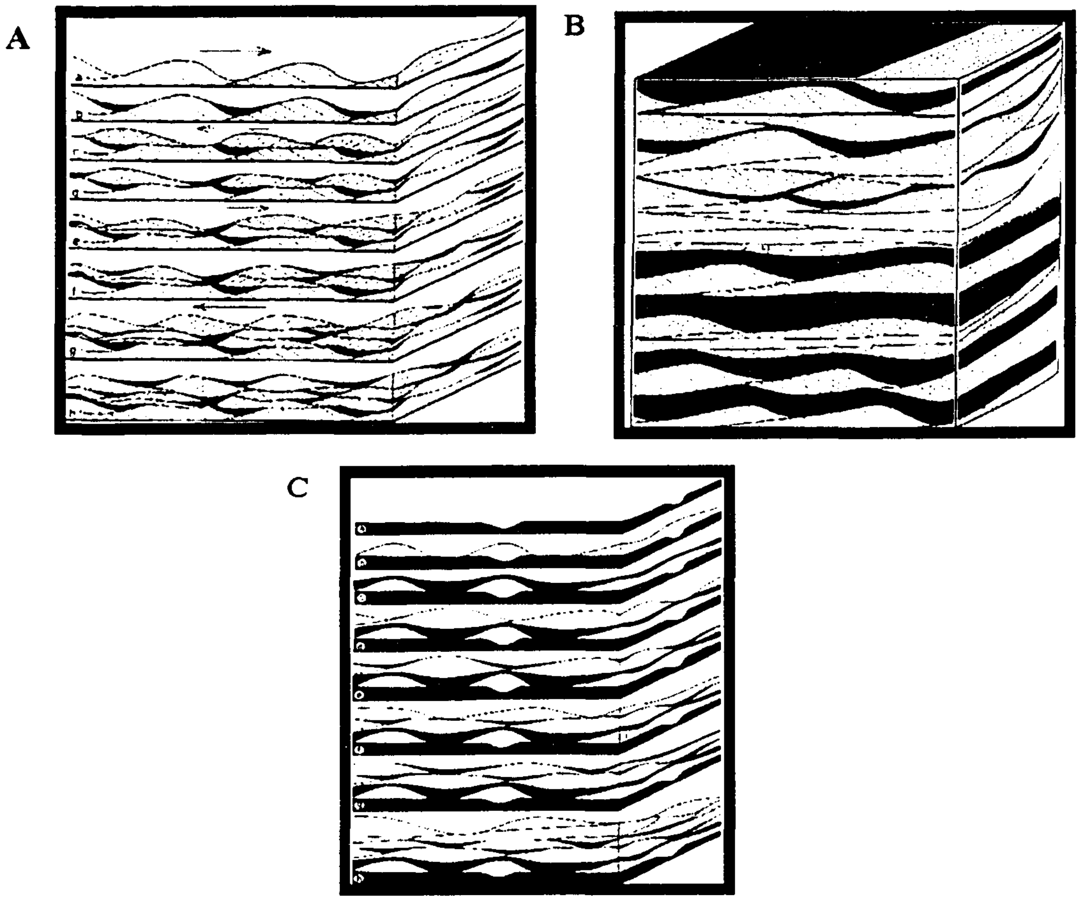


Figure 25
A. Schematic illustrating the genesis of flaser bedding in a tidal environment with opposing flood and ebb currents and high and low and water still-periods. For example, (a) flood current; (b) high water still-stand; (c) ebb current; (d) low water still-stand; and so on (modified from Reineck, 1960).
B. Wavy bedding with a range of bedding types produced by variation in mud layer thickness (modified from Reineck and Wunderlich, 1968).
C. Schematic illustrating the genesis of lenticular bedding. (a-d) depict the genesis of lenticular bedding as a result of formation of incomplete ripples on a muddy substrate; (f-h) later covered again by a mud layer, followed by deposition of sand in the form of ripples. Periods of current activity alternate with still-stand periods, resulting into deposition of sand and mud respectively. Only unidirectional current has been considered from left to right. In tidal environments, ripple-bedded units usually show two current directions (modified from Reineck, 1960).

Flat lying, thinly interbedded sand and mud represents deposition within intertidal flats flanking estuarine channels and point bar complexes.

F7 WHITE TO LIGHT GRAY MUD

Description

White to light gray mud occurs most commonly in the middle member, but does occur rarely throughout the McMurray Formation. This lithofacies is typically white to light gray color, ranging from apparently structureless (Plate 9, Photo A) to planar laminated, and commonly rooted (Plate 9, Photo B). The roots are commonly original carbonaceous material, and are rarely filled with sand or mud. Carbonaceous debris is scattered throughout as coaly fragments (a few centimetres in diameter), individual flakes (a few millimetres in diameter) and as rare coal laminae. Siderite and pyrite occur as nodules; pyrite also occurs in dendritic clusters and as disseminated grains. Mud cracks are rarely observed.

Surfaces may appear chalky or break in a blocky manner, with broken surfaces having a waxy texture, and possible slickensides. This lithofacies may be locally cemented. Swelling clays (such as smectite) are a matrix constituent in variable proportions, as cores swell and become slick when sprayed with water. Smectite may also occur in lenses (Plate 9, Photo C). Some examples of this facies are siltier.

Basal and upper contacts are commonly gradational but may be sharp or erosive (Plate 9, Photo C). White to light gray mud is most commonly found in association with gray mud (F5), dark gray to black carbonaceous mud (F8), and coal (F9).

Ichnology

Phytoturbation is the only form observed with variable intensity from rare to abundant in the upper portions.

Interpretation

White to light gray mud is interpreted as floodplain deposits. As a channel overflows its banks, fine-grained, suspended load material is carried out onto the flood plain. Clay settles from suspension due to a decrease in velocity of water flow (Galloway and Hobday, 1983; Collinson, 1986). Floodplains are rarely inundated; subaerial exposure is common, and pedogenesis (soil formation) may occur (Collinson, 1986). Development of soil is substantiated by the root traces and abundant carbonaceous debris observed.

Slickensides observed also provide evidence of soil formation (Leckie *et al.*, 1989; Retallack, 1990). They form in clayey soils when blocks of soil (peds) continually move past one another during swell-shrink cycles caused by wetting and drying of soil (Retallack, 1990). Slickensides also form by crushing of peds against one another during compaction or burial.

Subaerial exposure is indicated by rare mud cracks. The white to light gray colors of the mud is indicative of a subaerial, oxidizing environment (Visher, 1965). Siderite and pyrite are probably diagenetic in nature, precipitated from slightly reducing ground water (Collinson, 1986).

White to light gray mud is interpreted as floodplain deposits.

F8 DARK GRAY TO BLACK CARBONACEOUS MUD

Description

Dark gray to black carbonaceous mud is almost exclusive to the middle member. High organic content is responsible for the color of this facies (Plate 10, Photo A, B and C). Organics are present as carbonaceous debris, wood fragments, coaly fragments, and coal laminae. The lithofacies is apparently structureless, and along broken surfaces waxy texture and faint slickensides are rarely observed. Dark gray to black carbonaceous muds exhibit sand and silt laminae (Plate 10, Photo B and C). Pyrite occurrence as nodules and disseminated grains is common.

Dark gray to black carbonaceous mud is most commonly intercalated with other fine-grained sediment facies, especially coal (F9). Basal contacts may be gradational with white to light gray mud (F7). Upper contacts are distinct or sharp, commonly undulating, and/or fractured with infill by sediment from overlying facies.

Ichnology

Phytoturbation is rare to absent.

Interpretation

The high organic content of this facies is indicative of abundant vegetative growth and interpreted as a marsh, possibly associated with interchannel topographic lows (Kalkreuth and Leckie, 1989; Galloway and Hobday, 1983). Coal fragments and dispersed sand grains suggest baffling of overbank flows by marsh plants.

Mud substrates are typically characterized by anaerobic conditions and high levels of toxicity that can be fatal to many organisms (Purdy, 1964), which in part accounts for the lack of bioturbation. In addition, unconsolidated muddy substrates may be too soft for benthic organisms, as they contain high proportions of interstitial fluids. In contrast, dewatered and highly cohesive mud substrates may exclude many burrowing organisms that can not overcome the strength of the bed (Howard and Frey, 1973).

Mud sized particles have very low settling velocities. Spherical particles with grain diameter of 60 μm require 5 minutes to settle through 1 m of water, whereas particles with grain diameters of 4 μm require 30 hours to settle through the same water depth (Potter *et al.*, 1980). Because clay minerals and other mud sized grains are typically non-spherical, their settling velocities are further reduced. Suspended mud particles can be fixed or trapped by plants (Van Straaten and Keunen, 1957; Coles, 1979). Vascular plants, such as grasses, act as sediment traps reducing current velocities so that mud can settle from suspension. Gradational contact with white mud indicates continuation of plant growth on old overbank deposits.

Dark gray to black carbonaceous mud is interpreted as marsh deposits likely associated with interchannel topographic lows.

F9 COAL

Description

Coal is almost exclusive to the middle member. Coal beds range from 30 cm to 7 m and are dark gray to black coal. In macroscopic textural terms the coal can be described as durain (dense coal lacking glossy and conchoidal fracture) or fusain (fibrous and soils the fingers on contact) (Boggs, 1987). The facies is commonly fissile and fractured, which may be in part due to the coring process. Distinct layers may be observed. Sand and silt lenses, dispersed sand and silt grains, mud clasts (Plate 11, Photo A), carbonaceous debris (Plate 11, Photo B), and pyrite nodules are common (Plate 11, Photo C).

Upper contacts are sharp to erosive (Plate 11, Photo C and D) while lower contacts are gradational to sharp. Plate 11, Photo D illustrates a unique example of sand dykes intruding the coal facies from above. This facies is commonly intercalated with other fine-grained sediment facies especially dark gray to black carbonaceous mud (F8).

Coal is rare to absent within the cores examined on the Muskeg River Mine lease. However, the associated muddy facies occurs in thicknesses which typically exceed 10 m as the location of the lease is on a paleotopographic low of the sub-Cretaceous unconformity, which provides more accommodation space.

In the Sunrise Thermal Project lease area, a clastic bed intercalated may occur within the coal. This bed is variable in grain size, sedimentary structure, and bioturbation. It is typically medium grained with rare quartz granules in scour surfaces or interbedded with mud. Sedimentary structures may include large-scale cross-stratification, small-scale cross-stratification, chaotically bedded (Plate 12, Photo A and B), finely planar laminated sand and mud (Plate 12, Photo C), interbedded (Plate 12, Photo D), or apparently structureless.

Ichnology

Bioturbation is absent within the coal. The associated clastic beds may contain large monospecific *Teichichnus,* which mimics the appearance of *Scolicia* (Plate 12, Photo A, B, C, and D). *Teichichnus* exhibits retrusive and protrusive spreite (Plate 12, Photo D).

Interpretation

Coal results from the burial of peat deposits. Peat scientists use the general term mire to describe wetlands in which peat accumulates (McCabe and Parrish, 1992). Mires can be low lying or raised, although low lying mires are the most common (McCabe, 1984). Low lying mires occupy areas of low relief where constant flow of water provides a continual source of plant nutrients. The water table in low-lying mires closely approximates the regional ground-water table. In contrast, raised mires have a convex-upward surface that may be elevated several metres above the surrounding topography (Anderson, 1964; Styan and Bustin, 1983). Precipitation must occur on most days of the year in order to maintain the water table of raised mires above the regional groundwater level (McCabe and Parrish, 1992). During Albian/Aptian time, northern Alberta was located in the temperate zone (Saward, 1992) and abundant precipitation likely did not occur year round. McMurray coals encompass multiple townships, thus, they likely formed in extensive low lying mires due to their great lateral extent.

Compaction and loss of volatiles which accompanies burial of peat, results in the reduction of the peat to coal thickness ratio, by a magnitude as high as thirty to one (Ryer and Langer, 1980). Modern peat accumulation rates require between 4,000 and 100,000 years to amass sufficient peat to form 1 m of coal (McCabe and Parrish, 1992). Rough estimation using these figures imply that the thickest coal observed in this study (7 m) would have required as much as 210 m of peat, taking between 28,000 and 700,000 years to develop. Shallow depths of burial and the resulting low temperatures account for the low rank and poor compaction of this coal.

The sedimentary environments that precede, coexist with, or are post-depositional modify the shape of coal bodies, as do the internal processes active within the mires. The sedimentary environments that immediately precede the mire shape the topography on which the mire develops. This topography most directly affects variations in coal thickness, although, it also affects the lateral continuity of the coal to a lesser extent (Horne *et al.*, 1978). This is exemplified in the McMurray coal by increased accommodation space available due to karsting (Figure 26). Following burial of peat, processes of associated with successive environments, such as channel scouring, may impinge downward and modify the upper surface of the deposit. These processes cause local thinning and the interruption of the lateral continuity by the removal of coal (Horne *et al.*, 1978). This is exemplified by the erosion of coal by overlying lower and middle McMurray channels (Figure 27).

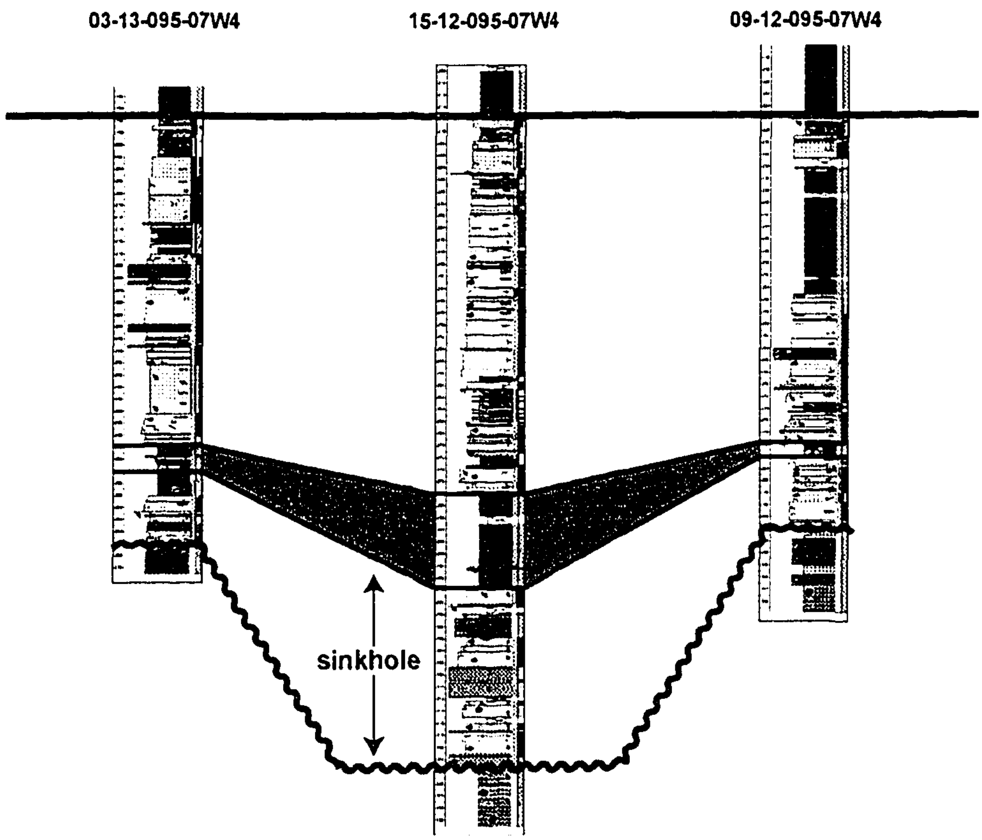


Figure 26
The topography that immediately precedes mire development directly affects variations in coal thickness. The above cross section illustrates the increased accumulation of organic shale thickness in a paleotopographic sag at the 15-12-95-7W4 well due to increased accommodation space created by karsting.

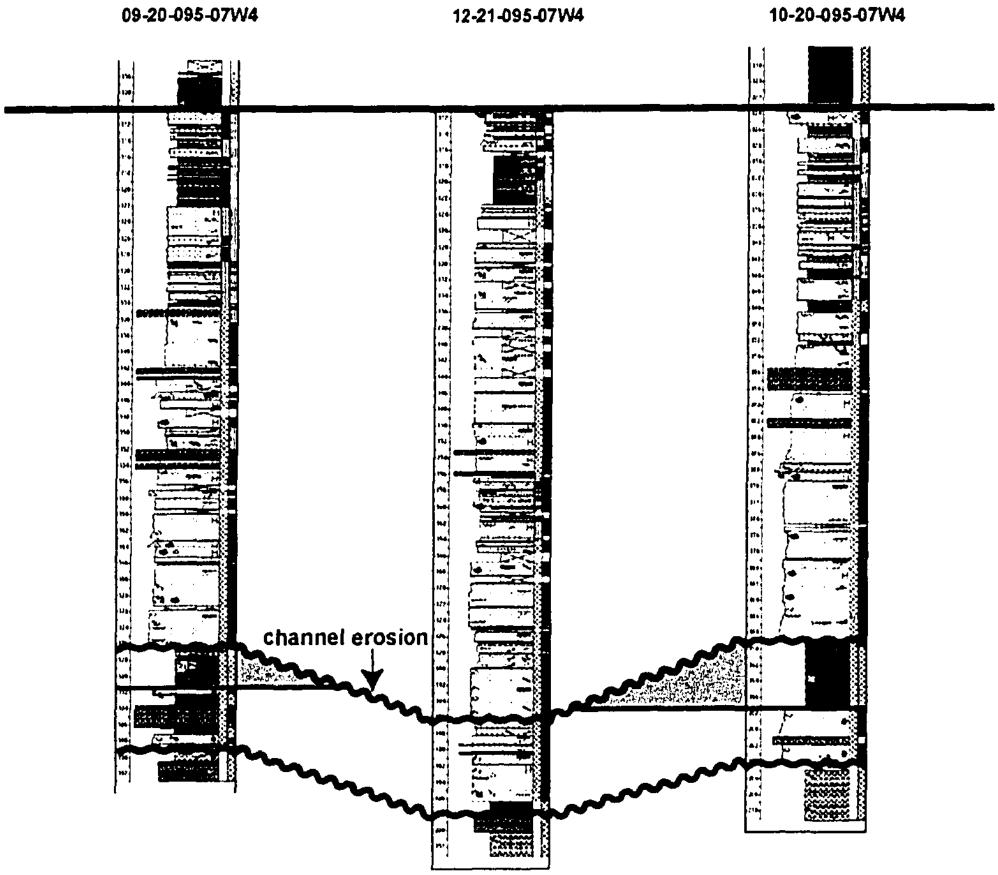


Figure 27
Post-depositional environments modify coal thickness. In this cross-section, channel erosion causes local thinning and removal of coal in the 12-21-85-7W4 well. This creates an interruption of coal continuity.

Peat formation requires abundant accumulation of dead vegetation, which is water saturated due to high ground water tables in an area free of inorganic sediment deposition (Blatt, 1982). Figure 28 is a coal lithofacies depositional model, where lithofacies are produced within an estuarine sequence developed during transgression of a preexisting fluvial system. A transgressional event would account for the large areal extent (township scale) of the McMurray coal.

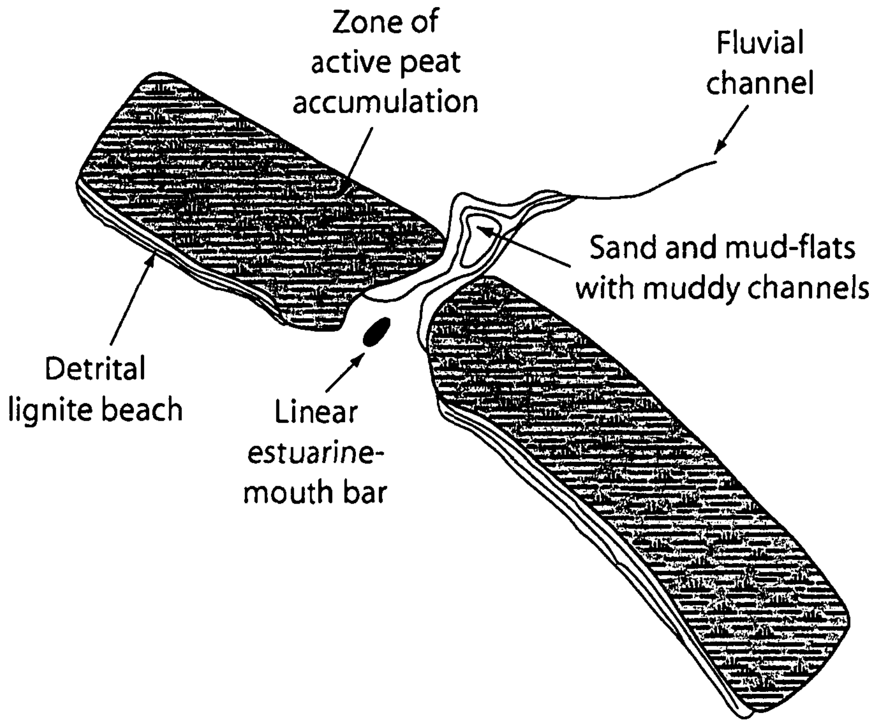


Figure 28
Coal lithofacies depositional model where lithofacies are produced within an estuarine sequence developed during transgression of a preexisting fluvial system (modified from Archer and Kvale, 1993).

Clastic sediments may be washed into mires by overbank flow (Horne *et al.*, 1978; McCabe and Parrish, 1992) or coastal flooding related to storm surges (McCabe and Parrish, 1992). The development of sand beds in coal begins with peat accumulation during normal flow conditions in a flood basin near the channel. During high flow conditions, coastal flooding related to storm surges or high fluvial flow into the estuary, crevasse channels and splays deposit clastic beds within the flood basin. With the return to normal flow conditions and the abandonment of the crevasse system, the marsh is re-established and, peat accumulation continues (Figure 29). Additional clastic material in the coal, silt or clay, may have been blown into the mire (McCabe and Parrish, 1992). Pebble sized grains observed may be due to entrainment by baffling marsh plants.

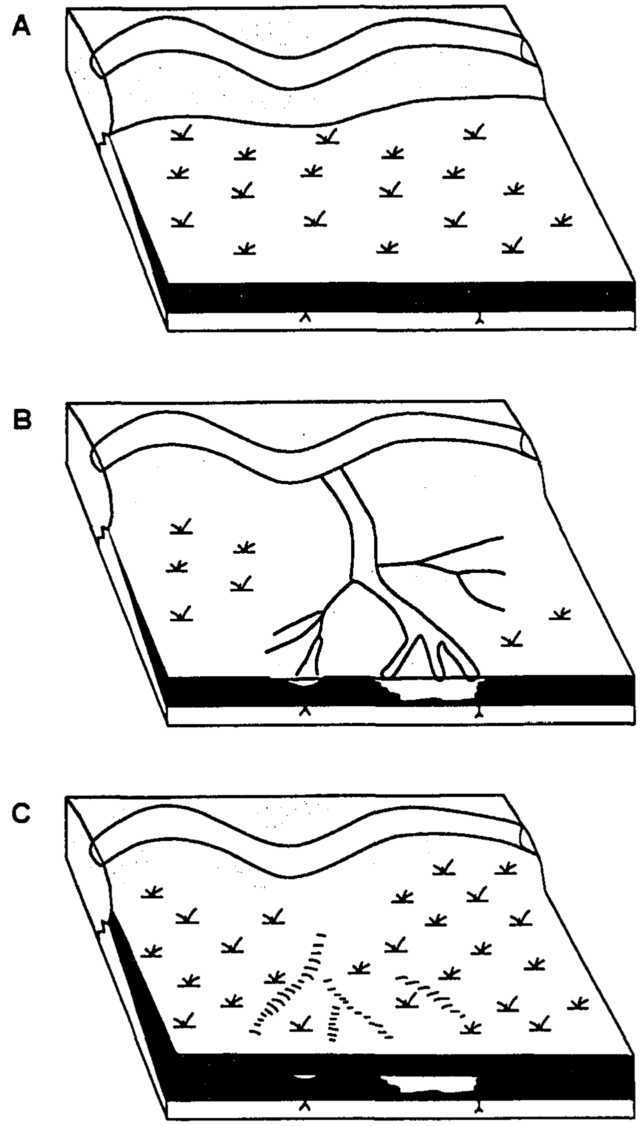


Figure 29
Stages in the development of sand beds in coal:
A. During normal flow conditions, peat accumulates in flood basin near channel,
B. During high flow conditions, crevasse splays result in clastic beds,
C. With the return to normal flow conditions and the abandonment of the crevasse system, the marsh is re-established with the continued accumulation of peat (modified from Guion, 1984).

Coal is deposited in a flood basin adjacent to a channel with influxes of saline water from overbank flow or from coastal flooding related to storm surges.

F10 CHAOTIC, INTERBEDDED SAND AND SILTY MUD

Description

Chaotic, interbedded sand and silty mud facies is highly variable in appearance. It is best characterized as interbedded sand and silty mud that commonly displays high angles of inclination and chaotic bedding (Plate 13, Photo A and B). It most commonly found in the middle member. This facies is typically 2 to 3 m thick in the Sunrise Thermal Project lease, but commonly attains greater thicknesses in the Muskeg River Mine lease where the accommodation space is greater. Bitumen saturation is highly variable, but typically low due to variation in grain sizes, poor sorting (Plate 13, Photo A and B), and the predominance of silt and clays (Plate 13, Photo C).

The dominant sedimentary structures in sand-dominated intervals of this facies are ripple cross-lamination, and local horizontal to low angle planar stratification (Plate 13, Photo D). Mud-dominated intervals are commonly convolute (Plate 13, Photo C). Chaotic bedding can persist throughout the entire unit. Irregular patches of relatively clean sand occur sporadically.

Subrounded quartzose granules and pebbles are infrequently scattered throughout the facies, but are locally concentrated at the base of beds. Siderite cementation and pyrite nodules may be present. Other common lithologic features may include carbonaceous debris, comprised of fine flakes to wood fragments 2 to 3 cm long (Plate 13, Photo A and B), rare coal laminae and mud clasts.

Basal contacts are typically flat to scoured, but gradational and loaded contacts are also common. The basal contact is sharp with a variety of other facies. Upper contacts may be gradational with gray mud (F5), white to light gray mud (F7), dark gray to black carbonaceous mud (F8) and coal (F9). Alternatively, the upper contact may be erosive and overlain by large-scale cross-stratified sand (F1).

Ichnology

Ichnofossils are either common, rare or absent. Bioturbation comprises small

Skolithos, Arenicolites and *Planolites*. Phytoturbation is also observed.

Interpretation

Chaotic, interbedded sand and silty mud is interpreted as crevasse splay deposits adjacent to a channel. Crevasse-splay deposits are the result of overbank flow breaching channel confines during a flooding event. They are typically tens of centimetres to a few metres thick (Reineck and Singh, 1980), which is consistent with thicknesses observed in this facies.

Common sedimentary structures within crevasse-splay deposits include; current ripple cross-lamination and horizontal to low angle planar stratification. However, climbing ripples, which are characteristic of these deposits (Reineck and Singh, 1980), are not commonly observed.

Interpretation of the profuse chaotic bedding is problematic. Poor sorting indicates current energy was low (Blatt, 1982). Deformation due to compaction of underlying muds, high subsidence events, or slope failure associated with a nearby channel may explain convolute bedding as the result of rapid depositional events. However, this facies may represent the churning of other facies due to karst collapse, as further described in Chapter 5.

The abundance of carbonaceous debris and coal laminae indicate low current energy levels, as with higher energy levels the larger debris would have been destroyed. Abundance of carbonaceous material indicates close proximity to a highly vegetated area, such as a marsh or a swamp. This is confirmed by the application of Walthers Law, as the vertical succession is related to marsh deposits, thus one may assume this to be the case laterally.

Deposition of suspended sediments occurs as flow energy decreases away from the channel. Coarser sands and silts are deposited close to the channel and finer sediments are deposited further out on the flood basin (Collinson, 1986). Muddy and silty portions of this facies represent the distal portion of a crevasse splay deposit. Morphologically, crevasse-splay deposits generate a tongue of sediment thinning from the channel breach in the direction of the flood basin (Reineck and Singh, 1980).

The trace fossil assemblage exhibits low diversity suggesting a stressed environment and deposition within a restricted brackish water environment (Pemberton and Wightman, 1992). As bioturbation is only locally present, portions of this facies may have been deposited in association with a greater fresh water component.

Chaotic, interbedded sand and silty mud is interpreted as crevasse splay deposits adjacent to a channel.

F11 INTERBEDDED SAND AND MUD WITH GASTROPODS

Description

Interbedded sand and mud with gastropods is characterized by transported gastropods, the only fossils found within the McMurray Formation (Plate 14, Photo A, B, C, and D). This facies is similar to laminated to burrowed sand subfacies of F12. Gastropods are only found on the Sunrise Thermal Project lease.

This facies is characterized by successions of sharp-based sands intercalated with sand and mud beds, breccia zones and/or bioturbated shaly sand (Plate 14, Photo B). The sandy lags of this facies are fine-grained, and rarely medium-grained. These lags commonly display apparently structureless (Plate 14, Photo A) or chaotic bedding (Plate 14, Photo D). Gastropods are most commonly found within these well saturated sands. Gastropods may define bedding or be chaotically oriented. The non-lag sand is variably stratified from wavy to flaser, low angle parallel laminated, ripple cross-laminated or a combination of these bedforms. Mud clasts are very common in this unit. Carbonaceous debris is also a component of this facies (Plate 14, Photo D).

Russell (1932) examined the biota of the McMurray Formation in sample material predominantly collected from the Ells 1931 field season from the Hangingstone River outcrop (approximately 50 km from Sunrise Thermal Project lease). He identified the clams *Unio biornatus*, and *Murraia naiadiformis*, and the gastropods *Viviparus murraiensis*, *Melania multorbis*, and *Melania athabascensis*, all of which were new species, and some of which were new genera at that time (Plate 15, illustrations 1-12). In the lag, or death assemblage, all are found on the Sunrise Thermal Project lease with the exception of the clams (Plate 16, illustrations A-E; C. Stelck, personal communication, 2004). The gastropod *Lioplacodes bituminis* was the most common in the samples described by Russell's (1932). In contrast, *Goniobasis? multicarinata* is the most common in the current study. An additional subspecies of *Goniobasis multicarinata* or an undescribed form showing a modification of the lined growth line pattern is identified in this study.

The lower contacts of this facies are sharp based to erosive. Upper contacts are commonly sharp with F12 laminated to burrowed sand subfacies.

Ichnology

Trace fossils are rare to absent within the sand beds, and rare in the mud beds. *Planolites*, *Cylindrichnus* and *Skolithos* are the most common traces observed.

Origin of gastropods

McMurray fauna is almost exclusively composed of non-marine or fresh water genera (Russell, 1932; Mattison and Pemberton, 1990). The presence of *Melania multorbis* suggests a toleration of brackish waters (C. Stelck, personal communication, 2004). A lacustrine environment is commonly proposed for *Vivparidae* and *Lioplacodes* (Mattison and Pemberton, 1990).

Uncertainty regarding the salinity tolerance of the various fossil taxa does permit brackish water environment interpretation, an idea supported by the close proximity of deposits to contemporaneous marine deposits. Recent studies have documented an increased number of marine and brackish water indicators including bioturbation (Wanklyn, 1985; Banerjee, 1990) echinoid spines, trace fossils of the Cruziana ichnofacies (Banerjee, 1990), synaeresis cracks, dinoflagellates (Banerjee and Davies, 1988), and wavy-bedded heterolithic structure indicative of tides (Banerjee and Kidwell, 1991). Other studies have promoted brackish water depositional hypotheses based largely on the assumption that mollusks of the

Ostracode Zone constitute a mixed assemblage of fresh and brackish water types (Finger, 1983; Wanklyn, 1985; Mattison, 1987; McPhee, 1994).

Studies of modern estuarine systems show that natural isotopic contrasts exist between marine and fresh waters, both for carbon and oxygen (Mook, 1970), and strontium (Ingram and Sloan, 1992; Andersson *et al.*, 1992). These isotopic variations may be used to infer salinities in the mixing zone. Isotopic analysis of fossil shells from ancient brackish water deposits may be converted to proxy salinity values with knowledge of the isotopic compositions and concentration of the fluviatile and marine mixing end-members.

Using samples collected from the Hangingstone River, Holmden *et al.* (1997) analyzed O, Sr and C isotopes. The narrow range in $\partial^{18}O$ values for shell material from the Ostracode Zone and equivalent strata indicated either a single well-mixed lake or a series of hydrologically connected lakes. The $\partial^{18}O$ enrichment of the gastropods relative to fluviatile inputs indicated long water residence times. Slow through-flow of fluviatile waters to the Moosebar-Clearwater Sea is postulated.

To account for the presence of marine indicators, such as dinoflagellates, in some Ostracode Zone strata, a restricted marine connection is postulated. This is similar in conception to modern Lake Maracaibo, Venezuela where low uniform salinities are maintained in a hydrological balance between fluvial and marine inputs (Figure 30). An ancient Lake Ostracode is postulated by Holmden *et al.* (1997), for the in situ gastropods found near Fort McMurray.

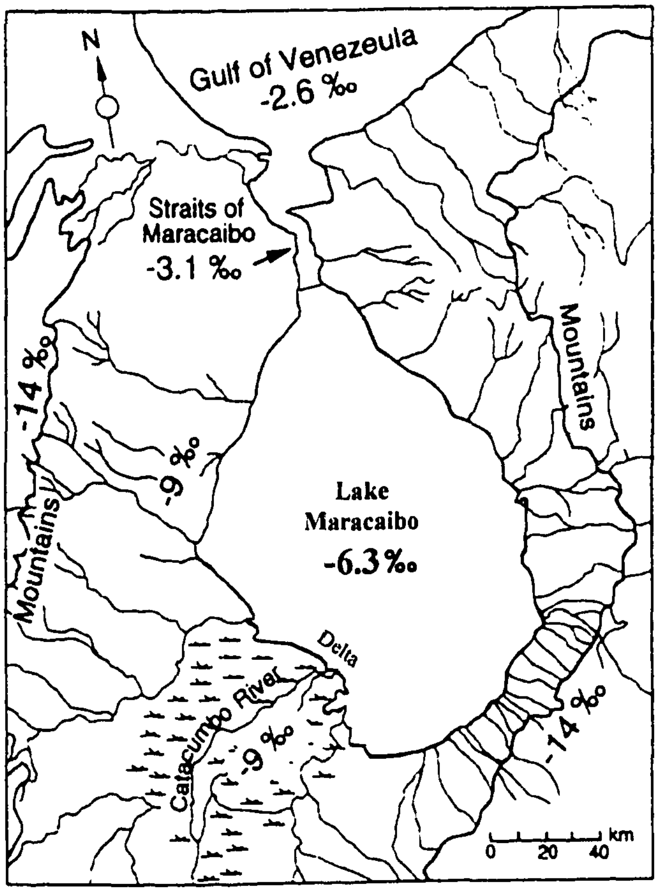


Figure 30
The physiography and oxygen isotope balance of modern Lake Maracaibo (Friedman *et al.*, 1959), suggested as a modern analogue for the paleohydrology and depositional environment of the Ostracode Zone (modified from Davey, 1949).

Interpretation

Interbedded sand and mud with gastropods formed within an areally-restricted setting comprised of a transitional zone, such as a bay or sound, between the estuarine regime of the middle McMurray and the marginal marine (shoal/shoreface) regime of the upper McMurray. This facies records the increased effects of marine transgression and the development of a protected, relatively quiet water environment during this transgression.

Bay/sound deposits are dominated by highly distinctive muds and silts interbedded with sand. Sedimentary structures of the interbedded sands are dominated by large-scale and small-scale wave ripple sets (Mattison and Pemberton, 1990).

Shell-hosted sands of the current study are usually massive, and the shells are chaotically oriented. Most shells are intact. Considering their extreme delicacy, these shells must have been buried rather quickly and were probably not subjected to destructive transport prior to their deposition. These shelly sand lags were likely deposited during high energy events such as storms, or alternatively during periods of greater terrestrial influence (e.g. seasonal fluvial flooding events).

It is likely that the environment of deposition was protected from the full effects of wave and current energies by seaward shoals, which comprise the bulk of upper McMurray sediments developed contemporaneously in nearshore settings to the north.

Interbedded sand and mud with gastropods formed within an areally-restricted setting, such as a bay or sound, transitional between the estuarine regime of the middle McMurray and the marginal marine (shoal/shoreface) regime of the upper McMurray.

F12 LAMINATED TO INTERBEDDED SAND AND MUD WITH VARIABLE BIOTURBATION

Description

Laminated to interbedded sand and mud with variable bioturbation is found within the upper member of the McMurray Formation. It is characterized by three subfacies: laminated to burrowed sand (F12a), well burrowed sand (F12b) and well burrowed interbedded sand and mud (F12c). The three subfacies tend to occur in a predictable order as they are listed, or subfacies may be absent. The subfacies are most commonly gradational, although, contacts can be sharp. Subfacies represent one facies with a variety of environmental conditions.

Subfacies F12a: Laminated to burrowed sand

Laminated to burrowed sand is found within the lower portion of the upper member of the McMurray Formation. This subfacies is characterized by successions of sharp-based, variably stratified fine sand intercalated with burrowed zones (Plate 17, Photo A). The amount of bioturbation increases upwards towards the contact with the overlying laminated sand succession.

Sand of this facies is well sorted, upper very fine- to lower fine-grained. It is variably stratified and may consist of either wavy to flaser, low angle parallel or ripple cross-lamination, or a combination of these bedforms (Plate 17, Photo B). Current ripple cross-laminations are predominant; however, examples of combined flow ripples and climbing ripples are also present. Carbonaceous debris commonly demarcates the laminated nature of the sand. Mud clasts may also be found within this unit.

The lower contacts of this facies are commonly sharp based to erosive (Plate 17, Photo C). When the lower contact is erosive a bed of coarser grained material, up to 60 cm thick is observed. The upper contact with well burrowed sand (F12b) is commonly gradational, but can be sharp (Plate 17, Photo D) however, F12a may also be in contact with numerous other overlying facies.

Subfacies F12b: Well burrowed sand

Well burrowed sand is found within the upper member of the McMurray Formation. This subfacies is characterized by pervasive bioturbation of very fine sands with laminated sand and mud interbeds. The high degree of bioturbation commonly results in thorough mixing of mud within the sands, and 'muddy sand' is often a more accurate descriptor (Plate 18, Photo A). Individual burrows can rarely be discerned.

The sand is very fine to fine grained, but may rarely be medium to coarse. Physical sedimentary structures are rare in this lithofacies, as they are obscured by a pervasive bioturbated texture. The preservation of physical structures is limited to muddy interbeds (Plate 18, Photo B) and sand interbeds. Sand interbeds are low angle parallel laminated and ripple cross-laminated (Plate 18, Photo C).

Mud drapes and partings have thicknesses that range from 1 mm to 2 cm, providing a sense of stratification. Drapes and partings appear to be continuous or discontinuous across the width of the core, with the main cause of discontinuity being bioturbation (Plate 18, Photo D). Bioturbation is commonly so intense that all that remains of a drape is a horizon of irregular mud patches within a matrix of bioturbated sand. Bitumen saturation is dependant on the mud content of the lithofacies. As mud is increasingly mixed with sand, the bitumen saturation decreased. Bitumen staining may also be irregular due to bioturbation.

This lithofacies is usually characterized by gradational to sharp basal contacts with laminated to burrowed sand (F12a). Sharp to scoured basal contacts with other lithofacies, such as sand-dominated IHS (F4) and flat lying, thinly interbedded sand and mud (F6) are evident. Sharp to erosive upper contacts may be observed with the blue gray sand and shale (F14) facies (*Glossifungites* surface). The upper contact is generally gradational with interbedded sand and mud (F12c).

Subfacies F12c: Interbedded sand and mud

Interbedded sand and mud is most commonly located in the upper McMurray. This subfacies is characterized by well burrowed, medium scale interbedded sand and mud (Plate 19, Photo A and B). It lacks the inclined nature of sand-dominated IHS (F4) and the interbed thickness is greater than that of flat-lying, thinly interbedded sand and mud (F6). This facies may also be represented solely by sand (Plate 19, Photo C) which grades from well saturated to unsaturated. Sand is lower very fine to lower fine, with upper very fine-grained being most common. Sand beds are commonly current and climbing ripple laminated (Plate 19, Photo B).

Lower contacts are gradational to sharp with well burrowed sand (F12b) (Plate 19, Photo A). Upper contacts are commonly burrowed or gradational, and overlain by flat-lying thinly interbedded sand and mud (F6).

Ichnology

The intensity of bioturbation of this facies varies from absent to abundant. Bioturbation varies from the laminated to unlaminated portions, sand-dominated to mud-dominated beds, and from the sharp base of sand beds to top of muddy portions. All of the subfacies display trace fossil assemblages that include: *Planolites, Palaeophycus, Skolithos, Arenicolites, Cylindrichnus,* and *Teichichnus*. *Rosselia*, *Conichnus* and escape structures are less common in occurrence. Trace fossils within burrowed intervals may be difficult to discern due to pervasive cross-cutting relationships. Trace fossil forms are small, predominantly less than 1 cm in length or diameter.

Interpretation

Laminated to interbedded sand and mud with variable bioturbation is interpreted as shallow marine sand bodies within the shoreface. Variations in the conditions acting on the sand bodies make it difficult to identify them in the rock record. Multiple scour events, periodic exposure, fluctuating tidal energies, and storm deposits are only a few of the variables that affect these sands. Furthermore, the abundance of terminology for different types of shallow sand bodies further confuses their identification. Sand bank, swash bar, sand flat, inlet shoal, channel bar, and sand wave are some of the examples of shallow sand bodies in the literature (Visher and Howard, 1974; Greer, 1975; Goldring *et al.*, 1978; Homewood and Allen, 1981; Archer *et al.*, 1994).

Ripple lamination, interpreted as the result of combined flow, are identified in all of the subfacies, but have variable appearance. Combined flow ripples tend to have symmetrical profiles, but an internal cross lamination that dips consistently in one direction (Figure 31), even though they have variable appearances. In the geological record, where the ripple profiles are not fully preserved, combined flow and current ripples can be difficult to distinguish (Walker and Plint, 1982).

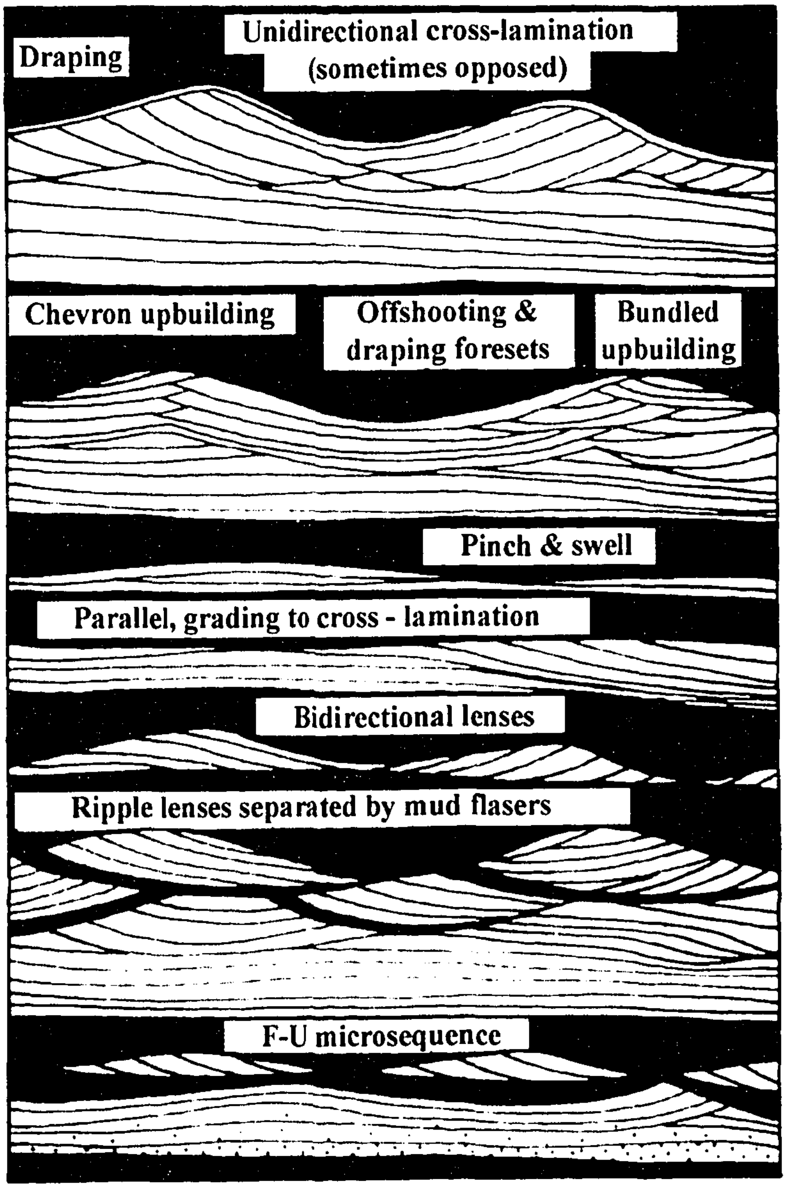


Figure 31
Sketch showing the various types of ripple cross-stratification formed by combined flow (modified from de Raaf *et al.*, 1977).

Undulatory, parallel laminated sands, which are common to all three subfacies, extend beyond the width of the core. These low angle to horizontal laminations and beds could be a component of hummocky cross-stratification (HCS), or swaley cross-stratification (SCS).

The term HCS was introduced by John Harms (Harms *et al.*, 1975), he interpreted HCS as storm deposits. HCS occurs most typically in fine sandstone to coarse siltstone (Walker, 1992). HCS is characterized by undulating sets of cross-laminae that are both concave-up (swales) and convex up (hummocks). The cross-bed sets cut gently into each other with curved erosion faces. HCS commonly occurs in sets 15 to 50 cm thick with wavy erosional bases and rippled, bioturbated tops (Harms *et al.*, 1975). Spacing of hummocks and swales ranges from 50 cm to several metres. The lower bounding surface of a hummocky unit is sharp and commonly erosional. Current-formed sole marks may be present on the base (Figure 32).

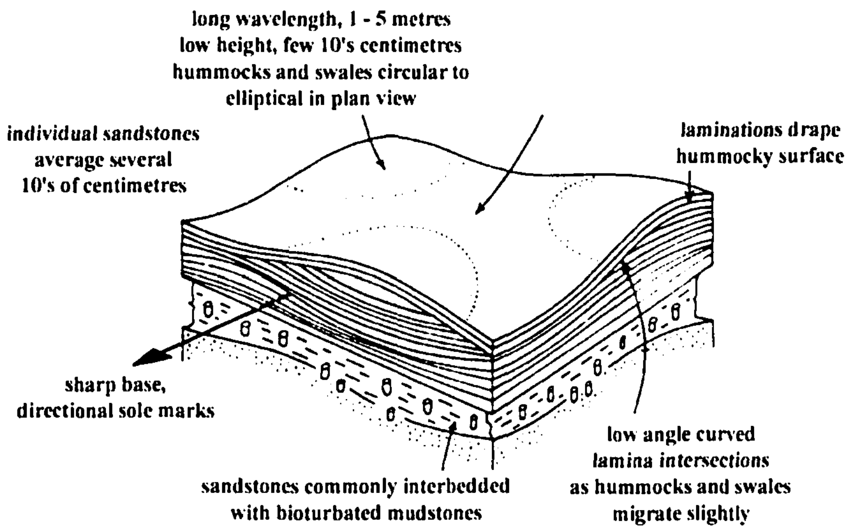


Figure 32
Schematic diagram of hummocky cross-stratification, which typically occurs interbedded with bioturbated mudstone (modified from Walker, 1982).

The sequence of events leading to the formation of HCS proposed by Duke *et al.*, (1991) begins with waves scouring the muddy substrate during rising phases of the storm. Coastal sand is then transported to offshore localities. Sand accumulates rapidly as the storm current wanes, producing flat laminations that drape the low-relief scours. Large ripples begin to form (and migrate) on the still-aggrading substrate, and anisotropic hummocky cross-stratification (asymmetrical dip directions and different dip angles) develops. In the final stage, isotropic hummocky cross-stratification (more or less symmetrical dip directions and uniform dip angles) is formed under very strongly oscillatory-dominant combined flow (Figure 33).

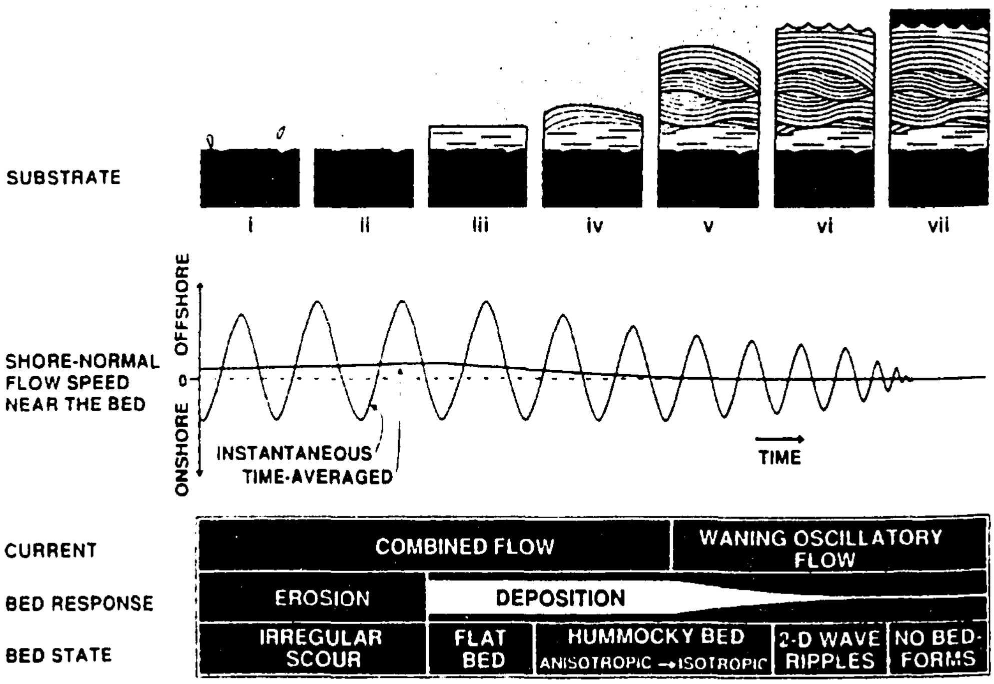


Figure 33
Possible sequence of events leading to formation of hummocky cross-stratification in inner shelf sands (modified from Duke *et al.*, 1991).

Swaley cross stratification (SCS) are HCS sand beds amalgamated together, and the interbedded muds are thin or absent. There has been little opportunity for the deposition and preservation of mud, suggesting a generally shallower, more agitated environment. The term SCS was introduced by Leckie and Walker (1982) for sand bodies by thicker than 2 m. The internal stratification is dominantly flat to very gently undulating and the swales cut into this lamination. Most SCS sand bodies represent prograding storm-dominated shorefaces, in which storm processes have overprinted all record of fair-weather sedimentation (Walker, 1992).

Both of these stratification types have low angle laminations and undulatory truncation surfaces (MacEachern, 1994). HCS and SCS are deposited during high energy oscillatory conditions associated with storm events (Arnott, 1993); SCS results from relatively higher energy conditions than HCS (Leckie and Walker, 1982). HCS is commonly associated with waning flow ripple cross-lamination, and hence, oscillation ripples may be found capping HCS beds. Ripple laminations are not commonly found in association with SCS as it is the result of erosional amalgamation of successive depositional events.

The foreshore consists of the portion above low tide line and is dominated by swash and backwash of breaking waves. The shoreface lies consistently below tide level and is characterized by day-to-day sand transport above fairweather wave base. The depth of fairweather wavebase varies from 5 to 15 m, depending on the general wave climate of the basin (Figure 34). In practice, the base of the shoreface can be defined at the point where interbedded sand and mud of the offshore/shelf pass into relatively clean sandstones (Walker, 1992).

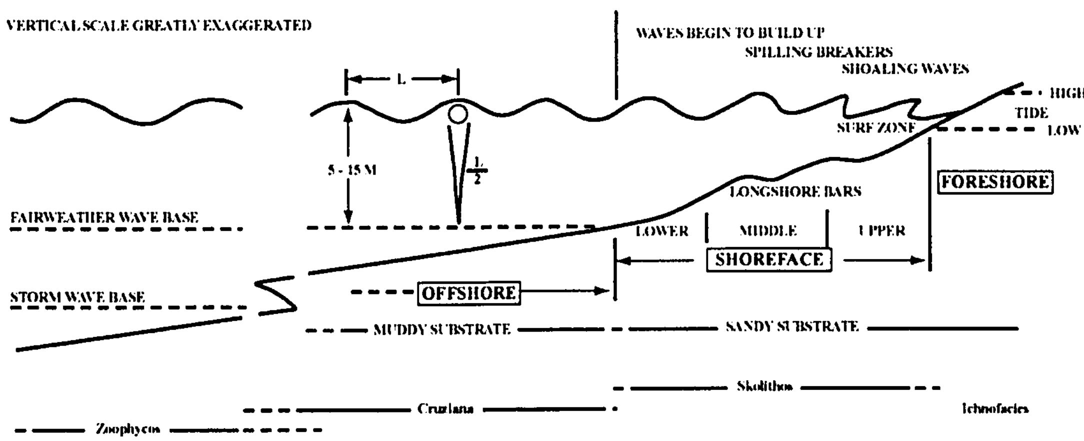


Figure 34
Shoreline to shallow marine profile locating foreshore, shoreface and offshore areas, as well as fairweather wave base and approximate ichnofacies occurrences. Note that fairweather waves of wavelength L cannot agitate the bed at depths greater than approximately L/2. Fairweather wave base lies at depth of about 5-15 m (modified from Walker, 1992).

In the laminated to burrowed sand subfacies, burrowing is limited to the upper portions of the laminated to burrowed sand couplets. The trace fossil assemblage represents colonization after storm deposition by opportunistic organisms and subsequent burrowing by equilibrium organisms. No attempt was made in this study to determine which traces were opportunistic and which traces constituted the equilibrium suite (Figure 35).

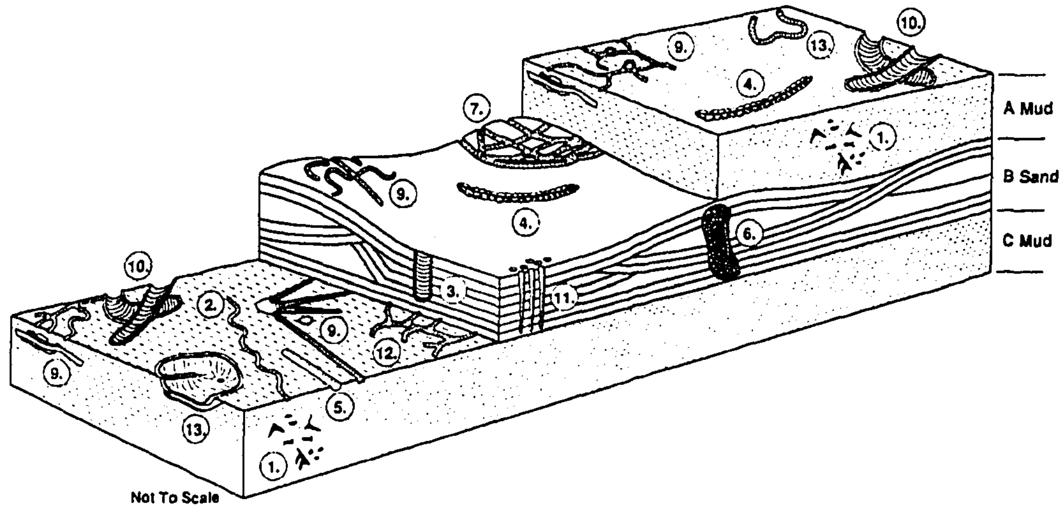


Figure 35
Schematic diagram illustrating the distribution of common trace fossils in the Upper Cretaceous Cardium Formation, Alberta. Trace fossils in Beds A and C are representative of the resident, fairweather assemblage, while those in Bed B are indicative of the opportunistic, storm-related assemblage. Representative forms include: 1. *Chondrites*; 2. *Cochlichnus*; 3. *Diplocraterion*; 4. *Gyrochorte*; 5. *Taenidium*; 6. *Ophiomorpha*; 7. *Palaeophycus*; 8. *Phoebichnus*; 9. *Planolites*; 10. *Rhizocorallium*; 11. *Skolithos*; 12. *Thalassinoides*; and 13. *Zoophycos* (modified from Pemberton and Frey, 1984).

The characteristic laminated to burrowed successions of this subfacies is interpreted to represent tempestites. This subfacies contains the features identified by MacEachern (1994) as those representing tempestite deposition, including: (1) a sharp erosional base, (2) a main sand interval with low angle laminations (HCS or SCS), (3) escape structures, (4) dwelling burrows of opportunistic organisms near the top of the beds representing initial colonization, (5) gradational burrowed tops with fair-weather suites cross-cutting the opportunistic assemblage, passing into (6) thoroughly burrowed fair-weather deposits containing an equilibrium trace fossil suite.

The relative abundance of physical structures to biogenic structures is useful in interpreting the frequency of these storm deposits. Assuming constant biologic activity, the frequency and magnitude of storm events controls the relative abundance of physical and biogenic structures. Higher frequency, greater magnitude events will result in a predominance of physical structures. Less frequent, lower magnitude events allow thorough bioturbation and a predominance of biogenic structures. The interplay of these variables results in the variable intensity of burrowing observed.

The higher degree of burrowing in the well burrowed subfacies indicates sufficient time available for complete bioturbation of the sand with corresponding low flow conditions to prevent reworking of the substrate. This suggests that well burrowed sand subfacies (F12b) was deposited in a portion of the estuary sheltered from the frequent depositional events of represented by the laminated to burrowed subfacies (F12a).

As a whole, the ichnofossils of the facies are interpreted as a stressed marine assemblage. The assemblage exhibits lower diversity, but high individual density of traces typically smaller than their marine counterparts. The increased prevalence of marine conditions within this depositional environment is responsible for the increased diversity of forms, but not the increased intensity of burrowing. Sufficient protection from physical reworking is responsible for the increased intensity of burrowing.

The three subfacies are members of a continuum from high energy, sand deposition with less burrowing to lower energy, sand and mud deposition with more burrowing.

Laminated to interbedded sand and mud with variable bioturbation is interpreted as shallow marine sand bodies within the shoreface.

F13 POORLY SORTED FINE TO COARSE SAND

Description

Poorly sorted fine to coarse sand is present as an erosional veneer. This facies attains thicknesses of 1 to 40 cm. Grain size ranges from fine to coarse sand (Plate 20, Photos A, B and C) with dispersed quartz grains (Plate 20, Photos A and C). Mud laminae are present. Sands are small-scale to large-scale cross-stratified or apparently structureless (Plate 20, Photos A and B). Other features include mud clasts (Plate 20, Photo A), coal or wood fragments, and rare pyrite nodules. Typically, a low degree of bitumen staining is observed when associated with a gas cap; otherwise bitumen saturation is excellent.

Basal contacts are always sharp and erosional (Plate 20, Photos A, B, and C). If the facies is not present, the erosive base is (Plate 20, Photo C). The upper contact is sharp with the sand and blue gray mud facies (F14).

Ichnology

Bioturbation is rare to absent, with rare *Planolites* associated with mud interlaminae.

Interpretation

Poorly sorted fine to coarse sand represents a transgressive lag associated with erosional shoreface retreat (Reinson, 1992). Erosive conditions are indicated by the sharp lower contact and the abundance of debris. The juxtaposition of the continental debris (mud clasts and carbonaceous material) within this unit indicates incorporation of underlying sediments.

Dispersed coarser grained quartz sand and granules may be the result of winnowing of grains or basinward transport by storms, submarine debris flows, and/or sediment gravity flows during erosional shoreface retreat (MacEachern, 1994). It is likely that both processes are responsible to some degree. Mud interlaminae indicate short lived deposition during low energy periods, which also allowed minor bioturbation to form the trace *Planolites*.

Poorly sorted fine to coarse sand represents a transgressive lag associated with erosional shoreface retreat.

F14 SAND AND BLUE GRAY MUD

Description

Sand and blue gray mud is distinctive for its robust trace fossils and color. Typical McMurray mud is pale gray, however, this facies exhibits an easily identifiable dark blue-gray color. This facies may be mud-dominated, mixed or sand-dominated. The sand typically has a very high degree of bitumen saturation. This facies comprises a coarsening-upward cycle, and may be interbedded, interlaminated or chaotic.

The sand is upper very fine- to lower fine-grained, rarely medium-grained, with rare dispersed coarse quartz grains. The sand interbeds are sharp-based and have oscillation ripple, combined flow ripple, and low angle parallel laminated intervals (Plate 21, Photos A and B). Bedding may also be commonly wavy bedded, but examples of flaser and lenticular bedding (Plate 21, Photo C) are also present. In sandy portions, the mud interbeds and laminations are commonly discontinuous, which is attributed to burrowing (Plate 21, Photo D). Mud interbeds have fine interlaminae of very fine sand to silt, or are structureless. Lithologic accessories include local carbonaceous debris.

This lithofacies has a sharp lower contact with poorly sorted fine to coarse sand (F13) and sharp upper contact with glauconitic sand and mud (F15).

Ichnology

The trace fossil assemblage of this facies shows the same low diversity as those facies found lower in the McMurray Formation, but does contain distinctive larger sized traces. The degree of burrowing is variable from absent to abundant. Robust examples of *Teichichnus*, *Thalassinoides*, *Palaeophycus*, *Arenicolites*, *Asterosoma*, and *Planolites* are common. Smaller examples of *Planolites*, *Palaeophycus*, and *Skolithos*, more typical for the McMurray Formation, are also present. Trace fossils appear to be most abundant in association with sandier portions. Chaotic texture due to abundant burrowing produces a lack of visible sedimentary structures. Unlined and sharp walled *Skolithos*, and possible *Arenicolites*, with coarser grained fill occur near the top of this facies with overlying glauconitic sand and shale (F15), producing a *Glossifungites* surface.

Interpretation

Interbedded sand and blue gray mud represents deposition within the upper offshore to shallow marine shoreface. The offshore zone lies below fair-weather wave base and above storm wave base. The lower and middle shoreface lies above fairweather and below low tide level (Figure 34). This facies is sufficiently distinct to allow correlation with previous studies, which interpreted the facies as marine in origin (Flach, 1984; Flach and Mossop, 1985; Rennie, 1987). Flach and Mossop (1985) used sedimentology, palynology, and the presence of glaucony to interpret open marine conditions for their upper McMurray 'marine unit'.

Sand interbeds result from distal storm event deposition, as supported by their sharp-based, rippled to low angle parallel laminated nature. The low angle parallel laminated sands are interpreted as HCS, or SCS. These stratification types are commonly interpreted as storm deposits (Walker and Plint, 1992; Arnott, 1993; MacEachern, 1994). Oscillation and combined flow ripple lamination represent waning flow conditions. Mud deposition occurred during low energy fair-weather conditions. The majority of bioturbation occurred under these favorable fair-weather conditions.

The trace fossil assemblage is curiously contradictory to the brackish to marine water transitional environment supported by previous facies. In this facies, higher diversity and larger forms suggest it was deposited in the fully marine realm. Trace fossils of this facies are larger than those found in underlying facies (suggesting marine conditions), yet their diversity remains low. In fact, the diversity is lower than some of the underlying facies.

The upper offshore environment of some Cretaceous shorelines is commonly burrowed by a higher diversity of forms (Pemberton *et al.*, 1992b; MacEachern and

Pemberton, 1992a). The lower diversity of forms observed in this facies may represent a stressed environment as the result of its proximity to an estuary. The lower diversity may also reflect deposition of a shoreface in a marine embayment, rather than along an open, fully marine shoreline. Reworking of the substrate by physical processes (storms) may have prevented significant colonization of the substrate.

The distinctive large, unlined and sharp-walled *Arenicolites* or *Skolithos* at the upper contact with glauconitic sand and mud (F15) represent the *Glossifungites* ichnofacies. The large burrows are excavated into firm substrates that have been exhumed (MacEachern *et al.*, 1992). The substrate is interpreted as firmground since softground substrates could not support such large unlined burrows. Exhumation was likely the result of transgressive ravinement, after which, the burrows are eventually passively filled by deposition of the overlying unit (Figure 36). MacEachern and Pemberton (1992a) reported an abundance of ichnologically demarcated transgressive surfaces of erosion (TSE) within the transgressive deposits of the Cretaceous Viking Formation.

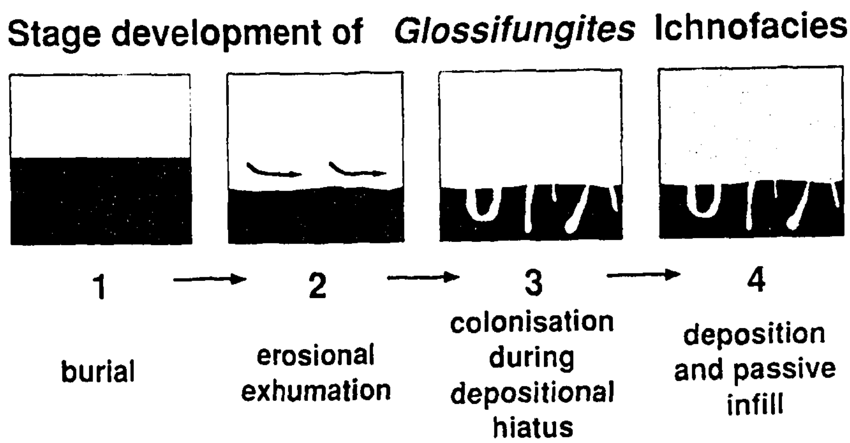


Figure 36

Schematic development of a *Glossifungites* demarcated erosional discontinuity.
1. The muddy substrate is buried and dewatered, resulting in a compacted, stiff character.
2. The bed is erosionally exhumed, resulting in development of a firm substrate.
3. Colonization of the discontinuity surface by trace makers of the *Glossifungites* ichnofacies proceeds under marine conditions during a depositional hiatus
4. The structures are passively filled during a succeeding depositional episode. (modified from MacEachern *et al.*, 1992).

Interbedded sand and blue gray mud represents deposition within upper offshore to shallow marine shoreface environments.

F15 GLAUCONITIC SAND AND MUD

Description

Glauconitic sand and mud is distinctive for the presence of pellet-forming accessory mineral glaucony. Bedding features are difficult to discern in well bioturbated sections, and the texture is best described as diffuse (Plate 22, Photo A). Where not bioturbated, bedding is predominantly composed of low angle bedding assumed to be HCS or SCS (Plate 22, Photos B and C), and possibly wave ripples. Dispersed sand grains are commonly present (Plate 22, Photos A, B and C).

Contacts with the underlying dark gray mud with sand interbeds (F14) are sharp and commonly constitute a *Glossifungites* horizon (Plate 22, Photo B). Contacts with the overlying silty shale of the Clearwater Formation are typically sharp and commonly siderite cemented.

Ichnology

The degree of burrowing varies from absent to abundant. Discrete trace fossils are difficult to discern in the abundantly bioturbation portions. Visible trace fossils include: *Planolites, Skolithos, Asterosoma, Arenicolites, Thalassinoides,* possible *Zoophycus*, and possible *Chondrites*. Glaucony appears to be concentrated within the burrows and is especially noticeable in vertical shafts of *Skolithos* and *Arenicolites*.

Interpretation

Glauconitic sand and mud represents deposition in the upper offshore environment. This first facies of the Clearwater Formation represents a portion of the

Wabiskaw Member. Sand interbeds reflect distal storm event beds. Mud deposition and burrowing occurred during fairweather conditions.

The lack of physical structures and the intensity of burrowing permit limited interpretation. However, the presence of glaucony, allows further analysis. Glaucony is a micaceous mineral (Kimberley, 1989; Ostwald and Bolton, 1992) which typically develops on the margins of continental shelves (Stonecipher, 1997). Glaucony generally occurs as widely dispersed pellets scattered throughout the host sediment. A high concentration of glaucony (15-50%) denotes winnowing and removal of the enclosing sediment, but not necessarily transport of the glaucony (Stonecipher, 1997).

Authigenic glaucony is formed under a limited range of geological and geochemical conditions, and hence it is commonly used as an indicator for transgressive sequences (Diaz *et al.*, 2001). The physical limits of glaucony include:

(1) marine waters of normal salinity,

(2) slightly reducing oxygenation conditions (at least at sites of origin),

(3) formation facilitated by the presence of organic content, which produces the reducing conditions; commonly associated with remains and fecal pellets of sediment ingesting organisms; glaucony authigenesis can occur in the intestines of the mud-eating fauna (Wright, 1968),

(4) depth: favored 10 – 400 fathoms; more current 50-500 m (Kimberley, 1989; Ostwald and Bolton, 1992),

(5) wide temperature tolerance,

(6) micaceous minerals or bottom muds of high iron content for source materials, and

(7) low sediment influx (Cloud, 1955).

The associated siderite cement with this facies is diagenetic in nature. Siderite precipitates either under fresh water reducing conditions or post-oxic marine conditions in sediments where the available iron content exceeds the amount of sulfate entrained in depositional pore waters. The occurrence of siderite nodules or beds is an indication of the amount of iron and the permeability of the sediment, not depositional environment (Stonecipher, 1997).

Glauconitic sand and mud represents deposition in the upper offshore environment.

SUMMARY

F1: Large-scale cross-stratified sand is deposited as a result of dune migration in channels.

F2: Apparently structureless sand and mud clast breccia resulted from collapse of channel banks along the cut-bank margins of meandering channels. These breccias form part of the normal processes of cutbank-point bar erosion and migration associated with meandering channel flow.

F3: Small-scale cross-stratification develops as a result of ripple migration under waning flow conditions across larger channel bedforms on the channel floor or on point bar surfaces of channels.

F4: IHS represents lateral accretion deposits associated with tidally influenced point bars of a meandering estuarine channel.

F5: Gray mud is interpreted as abandonment of a channel meander loop.

F6: Flat lying, thinly interbedded sand and mud represents deposition within intertidal flats flanking estuarine channels and point bar complexes.

F7: White to light gray mud is interpreted as floodplain deposits.

F8: Dark gray to black carbonaceous mud is interpreted as marsh deposits likely associated with interchannel topographic lows.

F9: Coal is deposited in a flood basin adjacent to a channel with influxes of saline water from overbank flow or from coastal flooding related to storm surges.

F10: Chaotic, interbedded sand and silty mud is interpreted as crevasse splay deposits adjacent to a channel.

F11: Interbedded sand and mud with gastropods formed within an areally-restricted setting, such as a bay or sound, transitional between the estuarine regime of the middle McMurray and the marginal marine (shoal/shoreface) regime of the upper McMurray.

F12: Laminated to interbedded sand and mud with variable bioturbation is interpreted as shallow marine sand bodies within the shoreface.

F13: Poorly sorted fine to coarse sand represents a transgressive lag associated with erosional shoreface retreat.

F14: Interbedded sand and blue gray mud represents deposition within upper offshore to shallow marine shoreface environments.

F15: Glauconitic sand and mud represents deposition in the upper offshore environment.

Bagdan, 2005 (current study)	Fox, 1988	Yuill, 1995	Bechtel, 1996
F1 Large-scale cross-stratified sand	Large-scale cross-stratified sand	F6 Large-scale cross-stratified sand	F1 Large-scale cross-stratified sand
F2 Apparently structureless sand and mud clast breccia	Structureless sand	F3 Structureless Sand	F1 subfacies mud intraclasts breccia
F3 Small-scale cross-stratified sand	Small-scale cross-stratified sand	F5 Small-scale cross-stratified sand	F2 Small-scale cross-stratified sand
F4 Inclined heterolithic stratification	N/A	F9 Interbedded sand and mud	F3 Sand-dominated inclined heterolithic stratification; F4 Mud-dominated inclined heterolithic stratification
F5 Gray mud	N/A	1c Gray structureless mudstone	F5 Grey mud
F6 Flat lying, thinly interbedded sand and mud	Interbedded sand and mud	F4 Flat to low angle planar stratified sand	F6 Flat lying, thinly interbedded sand and mud
F7 White to light gray mud	Structureless white to grey carbonaceous mud	1a Massive white to light gray mudstone	F7 Massive white to light grey mud
F8 Dark gray to black carbonaceous mud	Flat to low angle laminated white to grey carbonaceous mud	1b Dark gray to black carbonaceous mudstone	F8 Dark grey carbonaceous mud
F9 Coal	N/A	F2 Coal	F9 Coal
F10 Chaotic, interbedded sand and silty mud	N/A	N/A	F10 Chaotic, interbedded sand and silty mud; F11 Siltstone
F11 Interbedded sand and mud with gastropods	N/A	N/A	N/A
F12 Laminated to interbedded sand and mud with variable bioturbation F12a Laminated to burrowed sand F12b Well burrowed sand F12c Interbedded sand and mud	Heavily bioturbated muddy sand	F7 Heavily bioturbated Sand	F12 Laminated to burrowed sand; F13 Well burrowed sand; F14 Well burrowed interbedded sand and mud
F13 Poorly sorted fine to coarse sand	N/A	N/A	F15 Poorly sorted fine to coarse sand
F14 Sand and blue gray mud	N/A	N/A	F16 Interbedded sand and dark grey mud; F17 Fine grained sand with dark grey mud; F18 Chaotically bedded sand with dark grey mud; F19 Dark grey mud with sand interbeds
F15 Glauconitic sand and mud	N/A	N/A	F20 Well burrowed glauconitic sand mud

Table 1.
Comparison between facies of the current study and those of previous researchers.

Plate 2

Photos from F1: Large-scale cross-stratified sand

A. Large-scale tabular cross-stratification with sharp truncation between sets which dip in opposite directions. AA/12-02-095-07W4 (190.7 m)

B. Large-scale cross-stratification with tangential bedding and escape structures (fugichnia). AA/13-35-095-07W4 (153.1 m)

C. Cross-strata are differentiated by different grain size and resultant colour change due to variable bitumen saturations. AA/03-36-095-07W4 (192 m)

D. Pebbles and granules are so abundant that they can properly be termed conglomerates. AL/01-26-095-10W4 (53.2 m)

Plate 2

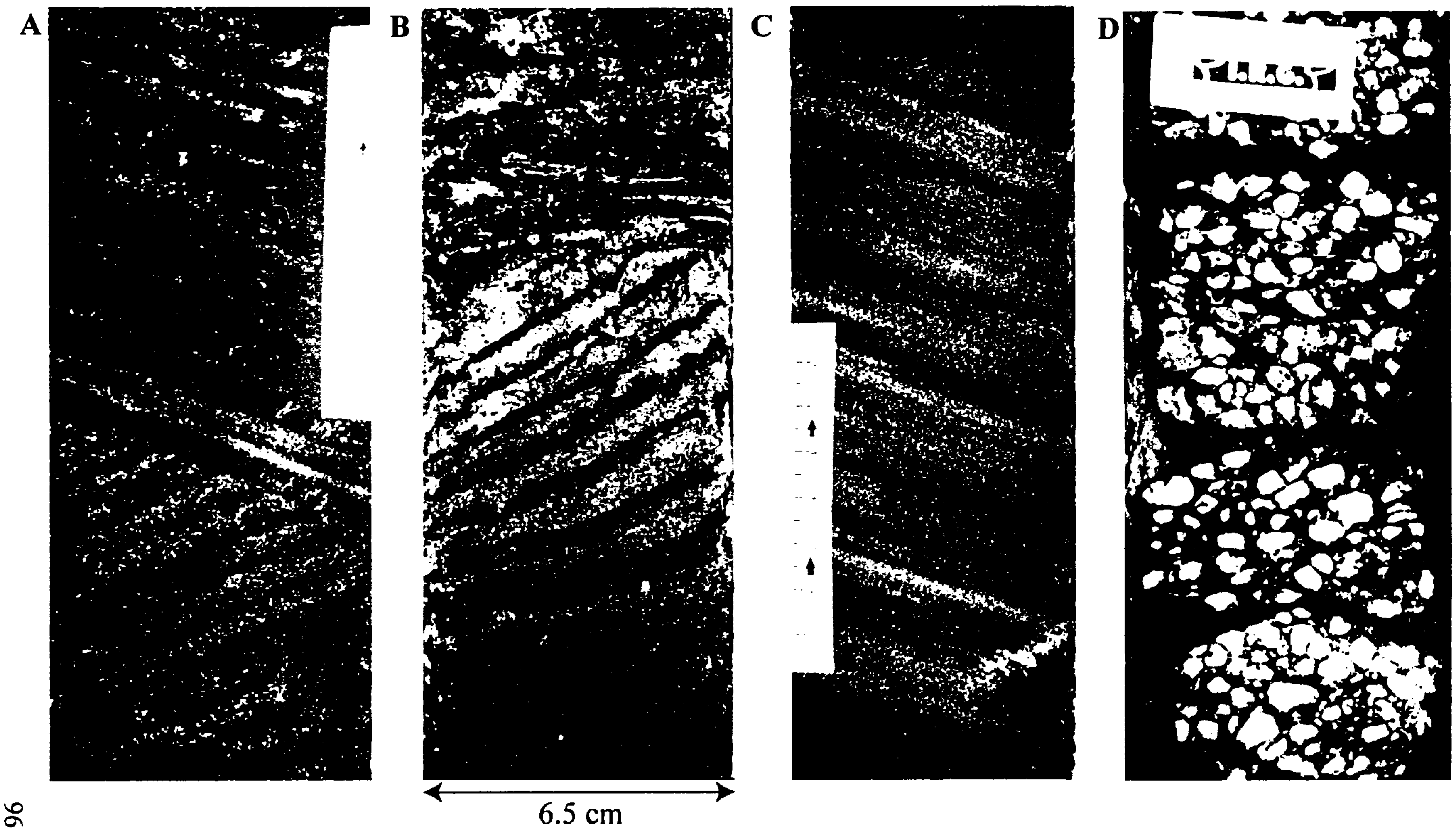


Plate 3

Photos from F2: Structureless sand and mud clast breccia.

A. Structureless sand with exceptional hydrocarbon saturation and no apparent physical or biological features. AE/02-26-095-07W4 (56.75 m)

B. Mud clast breccia with sub-angular clasts of flat to low-angle laminated light gray mud and interbedded sand. Matrix shows abundant dispersed pebbles. AA/11-23-095-07W4 (208.2 m)

C. Clast exceeding the width of the core (approximately 35 cm in length). This clast is likely a slump block, evidenced by faulting and rotational movement. AE/04-25-095-10W4 (39.1 m)

D. Possible log, greater than 15 cm long and exceeds the width of the core. Wood grain is clearly visible (inset). AF/02-26-095-10W4 (47.9 m)

Plate 3

A B C D

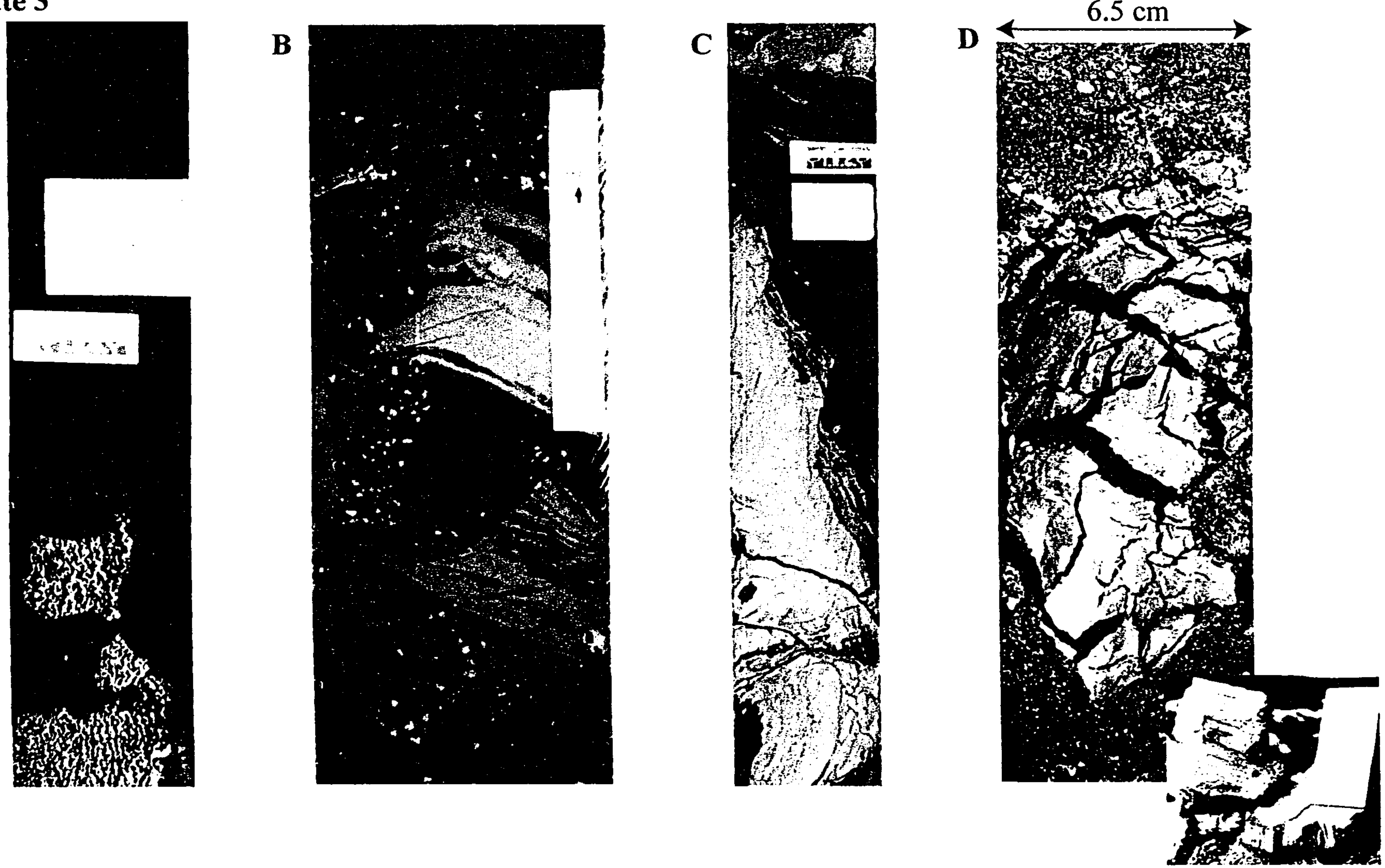


Plate 4

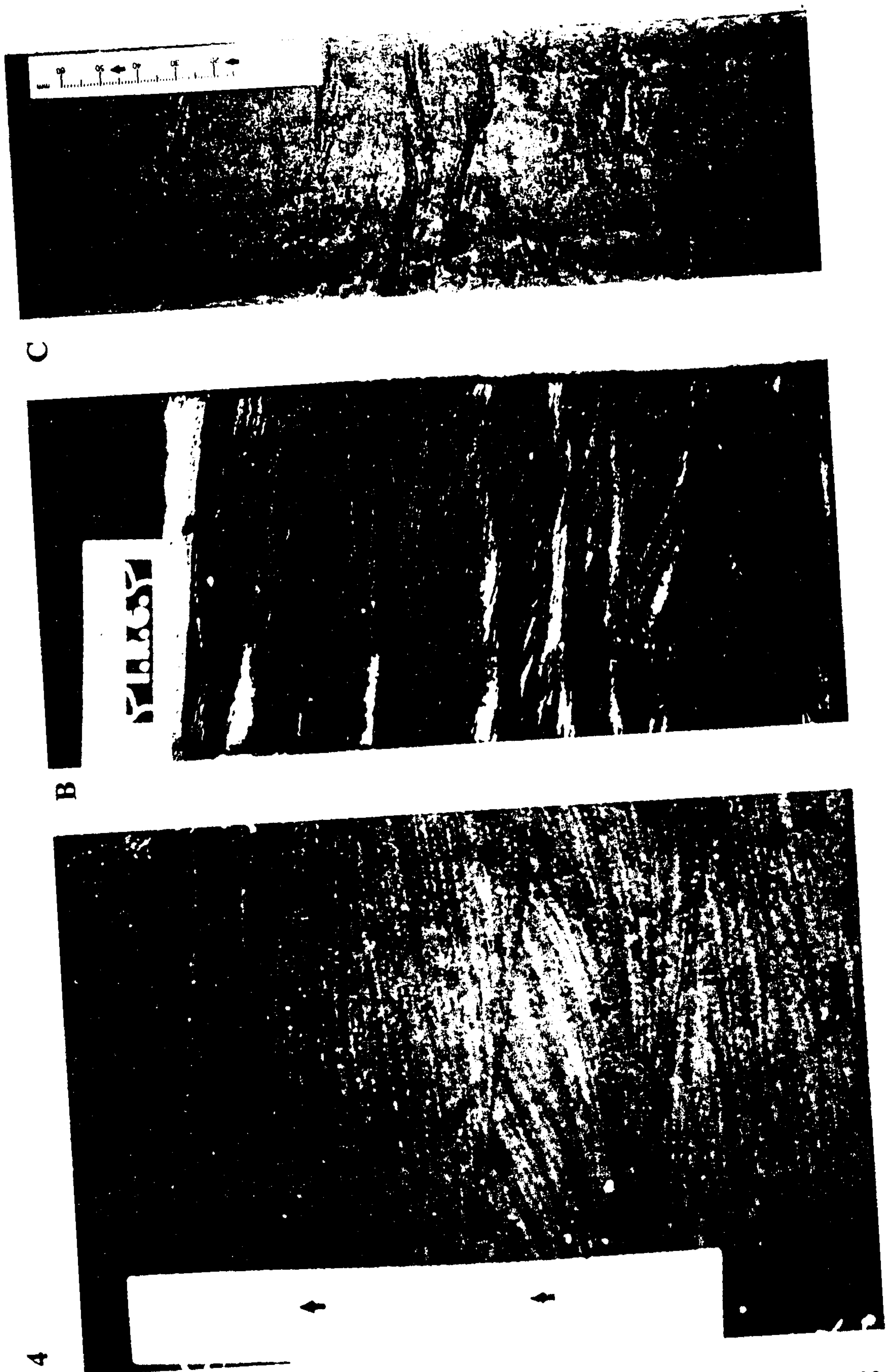
Photos from F3: Small-scale cross-stratified sand

A. Cross-sets are less than 5 cm in thickness. Both bounding surfaces are typically clearly visible in core. AA/01-34-095-07W4 (118.2m)

B. Mud drapes in small-scale cross-stratified sand ranging 1 to 5 mm thick are preferentially cemented with siderite (unknown location from Albian Sands lease).

C. Small-scale cross-stratified sand with examples of flaser to wavy bedding. A mix of carbonaceous debris and shale comprise the mud component in this gas saturated sand. AA/12-02-095-07W4 (179.75m)

Plate 4



A

B

C

Plate 5

Photos from F4: Inclined heterolithic stratification (IHS).

A. Sand-dominated IHS with decreasing sand bed size and increasing mud bed size. AE/02-26-095-10W4 (cores 22-24)

B. Mud-dominated IHS with decreasing sand bed size and increasing mud bed size. Monospecific *Gyrolithes* Type II (less robust) subtend from mud layers through sand layers. AE/02-26-095-10W4 (cores 4-5)

C. Enlargement of monospecific *Gyrolithes* Type II (less robust) subtend from mud layers through sand layers. AE/02-26-095-10W4 (box 5)

Plate 5

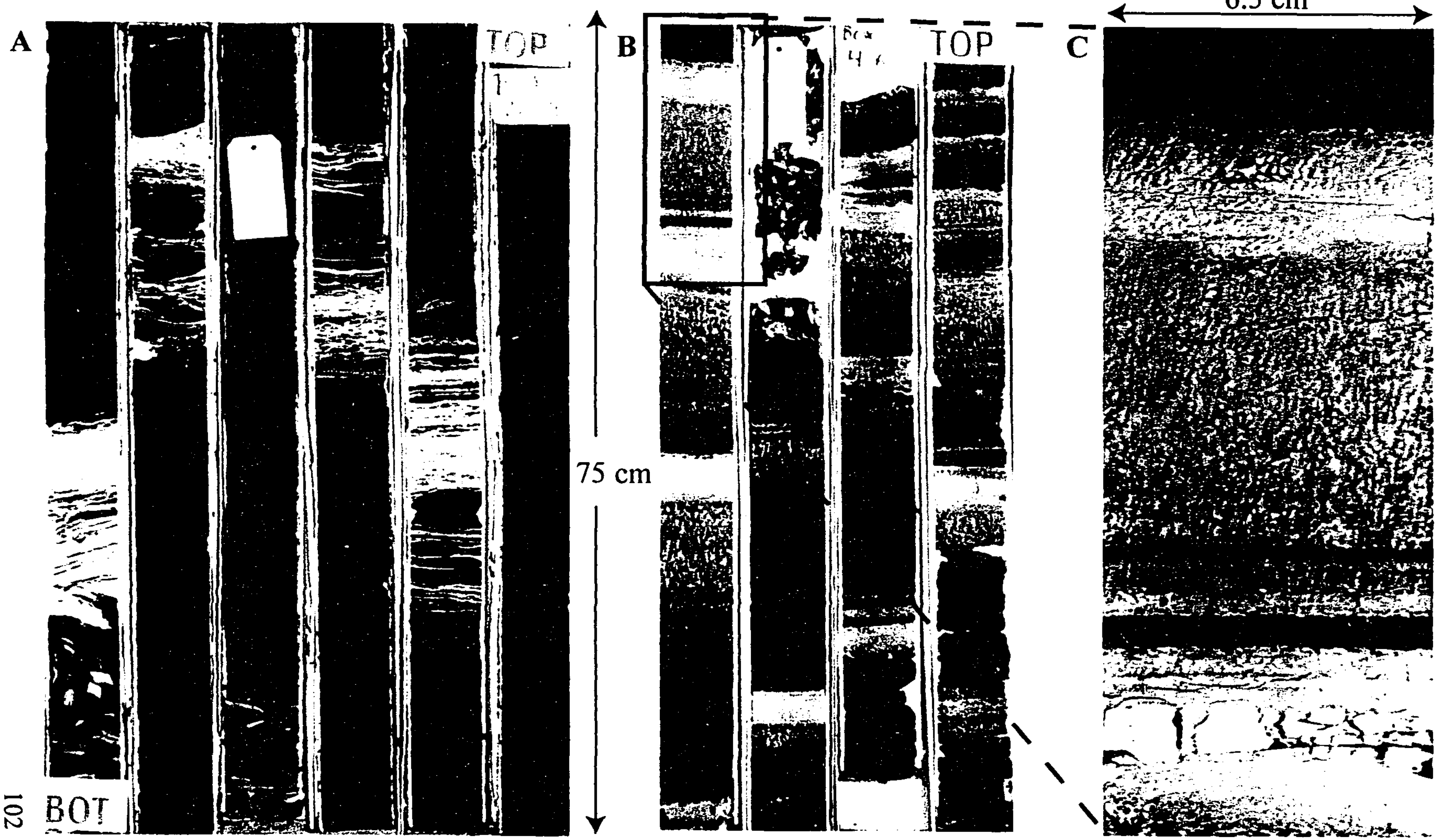


Plate 6

Photos from F4: Inclined heterolithic stratification (IHS).

A. Monospecific *Gyrolithes* Type I (more robust) subtend from mud layers through sandy layers. AD/14-23-095-10W4 (16.85 m)

B. IHS bed sets with angular clasts in the sand. Mud exposed during low water levels, consolidates and desiccates. Subsequent flood conditions erode and transport the mud clasts. AA/12-18-095-07W4 (108.7 m)

Plate 6

6.5 cm

A

B

Plate 7

Photos from F5: Gray mud

A. Core box photo of gray mud demonstrating the thickness and lack of variability within the facies. AA/16-22-0954-07W4 (160.1 – 164.8 m)

B. Gray mud is light to dark gray colour and lacks sedimentary or biogenic structures. AA/11-23-095-07W4 (174.0 m)

C. Pyrite discolours mud with greenish-brown alteration halos. AA/11-23-095-07W4 (174.5 m)

D. A unique example of a septarian nodule observed within this facies. AK/01-26-095-10W4 (63.55 m)

Plate 7

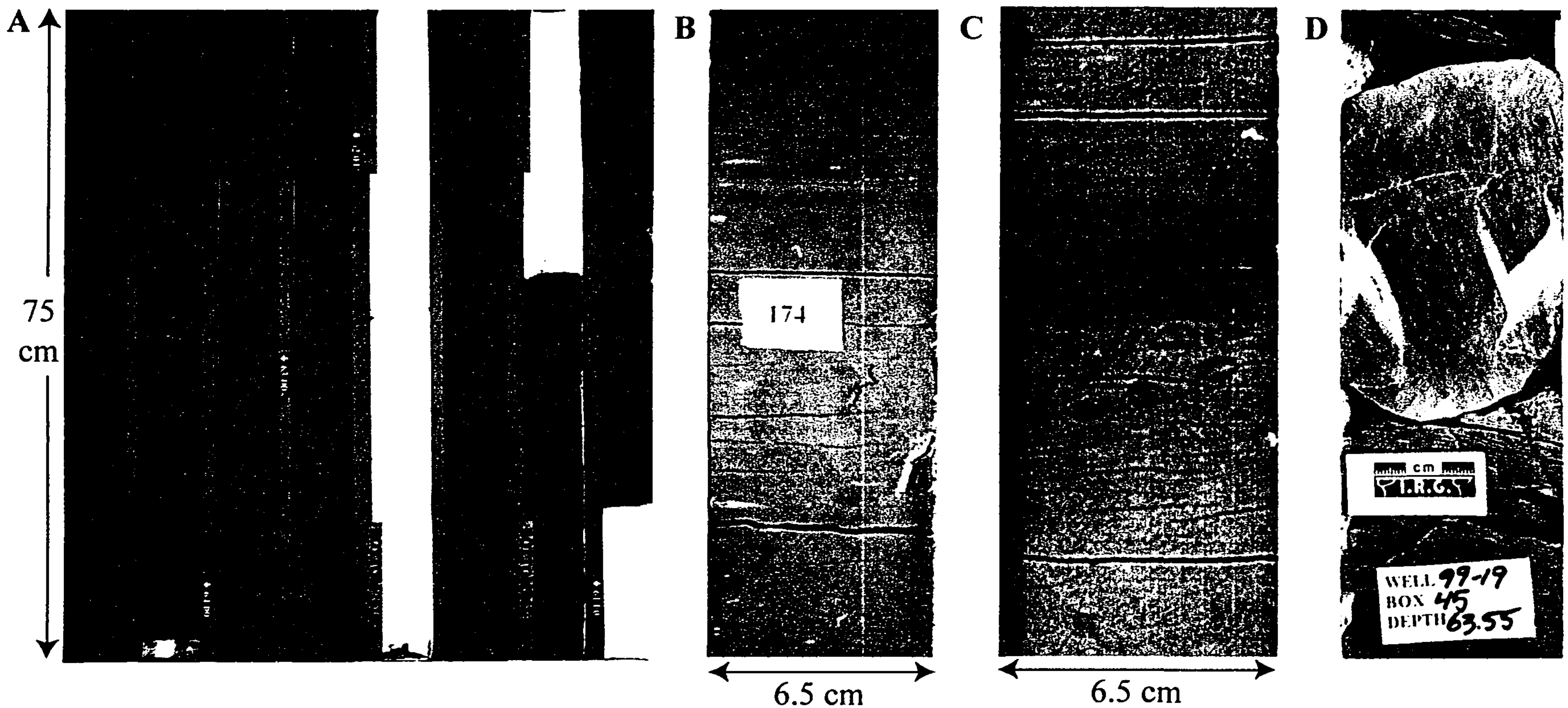


Plate 8

Photos from F6: Flat lying, thinly interbedded sand and mud

A. Regular alternation of thin interbeds of sand and mud where burrowing is rare. Ripples and wavy bedding are common with coal fragments forming a large component of the muddy portion. AA/03-28-095-07W4 (135.5 m)

B. Regular alternation of thin interbeds of sand and mud where burrowing is more common; example of *Teichichnus* and *Planolites*. Wavy bedding and ripple lamination are dominant sedimentary structure. AA/14-20-095-07W4 (100.3 m)

C. Interlaminated sand and mud displaying 'tidal bedding'. Microfault is likely due to the coring process. AA/02-07-095-07W4 (139.1 m)

D. Trace fossils are diminutive, with an example of *Conichnus*. AA/01-32-095-07W4 (150.0 m)

E. *Cylindrichnus* may constitute small *Rosselia* in some instances. AA/ 03-13-095-07W4 (201.5 m)

Plate 8

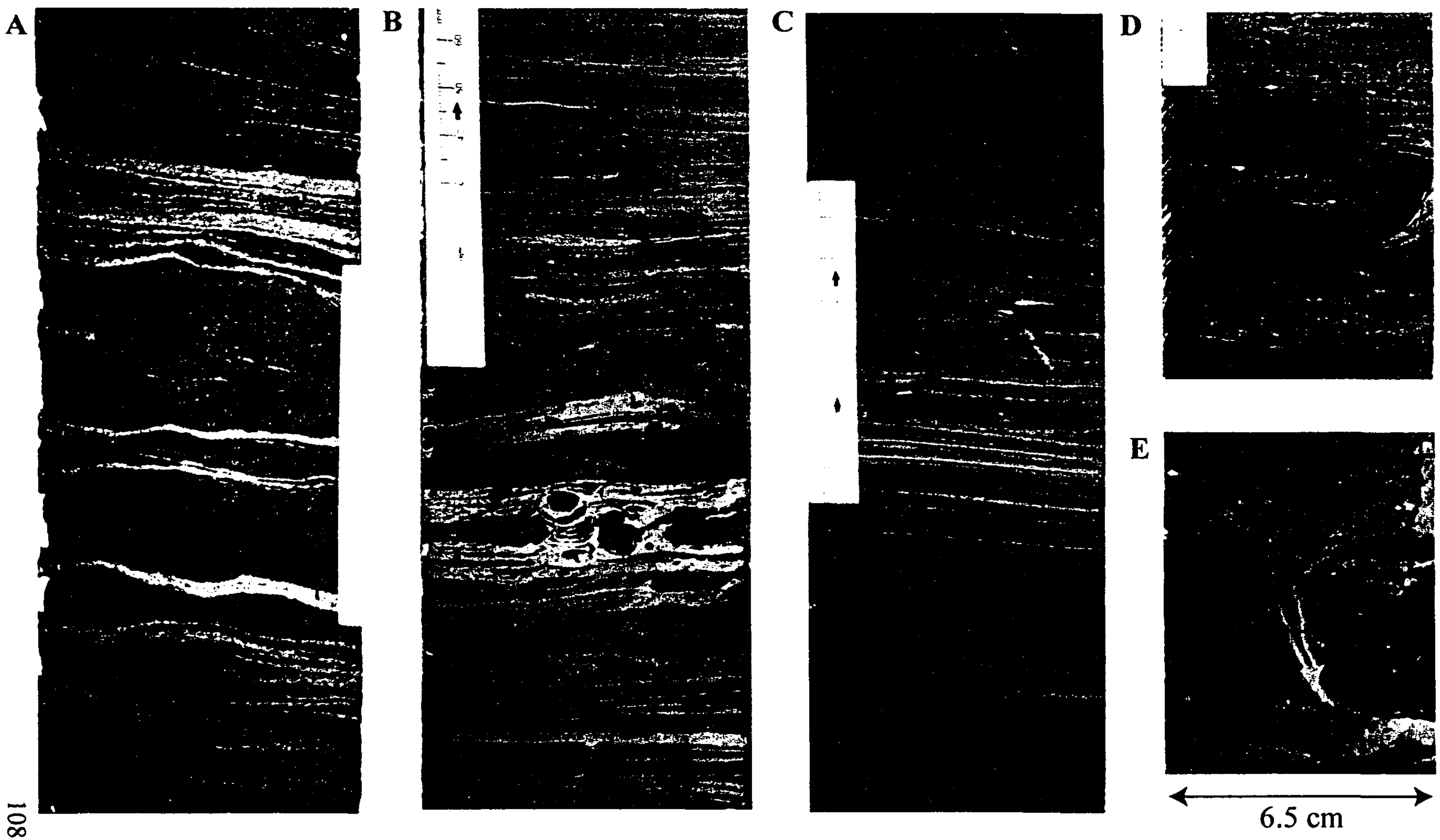


Plate 9

Photos from F7: White to light gray mud

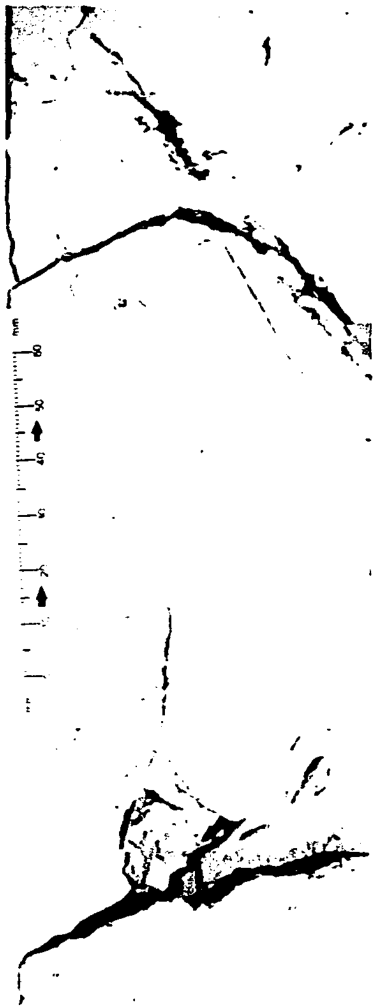
A. White to light gray mud is apparently structureless. Phytoturbation is evident and filled carbonaceous material. AA/03-25-095-07W4 (230.1 m)

B. Laminated white to light gray mud with abundance of rooting disrupting lamination. The upper contact is gradational with coal. AA/01-19-095-07W4 (111.0 m)

C. White to light gray mud with smectite lens and erosive upper contact with dark gray to black carbonaceous mud. AE/16-23-095-10W4 (61.6 m) Note: scale bar is upside down.

Plate 9

A



B

C

Plate 10

Photos from F8: Dark gray to black carbonaceous mud

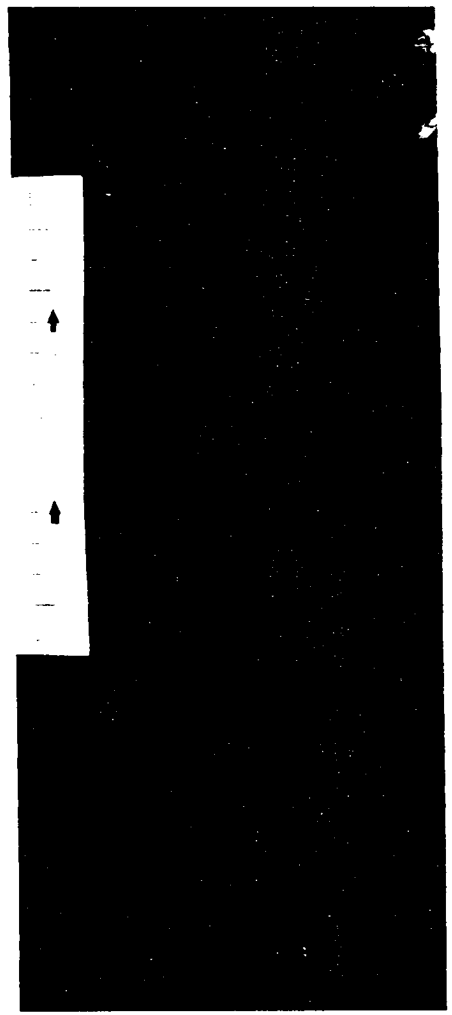
A. The high organic content is responsible for the dark gray to black color. AA/02-07-095-07W4 (134.8 m)

B. Dark gray to black carbonaceous mud with sand and silt laminae and organics present as carbonaceous debris, wood fragments, and coaly fragments. AD/02-26-095-10W4 (57.9 m)

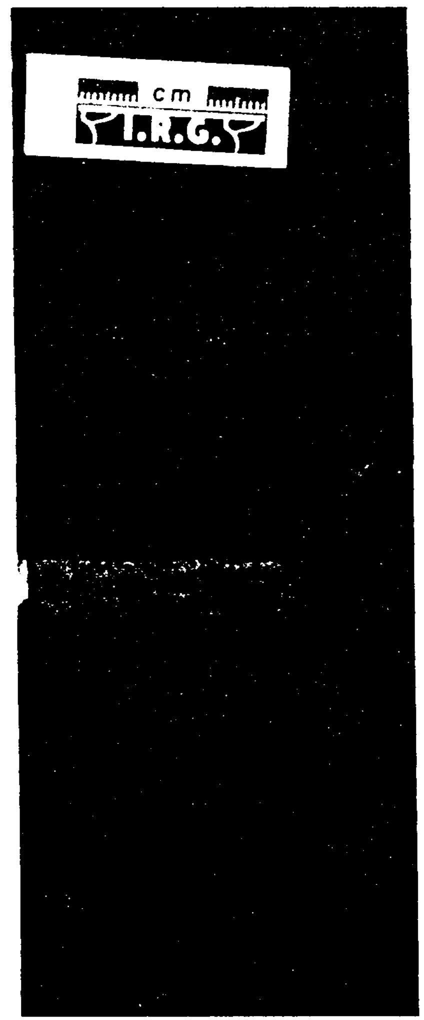
C. Silty sand laminations/beds that approximate IHS bedding, interpreted as a small channel in the marsh. AC/07-26-095-10W4 (55.4 m)

Plate 10

A



B



C

Plate 11

Photos from F9: Coal

A. Mud clasts within coal. AA/09-23-095-07W4 (220.8 m)

B. Carbonaceous debris in coal. AA/06-21-095-07W4 (174.5 m)

C. Pyrite nodules in coal and sharp erosive upper contact. AA/07-20-095-07W4 (176.0 m)

D. Sand dykes in coal. AA/14-21-095-07W4 (177.6 m)

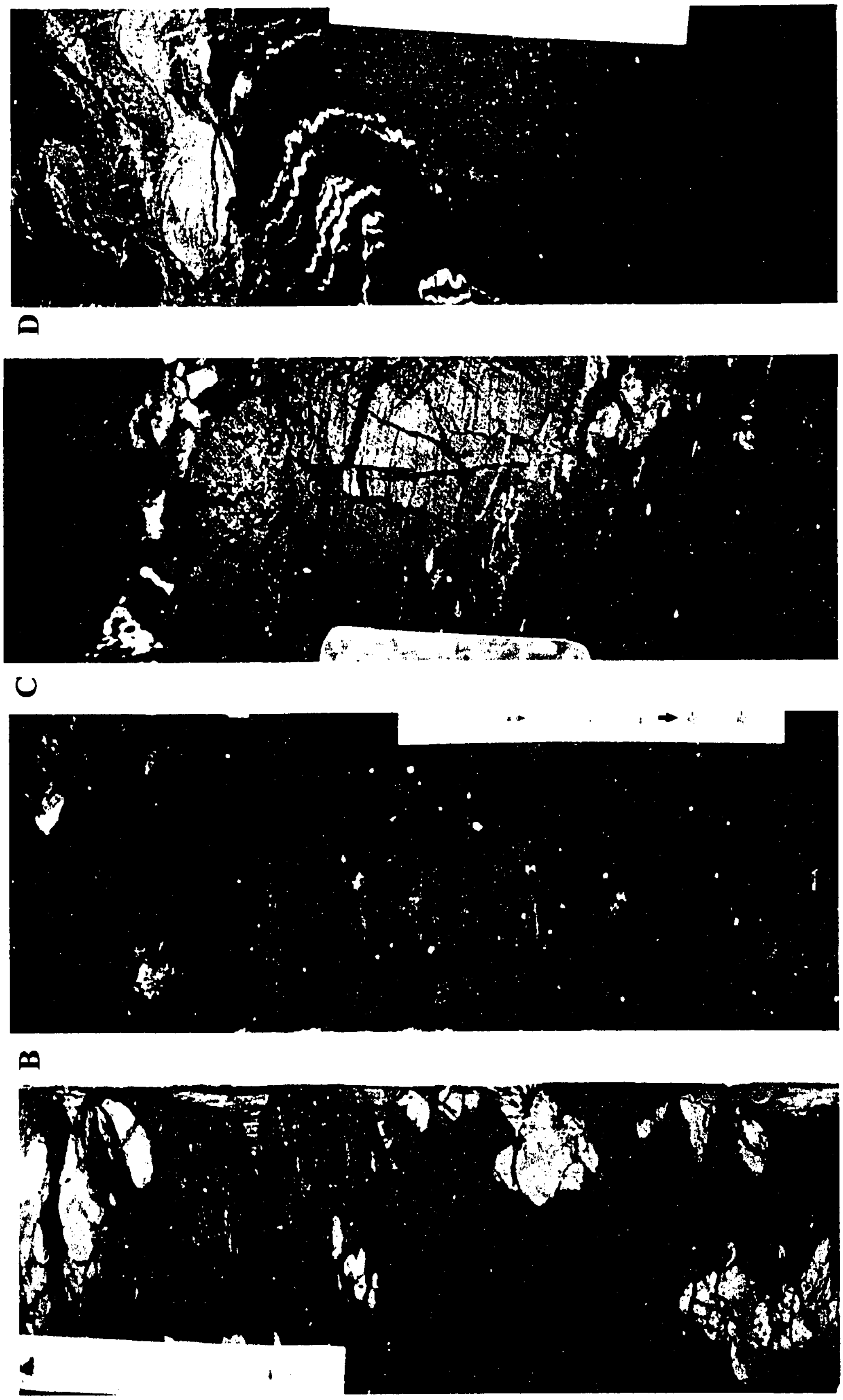


Plate 11

Plate 12

Photos from F9: Intercalated sand and mud beds within coal

A. Intercalated shaly sand within coal accentuating bioturbated texture and large bodied trace fossil with patterned fill. AA/02-14-095-07W4 (230.1 m)

B. Carbonaceous shale with bioturbate texture and large bodied trace fossil. AA/10-20-095-07W4 (166.0 m)

C. Laminated sand and shale with large bodied *Teichichnus* exhibiting poorly defined spreite. AE/16-23-095-10W4 (69.4 m)

D. Bioturbate texture and two notable *Teichichnus* with both protrusive and retrusive spreite, indicating different directions of movement. AD/16-23-095-10W4 (52.3 m)

Plate 12

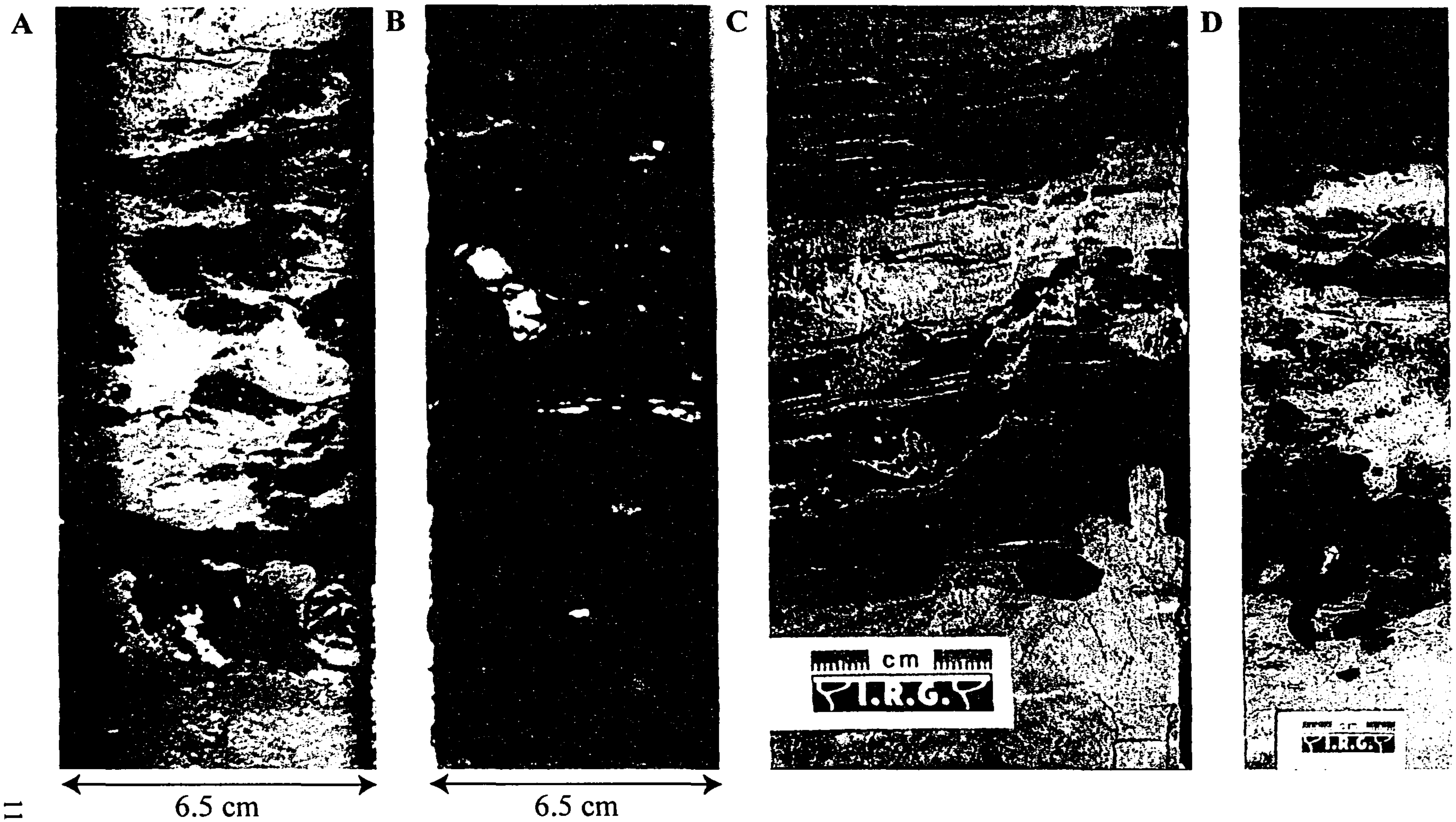


Plate 13

Photos from F10: Chaotic, interbedded sand and silty mud

A. Chaotic, interbedded sand and silty mud with abundant carbonaceous debris and poor bitumen saturation due to sorting. AL/01-26-095-10W4 (58.8 m)

B. Chaotic, interbedded sand and silty mud with abundant carbonaceous debris and poor bitumen saturation due to sorting. Residual lamination is visible in top of photo. AD/03-26-095-10W4 (53.6 m)

C. Silty clay with convolute lamination. This example was likely deposited more distally than sandy examples. AH/01-26-095-10W4 (Box 49)

D. Chaotic and laminated bedding with fair hydrocarbon saturation. Carbonaceous debris is common. AL/01-26-095-10W4 (53.6 m)

Plate 13

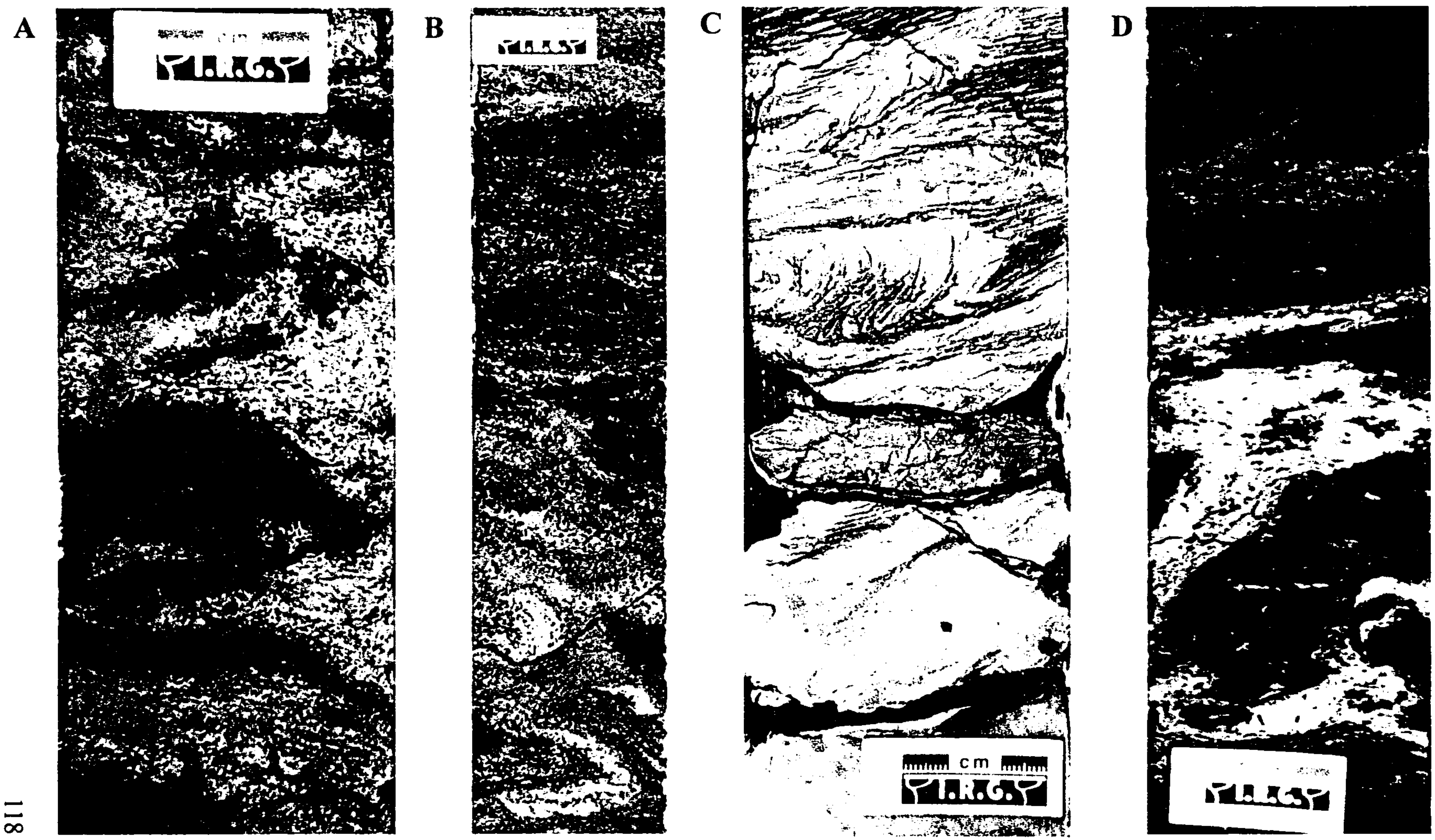


Plate 14

Photos from F11: Interbedded sand and mud with gastropods

A. Unfragmented gastropod lag with apparently structureless bedding. AA/16-11-095-07W4 (193.25 m)

B. Sand with large dark mud clast containing gastropods and bioturbated shaly sand. AA/10-05-095-07W4 (167.3 m)

C. Gastropods in bioturbated shaly sand. AA/16-11-095-07W4 (188.25 m)

D. Gastropods in chaotically bedded sand associated with large fragments of carbonaceous debris. AA/16-04-095-07W4 (195.75 m)

Plate 14

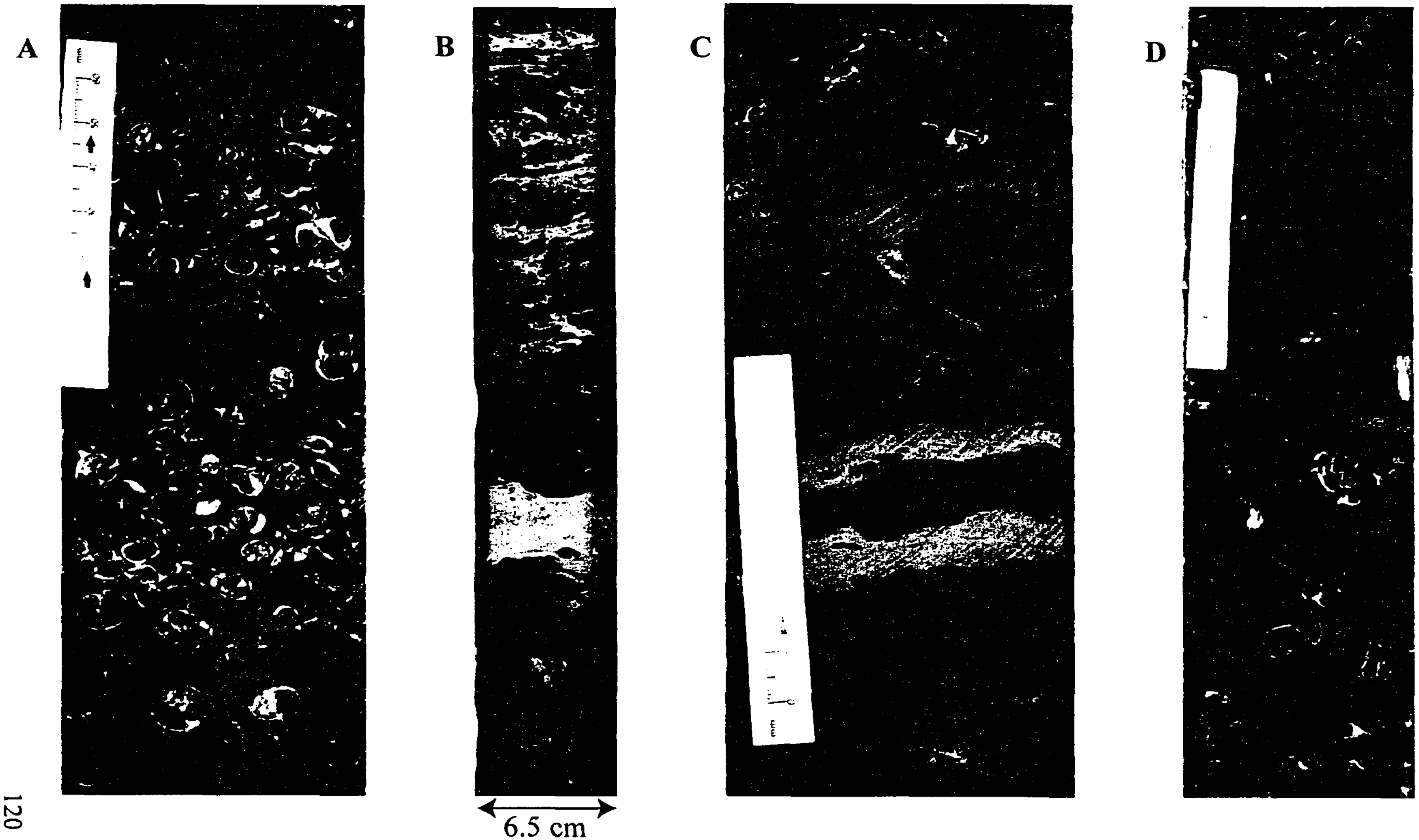


Plate 15

Mollusca of the McMurray Formation (from Russell, 1932):

Unio biornatus (Russell, 1932)

(1) Left lateral view of holotype

Murraia naiadiformis (Russell, 1932)

(2) External view of left valve, holotype

(3) Internal view of same

(4) Internal view of right valve, holotype

Viviparus murraiensis (Russell, 1932)

(5) Dorsal view of holotype

(6) Ventral view of same

Lioplacodes bituminis (Russell, 1932)

(7) Dorsal view of holotype

(8) Ventral view of same

Goniobasis? multicarinata (Russell, 1932)

(9) Ventral view of holotype

Melampus multorbis (Russell, 1932)

(10) Dorsal view, restoration, based on numerous imperfect specimens

Melania athabascensis (Russell, 1932)

(11) Dorsal view of holotype

(12) Ventral view of same

Plate 15

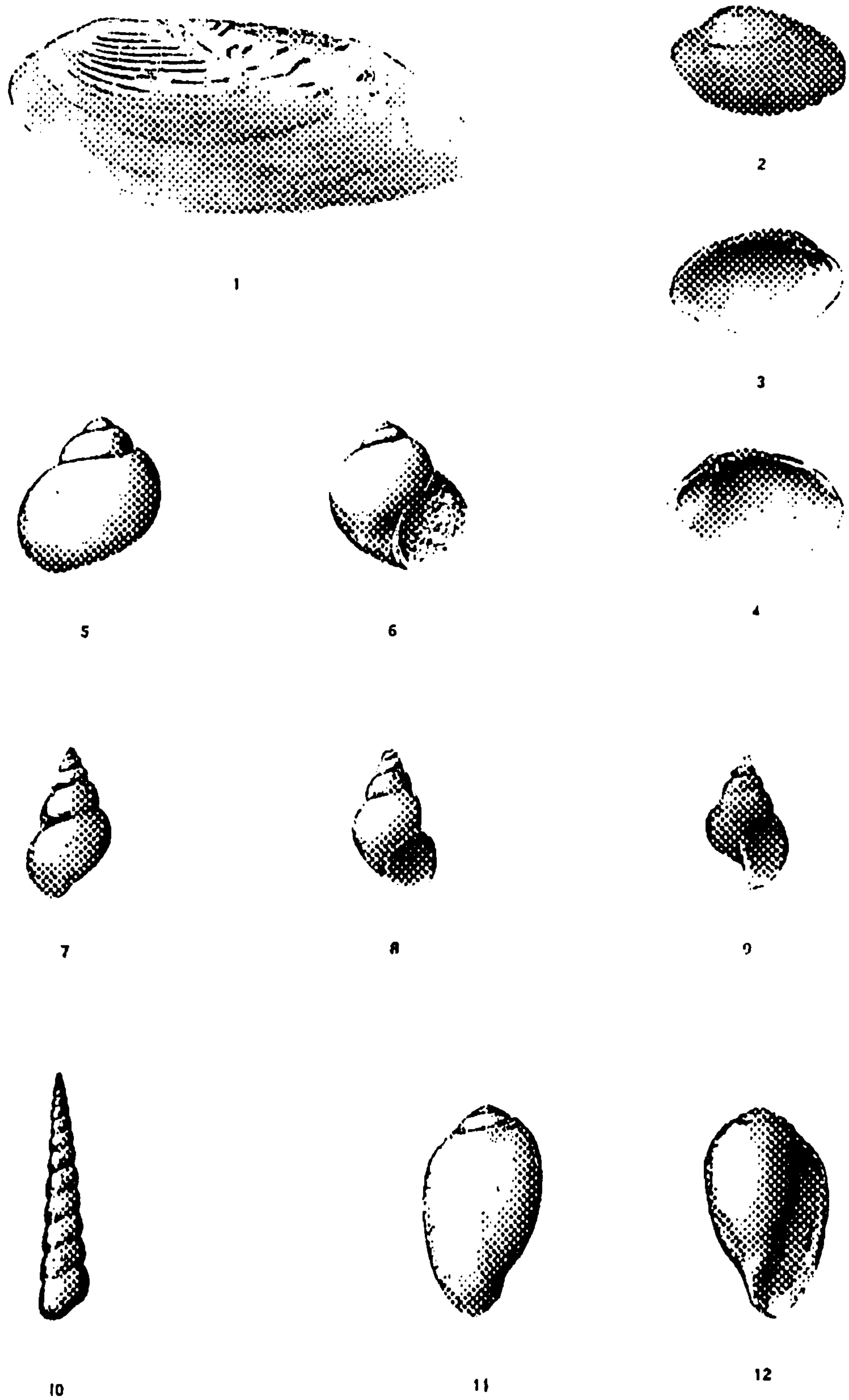


Plate 16
Sketches from C. Stelck (personal communication, 2004)

A
Viviparus murraiensis
AA/12-05-095-07W4 (170.8 m)

B
Melania multorbis
AA/05-10-095-07W4 (177.1 m)

C1
Lioplacodes bituminis
basal view specimen exhibited 68 growth lines
longitudinal lines not apparent
AA/10-02-095-07W4 (168.8 m)

C2.
Lioplacodes bituminis
Specimen had good ornament
AA/10-02-095-07w4 (168.9 m)

D
Melampus athabascensis
Identification based on posterior sinus ornament
AA/12-05-095-07W4 (170.8m)

E1
Goniobasis multicarinata
good lineal lines, at least 32 cross lines less common
AA/05-10-095-07W4 (177.0 m)

E2
Goniobasis multicarinata
Good lineal ornament.
AA/05-10-095-07W4 (177.0 m)

Plate 16

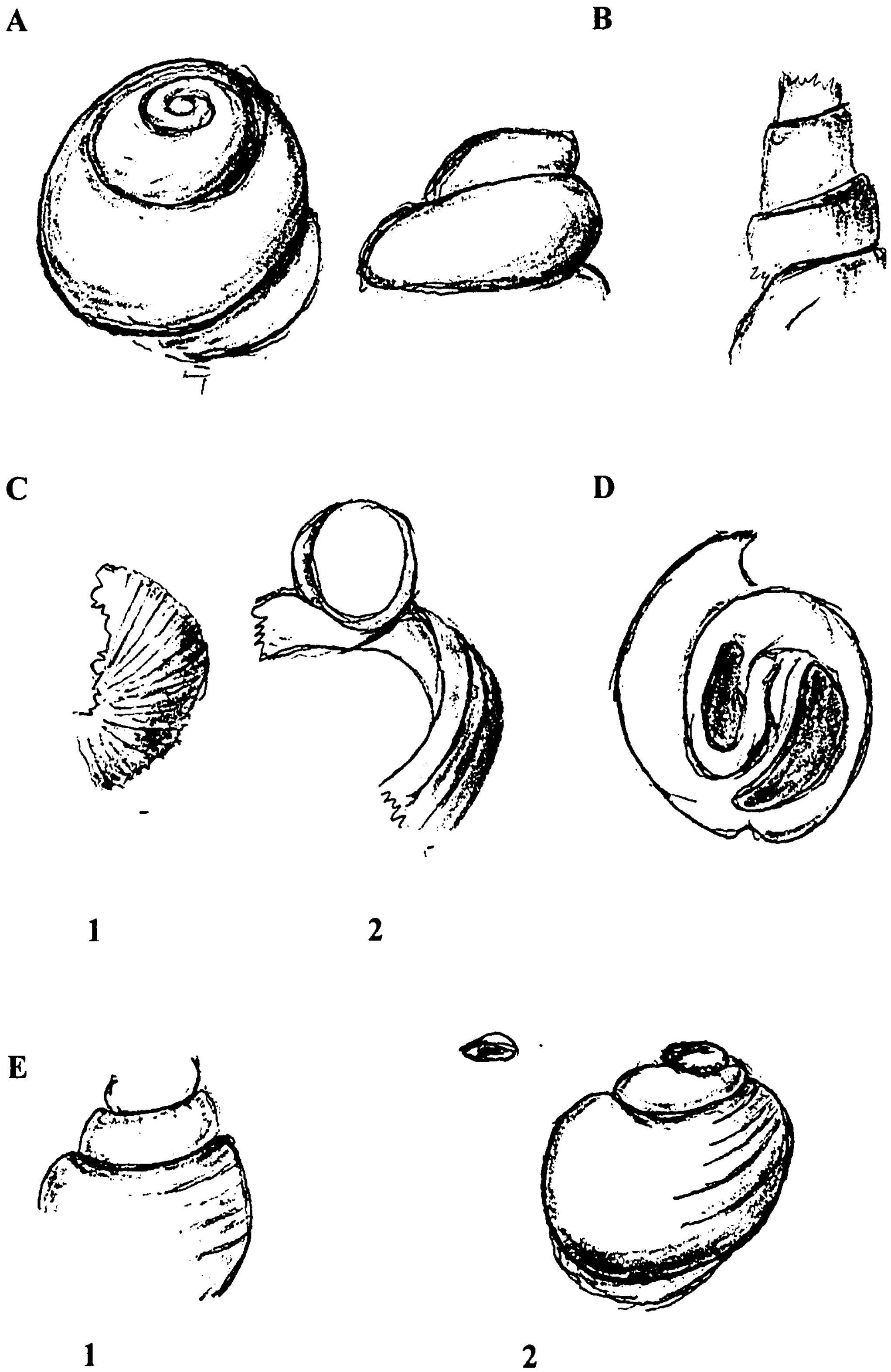


Plate 17

Photos from F12a subfacies: Laminated to burrowed sand

A. Laminated sand and mud with sharp based sand bed. Lowermost laminations display wavy bedding with a diminutive trace fossil association. The sand bed is trough cross bedded with escape traces (fugichnia). The upper laminated bed has a greater abundance of stressed trace fossils with a possible *Conichnus.* AA/11-05-095-07W4 (155.3 m)

B. Wavy to lenticular bedded sand and mud. The uppermost, sharp based sand is erosive with a rip up clast. Most common trace fossil is *Planolites.* AA/11-05-095-07W4 (160.6 m)

C. Laminated to burrowed sand exhibiting an erosive contact with coal. Upper beds are planar laminated. Bioturbation increases upwards toward the mud beds. AA/06-21-094-06W4 (268.0 m)

D. Upper contact of laminated sand with well burrowed sand is sharp. Sand is ripple laminated and sand dykes or sand-filled synaeresis cracks are evident. AA/06-21-094-06W4 (267.7 m)

Plate 17

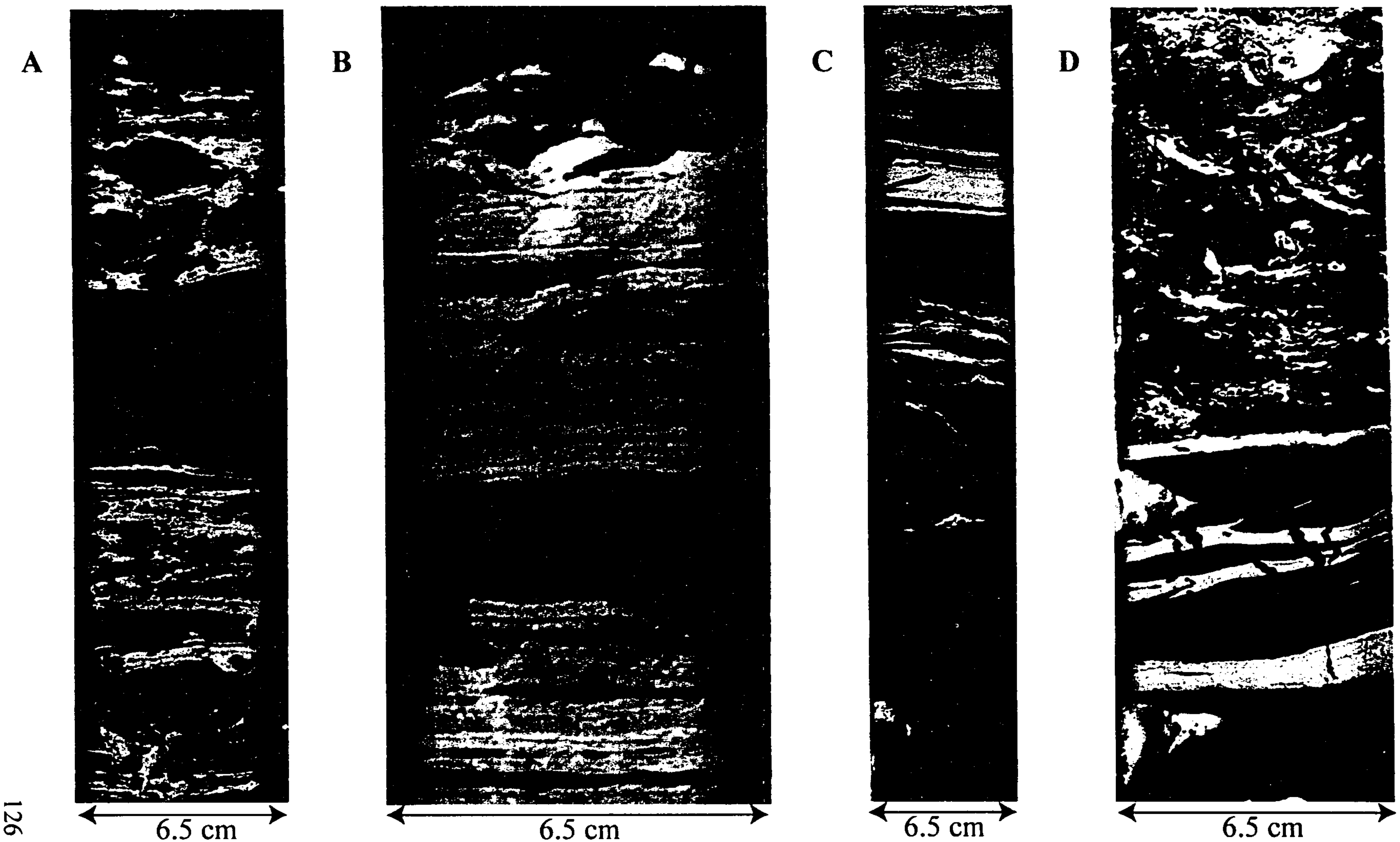


Plate 18

Photos from F12b subfacies: Well burrowed sand

A. Bioturbation is so intense that sand and mud beds are thoroughly mixed and individual burrows are difficult to discern. AA/12-05-095-07W4 (149.0 m)

B. Bioturbation typically subtends from mud lamination, although the individual laminations are not always clear. AA/12-07-095-07W4 (195.0 m)

C. Highly bioturbated sand beds with ripple cross-laminated unburrowed sand. AA/16-22-095-07W4 (154.3 m)

D. Mud drapes appear to be discontinuous across width of core. The main cause of this discontinuity is bioturbation. AA/04-10-095-07W4 (167.0 m)

Plate 18

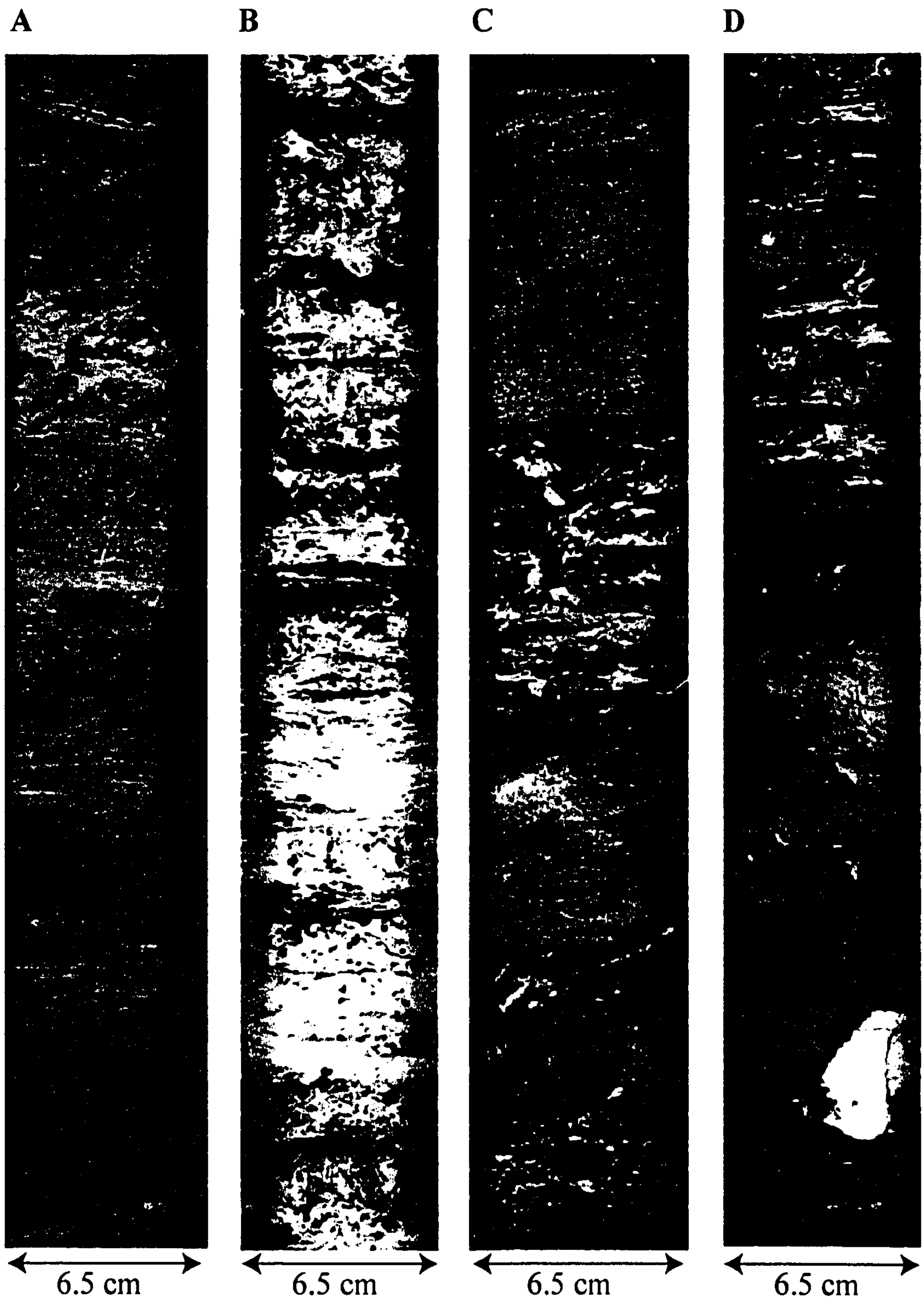


Plate 19

Photos from F12c subfacies: Interbedded sand and mud

A. Medium-scale interbedded sand and mud; gradational lower contact with well burrowed sand is evident. AA/11-05-095-07W4 (144.0 - 146.4 m)

B. This facies lacks the inclined nature of IHS (F4) and the interbed thickness is greater than flat-lying, thinly interbedded sand and mud (F4). Sand beds are commonly ripple laminated. AA/12-05-095-07W4 (144.0 - 145.5 m)

C. Example of this facies represented solely by bitumen saturated sand. AA/01-35-094-07W4 (209.1 – 211.4 m)

Plate 19

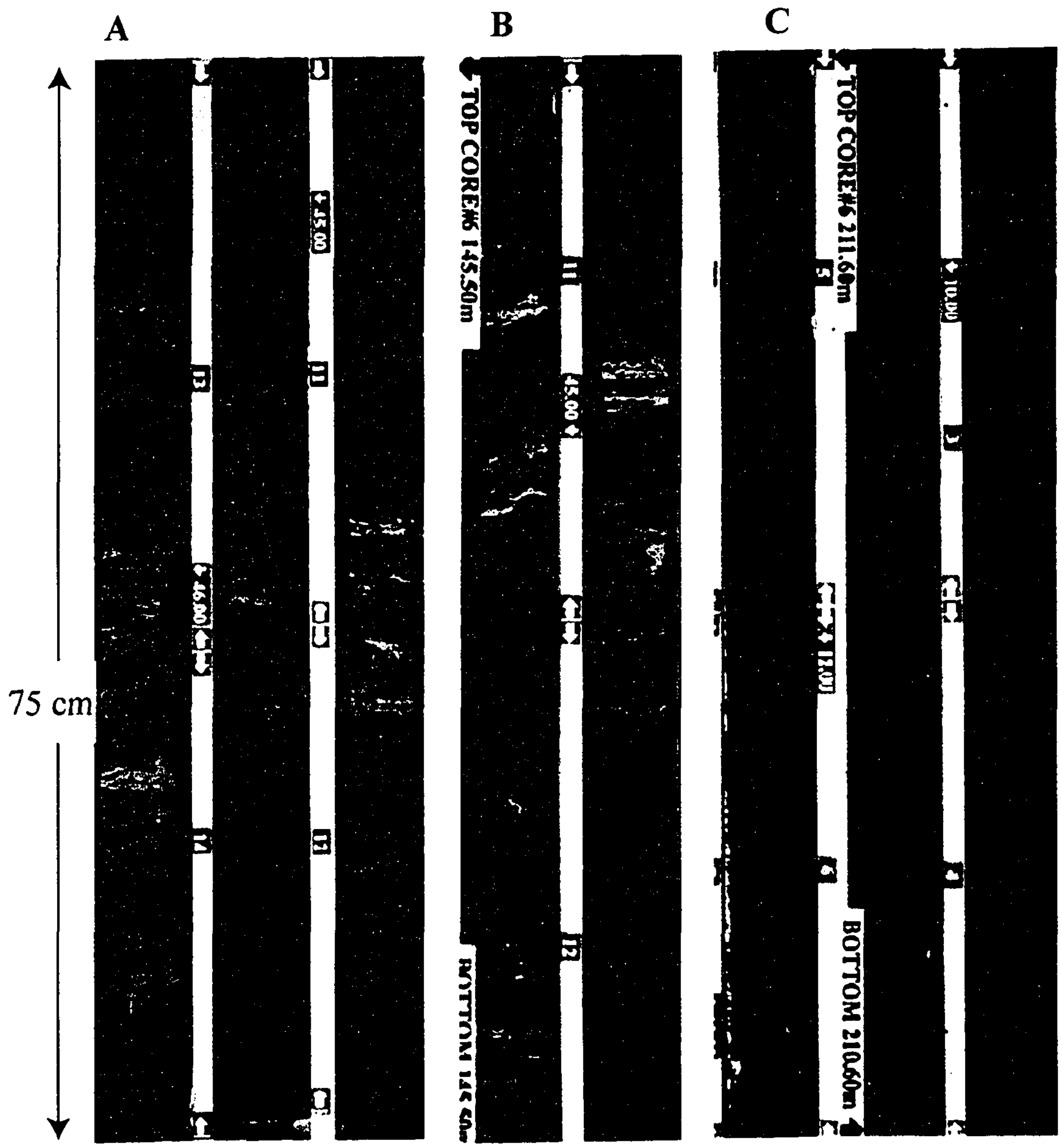


Plate 20

Photos from F13: Poorly sorted fine to coarse sand

A. Poorly sorted fine to coarse sand with quartz pebbles, and mud clasts. AA/06-21-094-06W4 (265.2 m)

B. Medium-grained well saturated sand with erosional base. AA/07-20-095-07W4 (112.6 m)

C. Where the poorly sorted fine to coarse sand is not present, the erosional base is, as indicated by the quartz grain lag. AA/14-19-094-06W4 (233.8 m)

Plate 20

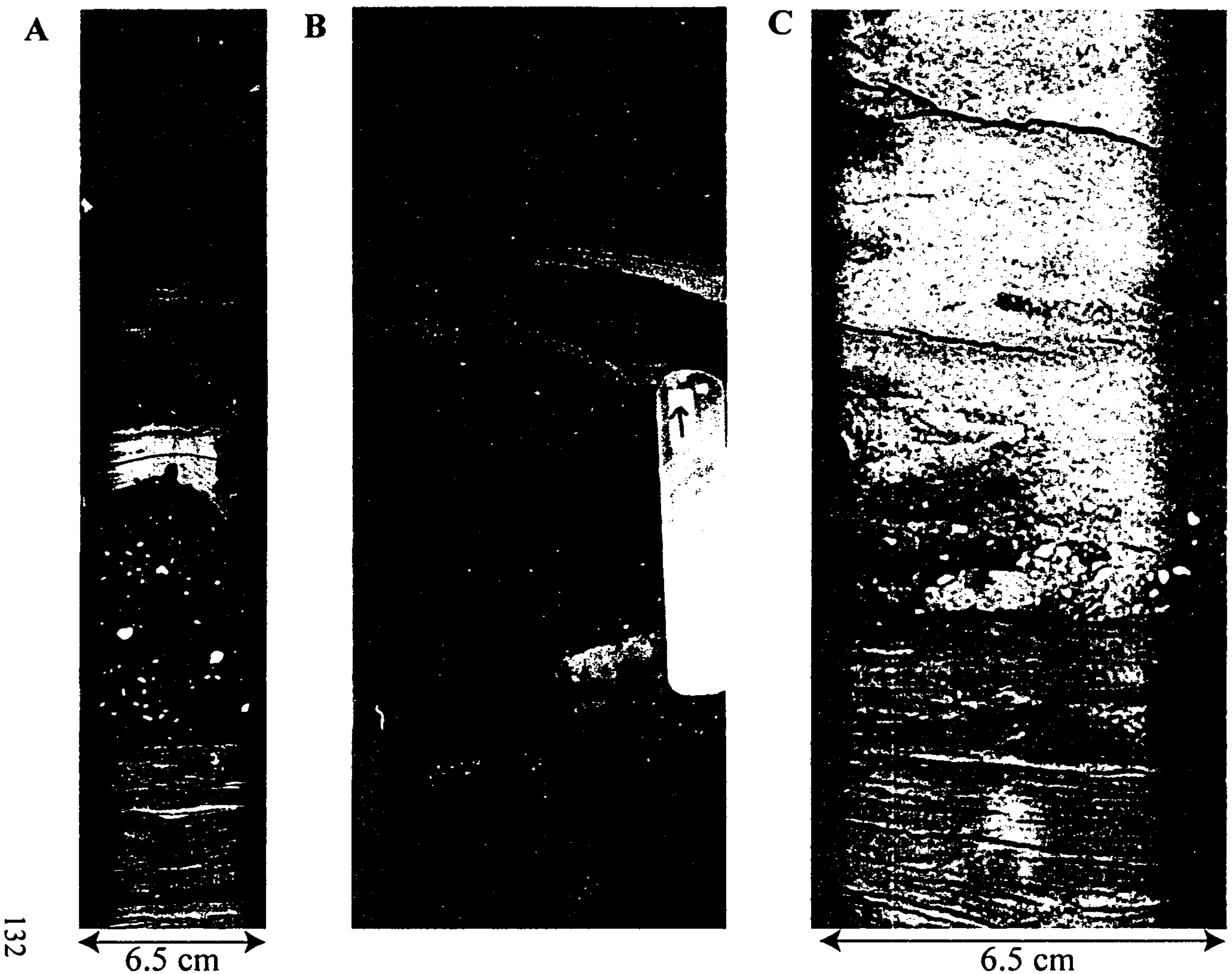


Plate 21

Photos from F14; Sand and blue gray mud

A. Combined flow ripple lamination. AA/12-07-095-07W4 (86.4 m)

B. Erosive sand base, low angle parallel laminated intervals. AA/12-07-095-07W4 (89.6 m)

C. Thick succession of lenticular bedding AA/6-21-094-06W4 (265.1 – 265.6 m)

D. Mud interbeds and laminations are often discontinuous; attributed to burrowing. AA/5-18-095-07W4 (110.2 – 110.6 m)

Plate 21

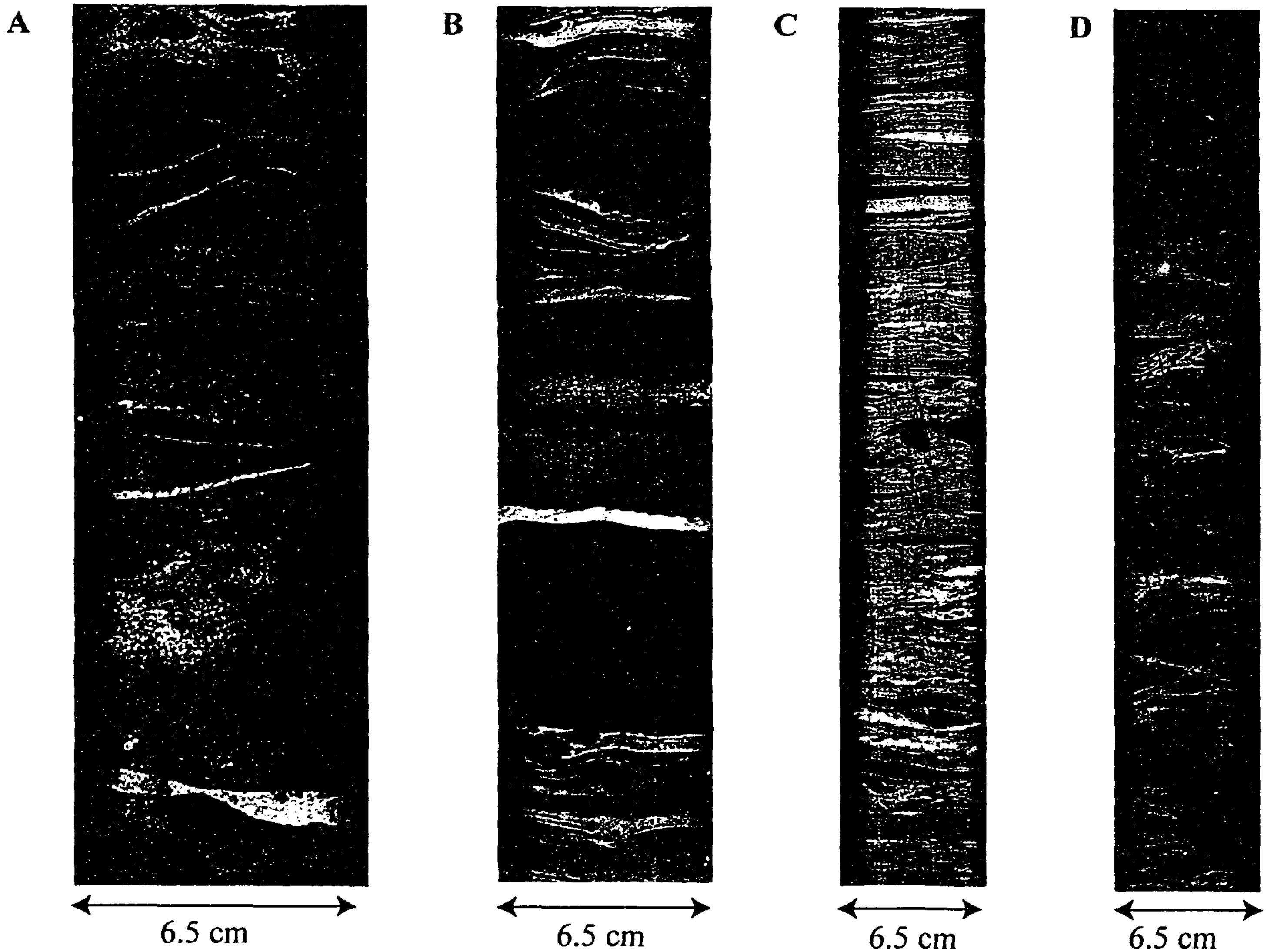


Plate 22

Photos from F15: Glauconitic sand and mud

A. Diffuse bioturbated texture of green glauconitic sand and mud. AA/07-20-095-07W4 (112.3 m)

B. *Glossifungites* horizon at the lowermost contact. Quartz pebbles are present as a lag. Bedding above this represents HCS or SCS. AA/13-36-095-07W4 (137.8 m)

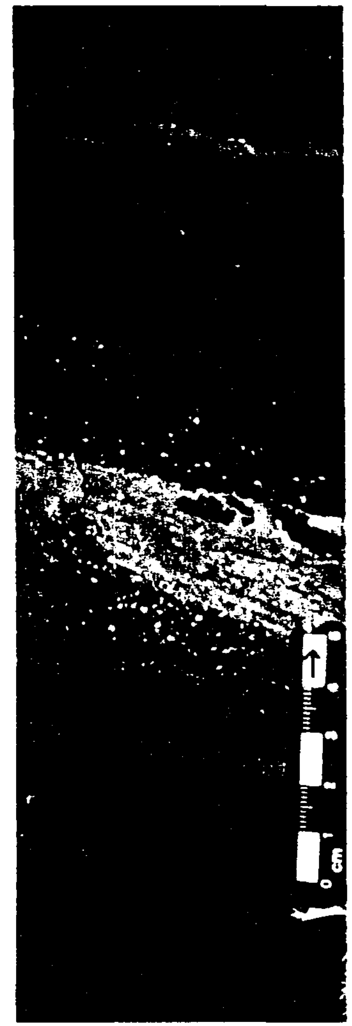
C. Stratified sands representing a storm bed. AA/06-02-095-07W4 (178.4 m)

Plate 22

A

B

C



CHAPTER 3
ICHNOLOGY AND STRATIGRAPHIC SIGNIFICANCE OF THE COAL-BEARING UNIT OF THE MCMURRAY FORMATION

INTRODUCTION

In northeast Athabasca, it has become a rule-of-thumb for the petroleum industry to place the stratigraphic break between lower member McMurray fluvial deposits and middle McMurray estuarine deposits at the top of an extensive and regionally correlateable coal-bearing interval. The coals are typically of low quality with variable sand content. This dominantly muddy suite of facies includes paleosols and organic mud, although coarse-grained sand lenses and channels are also commonly observed within this unit. Application of ichnology and sedimentology provide considerable evidence indicating that this coal unit and the immediately underlying unit are probably not part of the lower McMurray member as traditionally defined, but rather are genetic units of the middle McMurray.

Lateral accretion deposits underlying the coal-bearing unit incorporate a brackish ichnological signature. The same holds true for the muddy facies of the coal-bearing unit itself, which indicates that the unit was in close proximity to an estuarine shoreline. Sand and shale lenses within the coal-bearing unit are interpreted as brackish splays.

The stratigraphic arrangement of the depositional systems within the lower portion of the McMurray Formation is complex. Although the coal-bearing unit is an important stratigraphic marker, and no doubt has sequence stratigraphic significance, its employment as a simple marker for the separation of continental and marginal marine deposits is erroneous. The 'true' lower to middle McMurray contact occurs below this coal-bearing unit.

INDUSTRY RULE-OF-THUMB

The McMurray Formation is subdivided into three informal units (Carrigy, 1959a). The lower McMurray is commonly described as continental deposits overlying the sub-Cretaceous unconformity and capped by coal. The middle McMurray overlies the coal and extends upwards to where a marine ichnofossil assemblage is recognized. It encompasses sediments that have a diminutive brackish water ichnofossil assemblage, thus, are marginal marine in origin. The upper McMurray extends from the base of the marine ichnofossil assemblage to the base of the Clearwater, and is defined as marine in origin. This succession assumes that the deposit is transgressive, representing one cycle of relative sea level change from continental to marginal marine to marine facies changes (Figure 37).

In general, the sequence stratigraphic boundaries include the sequence boundary separating the McMurray succession from the Devonian succession, and a flooding surface separating the McMurray succession from the Clearwater succession. This places the low stand systems tract between the sequence boundary and the top of the coal. It represents high topography and the filling of lows by continental sediments. The shoreface is some distance away. The transgressive systems tract extends from the top of the coal to the base of the marine succession. This represents nearshore deposition by a combination of fluvial and marine sourced sediments as sea level rises. The highstand system tract exists above this and represents flooding of the area by the sea (Figure 37).

DEFINITION OF THE COAL-BEARING UNIT

The McMurray coal-bearing unit (F8 and F9) varies from organic rich gray shale to a "true coal" or lignite. During peat formation, incorporated sediments include: mud clasts, quartz grains, and carbonaceous debris. During compaction, sand dikes may form. Later, diagenetic fluid may produce pyrite. This unit is extremely variable in appearance (see facies description F8 and F9, chapter 2).

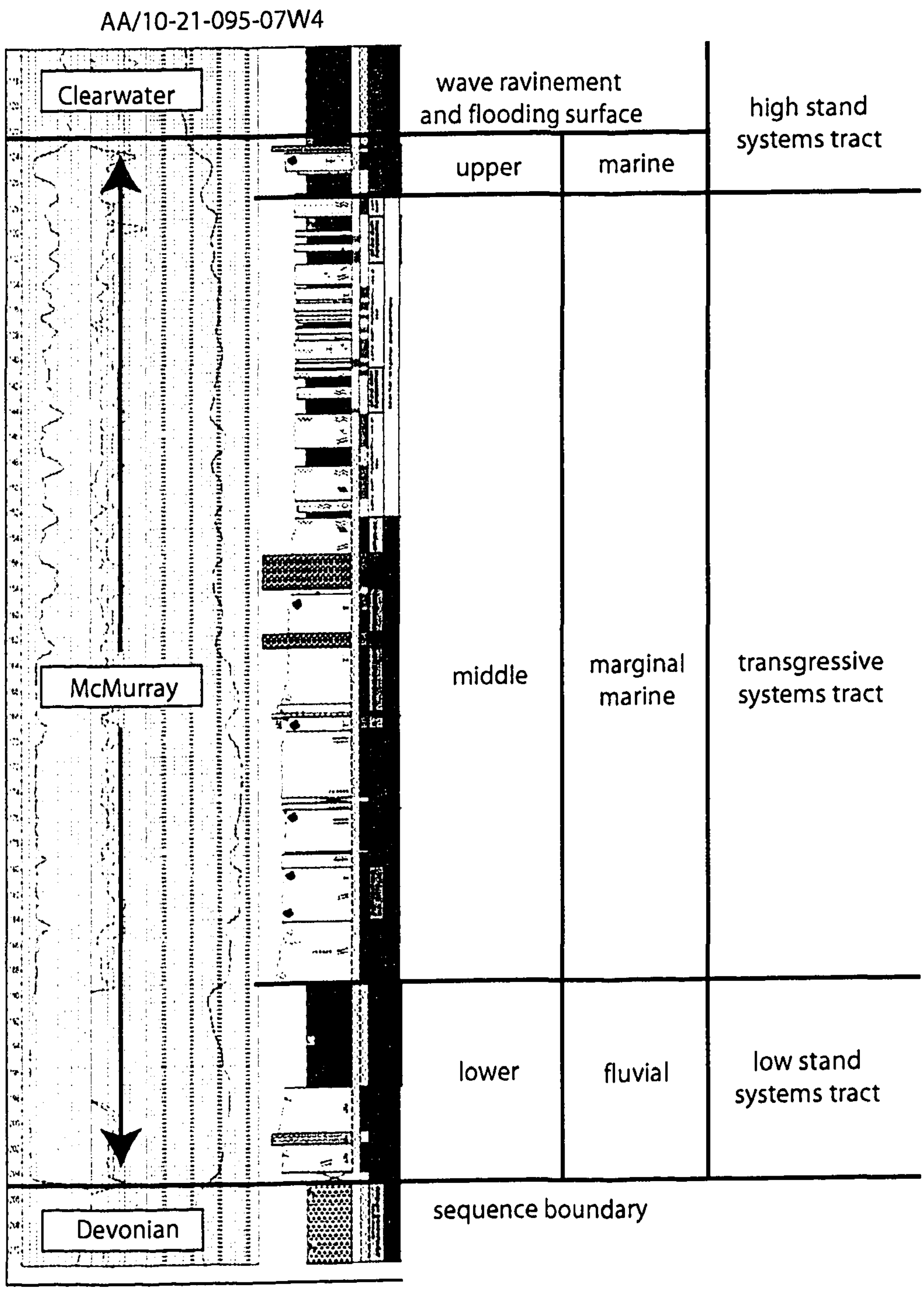


Figure 37

The industry rule-of-thumb places the division between the lower and middle members at the top of the coal or erosive equivalent. This classification describes all the sediments below the coal as continental in origin.

CREVASSES WITHIN THE COAL

Sand beds, commonly found within the coal, are interpreted as brackish splay deposits. The genesis of these sand beds is a three stage process, from normal flow to flood flow and the re-establishment of normal flow conditions. Initially during normal flow conditions, peat accumulates in the flood basin near a channel (Figure 29A). During high flow conditions, crevasse channels bring clastics into the marsh (Figure 29B). With the return to normal flow conditions and the abandonment of the crevasses system, the marsh is re-established with the continued accumulation of peat (Figure 29C). A coal-sand/mud-coal package is common (Plate 23).

The crevasses are significant as the sands and muds within the coal are bioturbated. The bioturbaters are commonly large-bodied, and the ichnofossil assemblage is one of low diversity with *Teichichnus* dominant (Plate 12, Photos A, B, C, and D). These trace fossils are interpreted as brackish water dwellers, and may represent an opportunistic community. These trace fossils imply that water during the time of coal deposition was brackish and close to the shoreface, contrary to the fully continental interpretation accepted by industry.

ICHNOLOGY AND SEDIMENTOLOGY BELOW THE COAL

Below the coal, evidence for brackish water and tidal influence is abundant. Rhythmic alternation of sand and mud, and bioturbation of mud beds suggest that their genesis is not continental, but rather, tidally influenced. Rhythmic bedding (Plate 24, Photo A) is interpreted as lateral accretion or tidal flat deposits depending on bed size and lamination angle. Magnification of these rhythmic beds reveal burrows subtending from mud lamination (Plate 24, Photos B, C, and D). Traces, such as, *Thalassinoides, Cylindrichnus, Palaeophycus,* possible *Asterosoma* and *Rosselia,* and other small undifferentiated burrows are present. Therefore, sediments below the coal are not continental, as currently described by industry.

GENETIC RELATIONSHIP OF SEDIMENTS ABOVE AND BELOW THE COAL

The bioturbated sediments above and below the coal are genetically related. Three examples taken from just below the marine member of the McMurray (Plate 25, Photo B), above the coal (Plate 25, Photo C), and below the coal (Plate 25, Photo D), all contain diminutive fossils of the Skolithos-Cruziana ichnofacies. Note that it would be impossible to interpret which photo goes with which location in the absence of the labels. They all occur under similar environmental conditions, as supported by a consistent brackish water trace fossil assemblage and variable proportions of sand and mud.

LOWER AND MIDDLE MCMURRAY DEFINITION

Carrigy (1959a) described the informal lower and middle McMurray members as follows: "*Lower Member: Coarse grained sands well-rounded quartz, numerous feldspar cleavage fragments and small amounts of mica*; *Middle member – quartz sand of uniform mineralogy – fine sand.*" The lower member, characterized by coarse sand, is interpreted by Carrigy as lacustrine beach sand. The clay/ coal unit is interpreted by Carrigy as paludal clay. The middle member, depicted by fine sand and silt, is interpreted by Carrigy as lacustrine sands (Figure 38). Of particular interest is the presence of Carrigy's middle member (fine sand and silt – lacustrine sands), which are both above and below the coal/clay unit (Figure 38). Carrigy did not consider the units above and below the coal to be genetically distinct. The lower member is depicted as representing only a small portion at the base (Figure 38).

As defined by Carrigy (1959a), the key attribute in differentiating the lower and middle members is the change in mineralogy. The middle member is dominated by white quartz sand (Plate 26, Photo A). In the lower member, quartz is dominant, but the most notable feature is the angular pink grains of potassium feldspar (Plate 26, Photo B and C). The presence of feldspar is intriguing, as it cannot be transported long distances. It's chemical composition makes it unstable, and hence, it commonly breaks down to clays. The sediments of the lower McMurray are immature and have not been transported far. The origin of the feldspar is problematic at present.

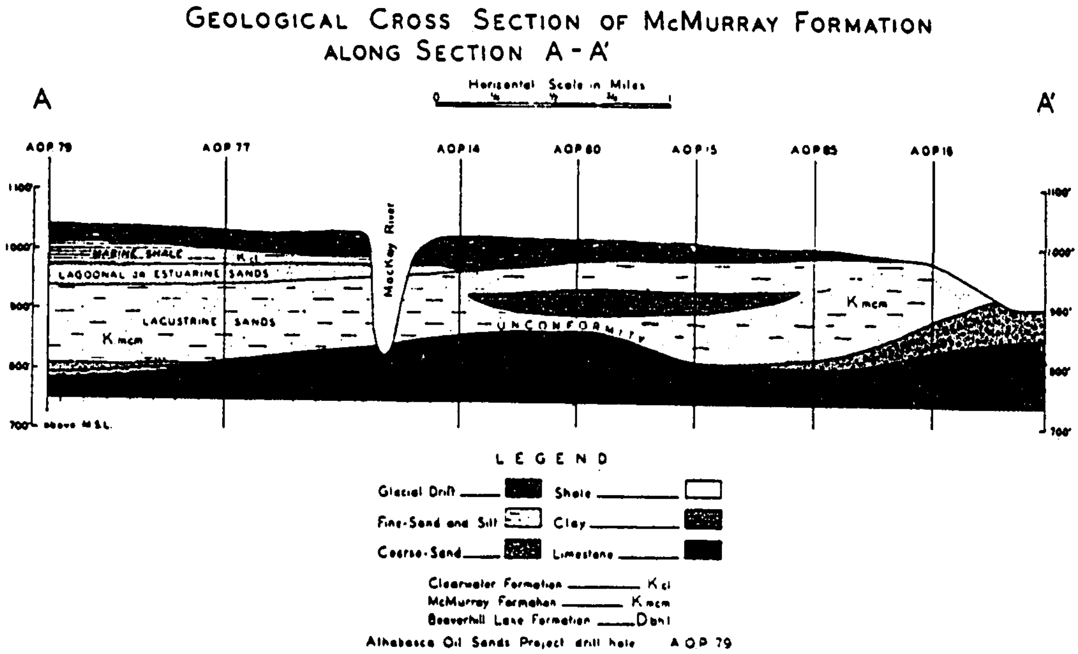


Figure 38
Geological cross-section of the strata displaying stratigraphical location of the units derived from various sedimentary environments (modified from Carrigy, 1959b).

LOWER MEMBER DISCUSSION

The sub-Cretaceous unconformity (Figure 39) is the surface on which the lower member was initially deposited, filling topographic lows. On the majority of the highs, coal and lower McMurray sediments are either not deposited or exist only as a thin veneer. On the mid ranges, the lower McMurray exists, but not in great thicknesses. The greatest proportion of lower member sediment occur on the lows.

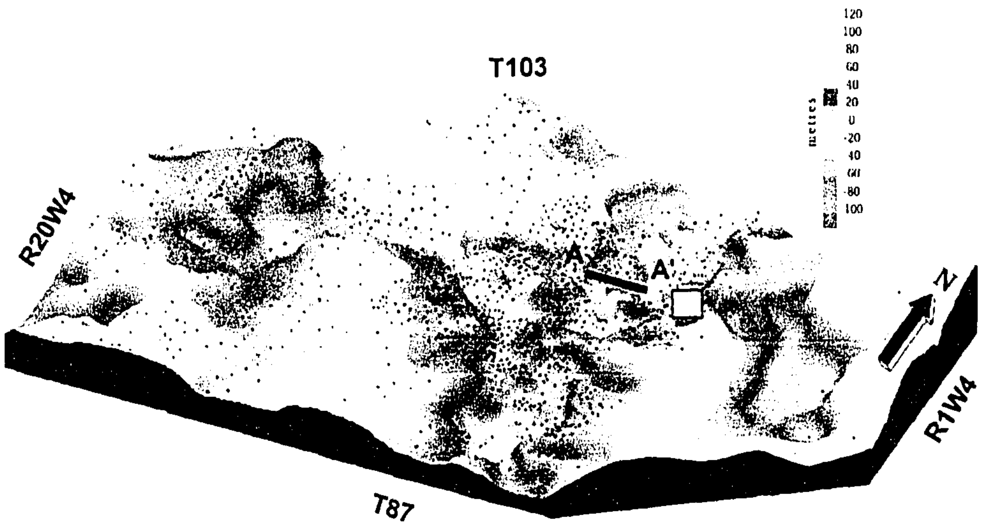


Figure 39
The inferred paleotopography of the sub-Cretaceous unconformity on which the lower member was initially deposited. The line of section is that of Carrigy (1959b) (Figure 38), and the square indicates the Sunrise thermal project location. On the majority of the highs, lower member sediments were not deposited or exist as a thin veneer. The thickest successions of the lower member occur infilling the lows.

Alluvial depositional systems (Figure 40) may have existed on this rugged topography. Distinguishing characteristics of alluvial fans include:

(1) texture – poor sorting; great range of grain sizes; poorly rounded, reflecting short distance of transport,

(2) composition – compositionally immature; composed of a wide variety of clast types, and

(3) sedimentary structures – medium to large-scale trough or planar cross-bedding, cut and fill structures (Bull, 1972).

Texture, composition, and sedimentary structures of the lower member (as defined in this study) are consistent with the aforementioned alluvial characteristics. In the lower member, these include: the presence of potassium feldspar, poor rounding, coarser grain sizes, poor sorting, abundance of trough cross-stratification and numerous scour surfaces.

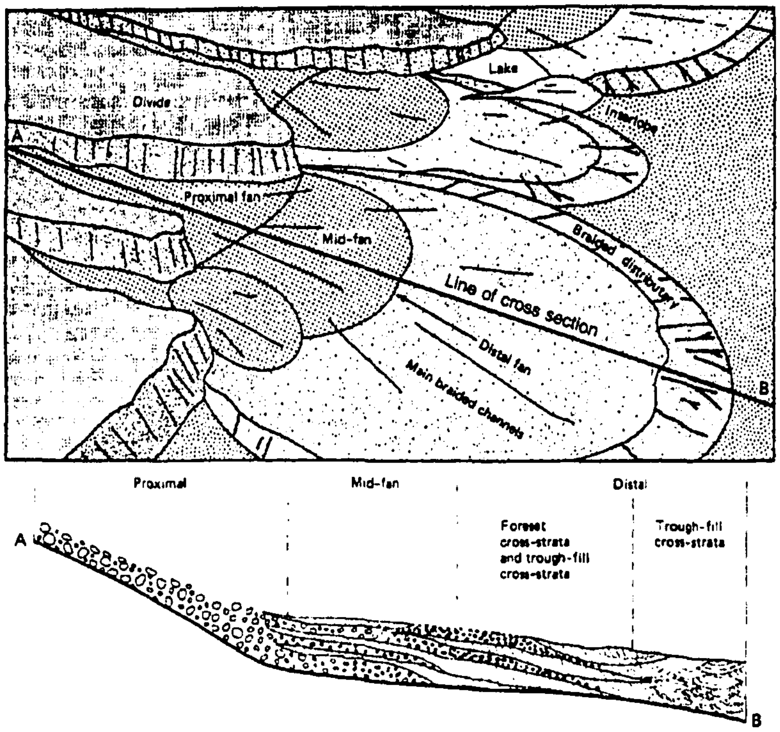


Figure 40
Continental alluvial deposit model of the Van Horn Sandstone, Texas (modified from McGowen, and Groat, 1971). This model has similar characteristics to those observed in the McMurray Formation including, facies, initial topography, and sedimentary structures.

MIDDLE MEMBER DISCUSSION

The coal depositional model illustrated in Figure 28, produces a lithofacies distribution for subenvironments in an estuarine setting during transgression. This model accounts for the large lateral extent of coals as recognized from many leases across many townships. The close proximity to the shoreline provides the saline water required by the bioturbators below the coal and within the coal.

Reconstruction of McMurray sediments as marginal marine, both above and below the coal, can be accomplished through the identification of parasequences. The stratal characteristics of upward-fining parasequences form in a tidal flat to subtidal environment on a muddy, tide-dominated shoreline (Figure 41). The repetition of parasequences is produced during a punctuated transgression. Relative sea rise was likely not constant, but instead, characterized by small-scale rises and falls. However, this parasequence interpretation requires the observation of additional coals.

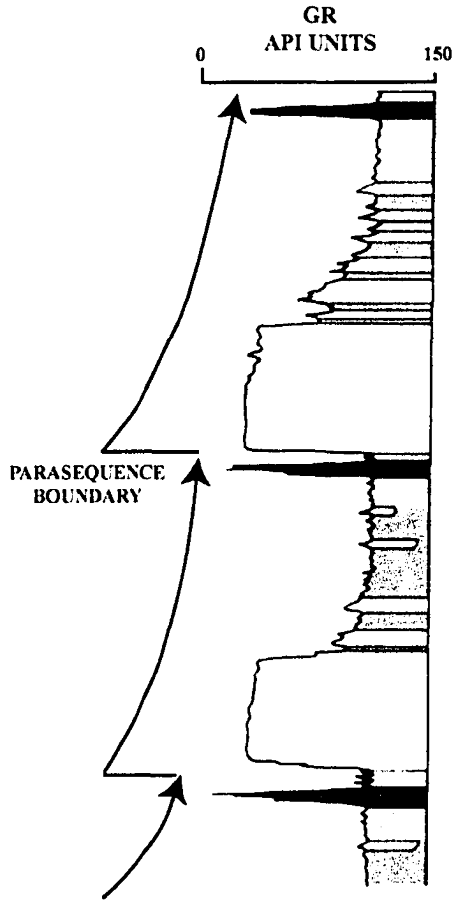


Figure 41
Stratal characteristics of two upward-fining parasequences. These types of parasequences are interpreted to form in a tidal flat to subtidal environment on a muddy tide-dominated shoreline (modified from Van Wagoner *et al.*, 1990).

In addition to the previously described coal, another regional coal event is present at the top of the middle member. This regional event is commonly represented by a paleosol with rooting overlain by the marine upper member of the McMurray Formation (Plate 27, Photo A), and actual coal development is less common (Plate 27, Photo B). Additional regional coal horizons likely exist. A third coal may be present between these two regional coals, but its preservation is poor, and its extent cannot be determined within the Sunrise Thermal Project study area.

MODIFICATION OF INDUSTRY INTERPRETATION

The industry rule of thumb (Figure 37) for the middle member is herein modified to a parasequence interpretation (Figure 42). If present, the lower member boundary is moved stratigraphically lower to incorporate only the mineralogical change. The marginal marine section is larger, the continental portion is smaller, and the marine section remains the same. The marginal marine middle member is modified to reflect pulsed transgression, and three probable parasequences are identified within the Sunrise project area (Figure 42).

SUMMARY

The upper boundary of the lower member of the McMurray Formation has historically been erroneously defined. Ichnological evidence within coal crevasses indicates brackish biota. Sediments below the coal are rhythmically bedded with brackish trace fossils, and are interpreted as lateral accretion deposits of meandering estuarine point bars and tidal flats. The boundary between the lower and middle members is represented by a mineralogical change with the inclusion of potassium feldspar as a component. The middle McMurray is interpreted as a pulsed transgression with many episodes of peat formation.

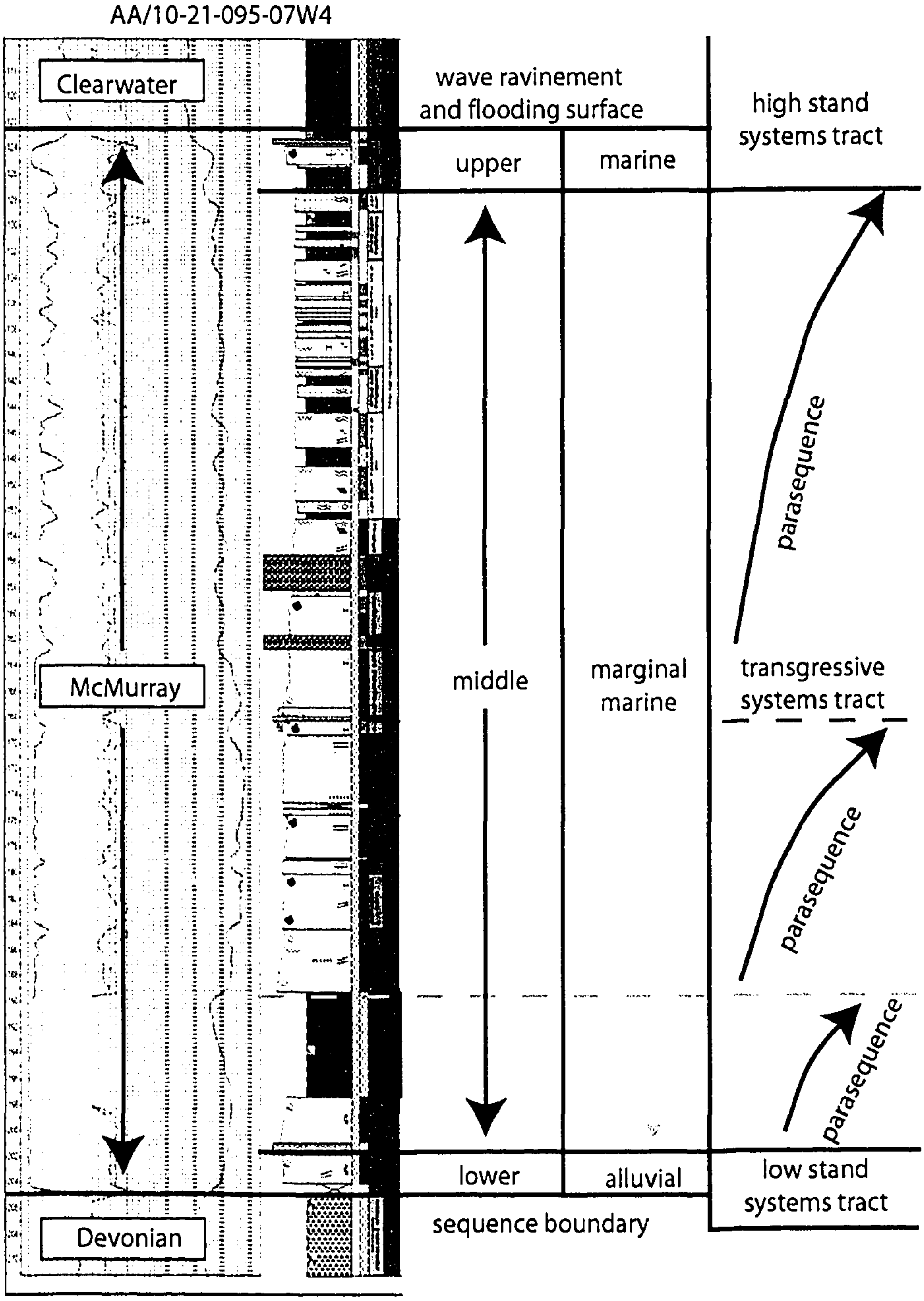


Figure 42
The industry rule-of-thumb (Figure 37) is modified on the Sunrise study area by moving the top of the lower member of the McMurray Formation stratigraphically deeper or earlier to incorporate only those sediments with feldspar. All other boundaries remain the same. The middle member displays fining upward parasequences capped by coal in a pulsed transgression.

Plate 23

A. Wireline logs and AppleCore description of splay sand in coal. AA/11-23-095-07W4

B. Associated core box photo displaying paleosols grading into organic shales into coal. The coal is eroded by sand beds which fine upward and are overlain by coal again. AA/11-23-095-07W4 (217.5 – 221.25 m)

Plate 23

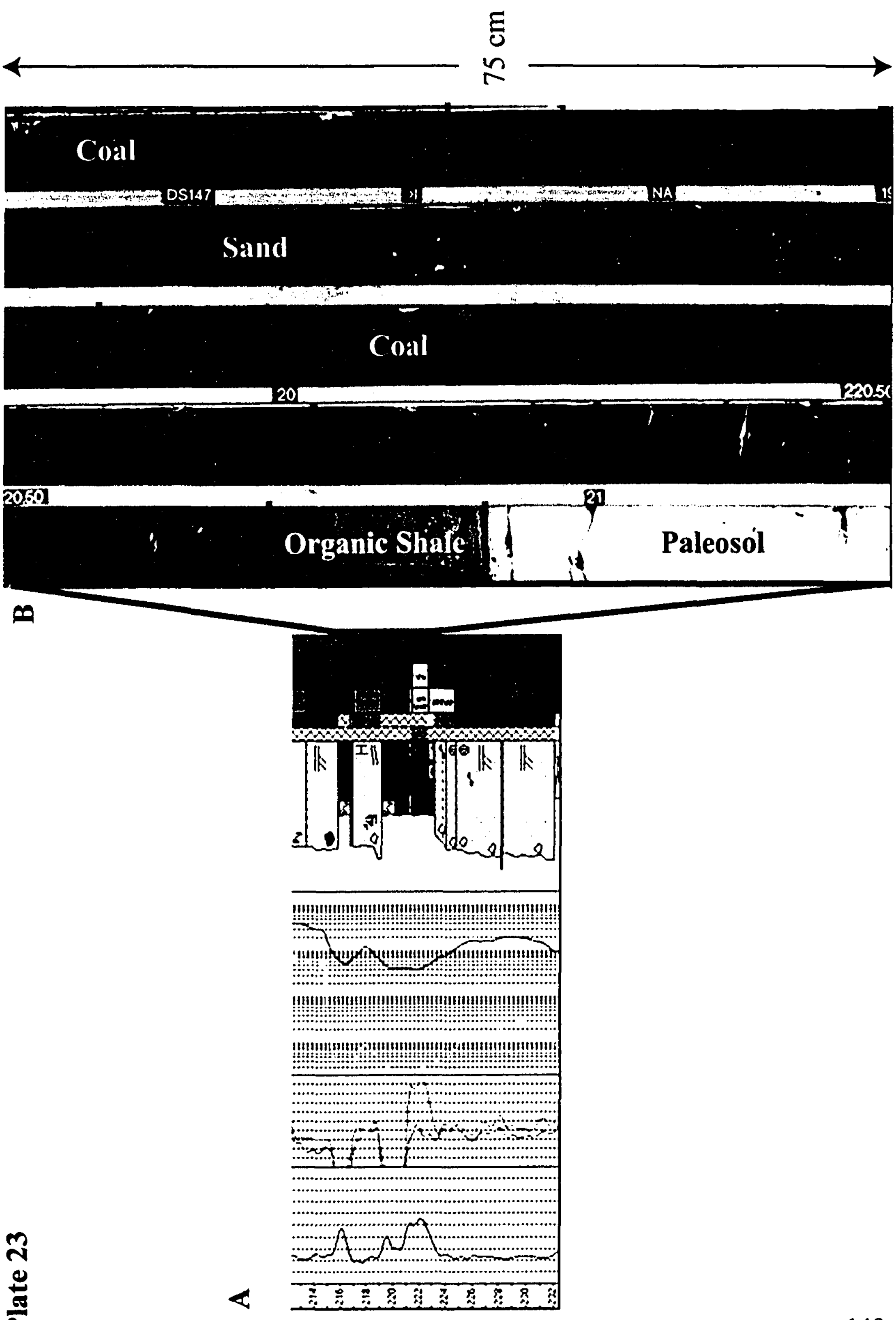

75 cm
Coal
DS147
NA
Sand
Coal
20
220.5
20.50
21
Organic Shale
Paleosol
B
A

Plate 24

Ichnological and sedimentological evidence for brackish signatures below coal.

A. Rhythmic alternation of sand and mud and bioturbation of mud beds establish that the genesis of sediments below the coal is not continental, but instead, has tidal influences AB/07-22-095-07W4 (203.75- 217.25 m)

B. *Planolites, Cylindrichnus* and other diminutive undifferentiated burrows below coal. AB/07-22-095-07W4 (210.9 m)

C. Magnification of *Cylindrichnus* dominated horizon below coal. AB/07-22-095-07W4 (210.1 m)

D. *Palaeophycus, Cylindrichnus*, possible *Asterosoma*, branched tubes and other diminutive undifferentiated burrows below coal. AB/07-22-095-07W4 (208.75 m)

Plate 24

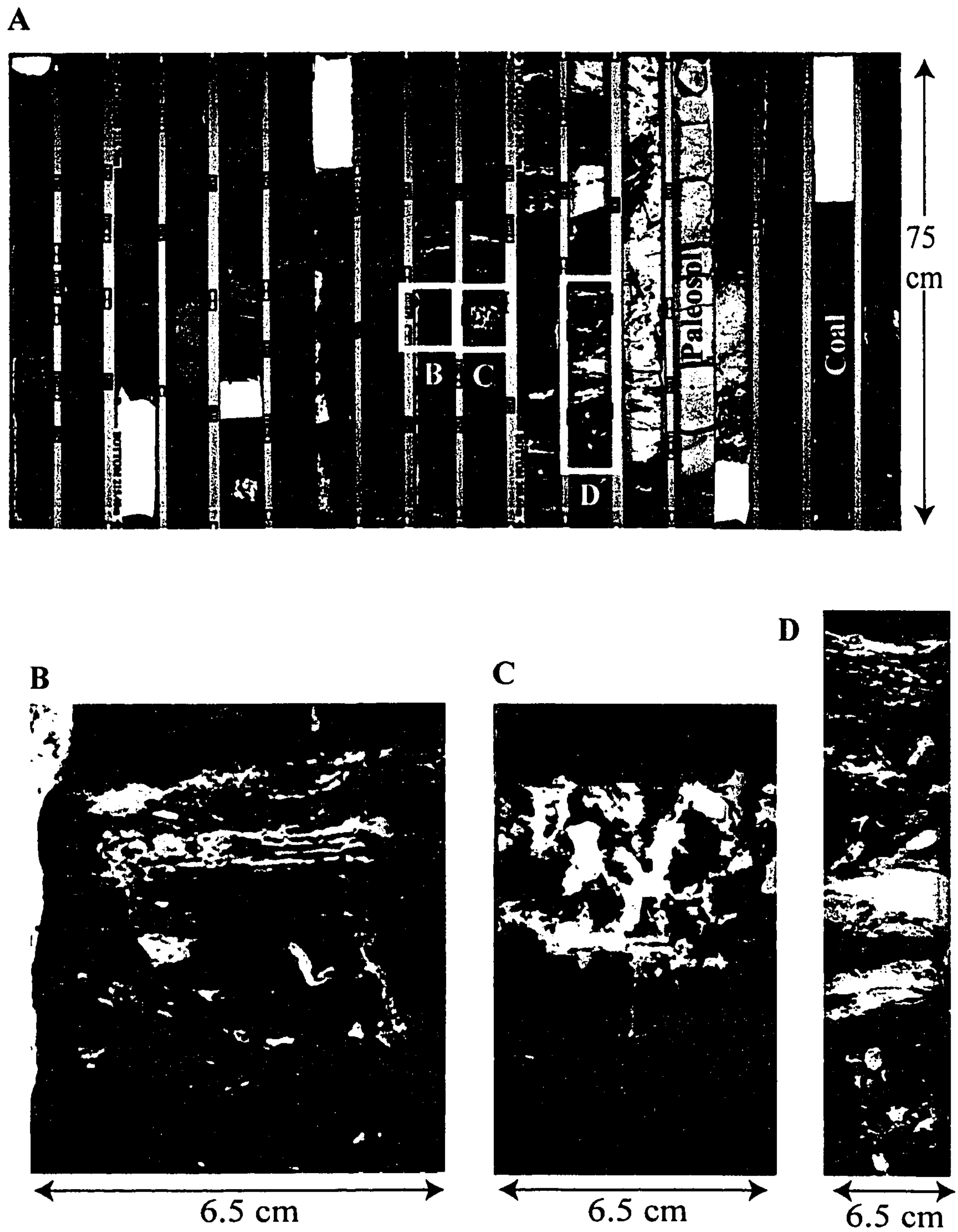


Plate 25

Middle member bioturbation exhibits a genetic relationship, containing diminutive fossils of the Skolithos-Cruziana ichnofacies, and variable proportions of sand and mud.

A. Wireline log of AB/07-22-095-07W4.

B. Abundant diminutive bioturbation of the middle member just below the upper marine member of the McMurray Formation. AB/07-22-095-07W4 (210.1 m)

C. Diminutive, low diversity bioturbation above coal of the middle member. AB/07-22-095-07W4 (185.75 m)

D. Diminutive undifferentiated burrows below coal. AB/07-22-095-07W4 (214.5 m)

Plate 25

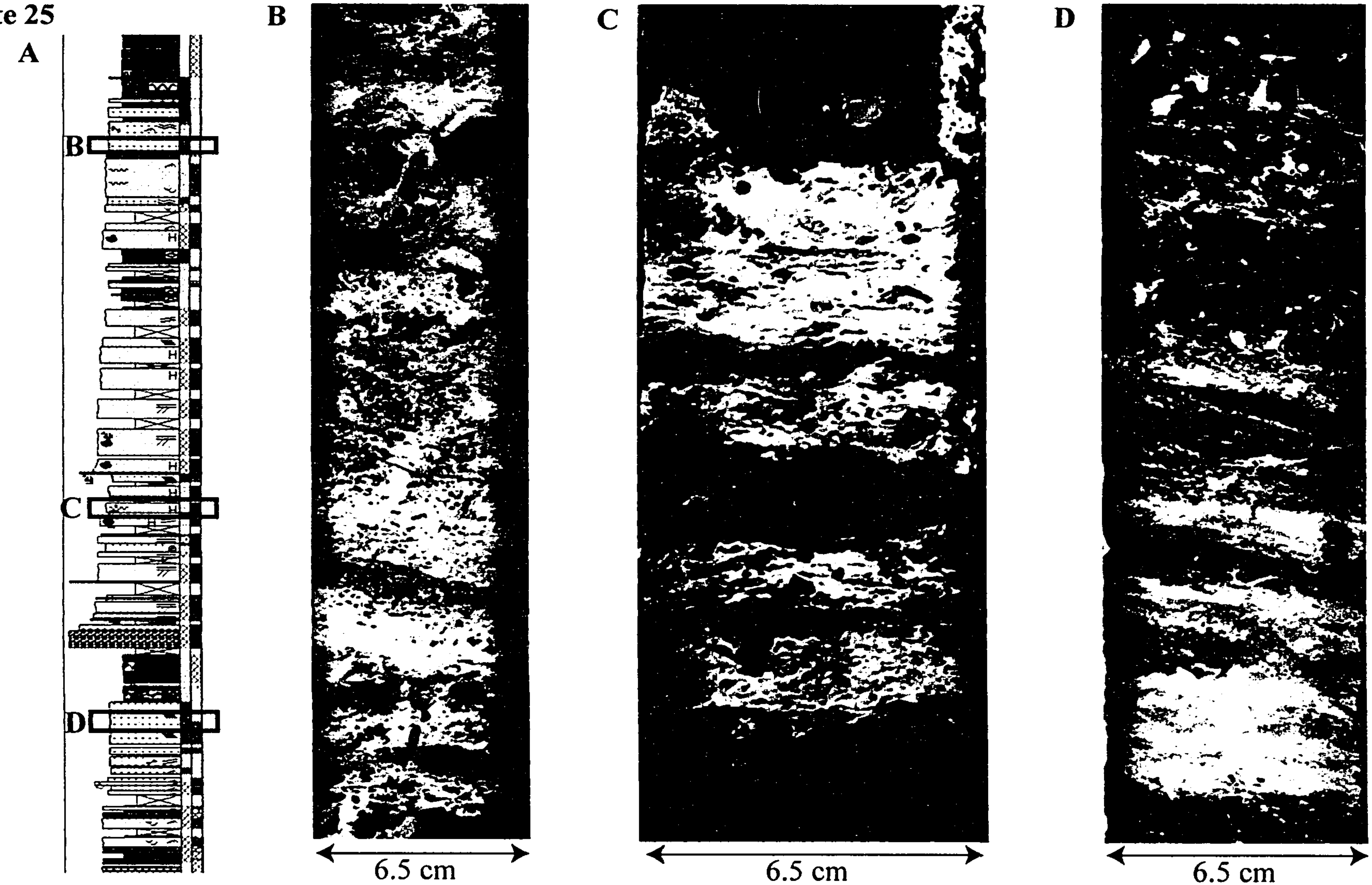


Plate 26

A. White quartz sand of the middle member of the McMurray Formation. Note mineralogical difference revealed by color contrast between this and subsequent photos. Vertical tubes are a result of bitumen migration avoiding pore throat constriction. AA/10-30-087-07W4 (162.6 m)

B. Coarse grained sand of the lower member of the McMurray Formation. Pink grains are potassium feldspar. AA/10-21-095-07W4 (201.1 m)

C. Coarse grained sand of the lower member of the McMurray Formation. Pink grains are potassium feldspar. AA/07-18-095-07W4 (182.25 m)

Plate 26

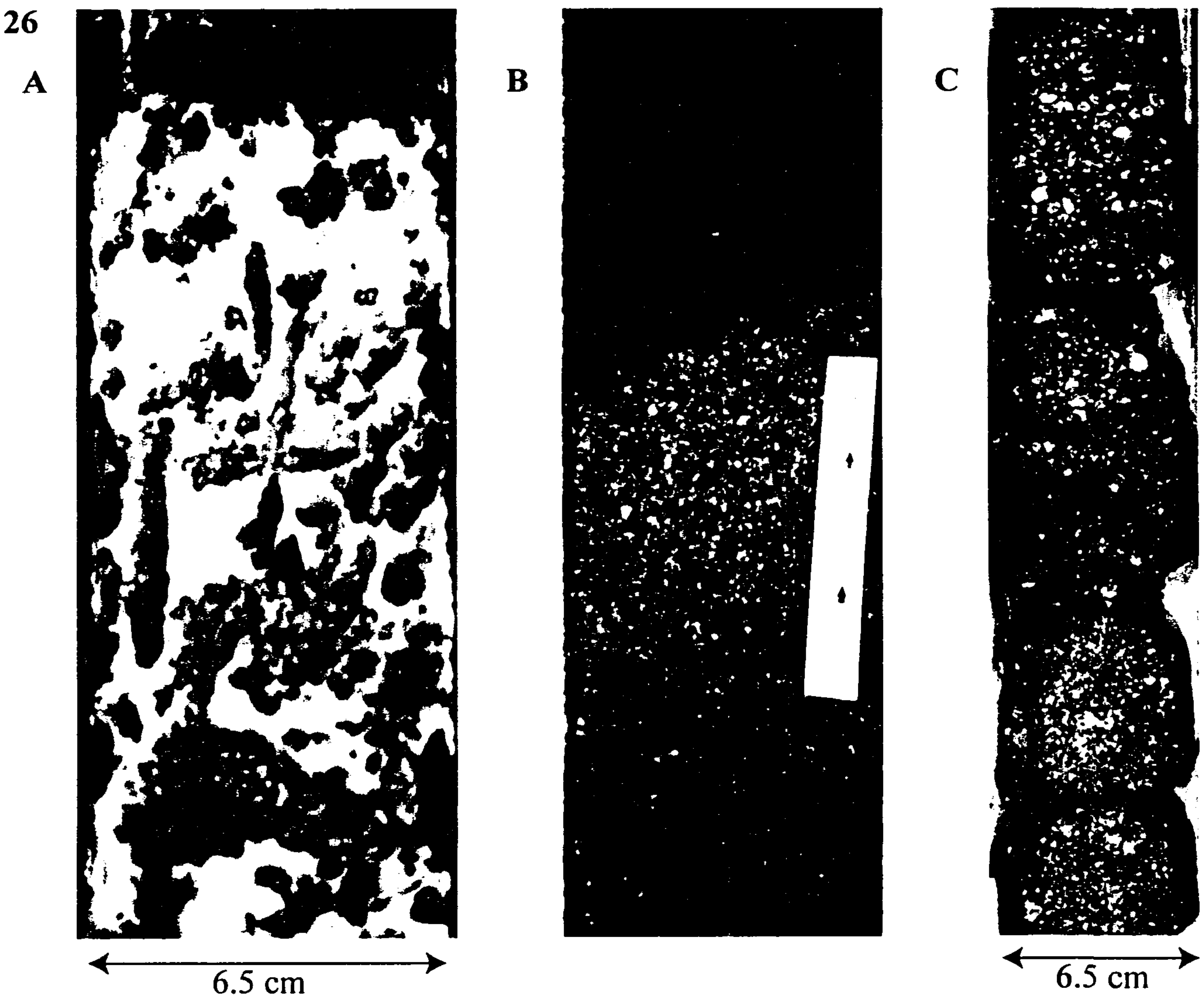
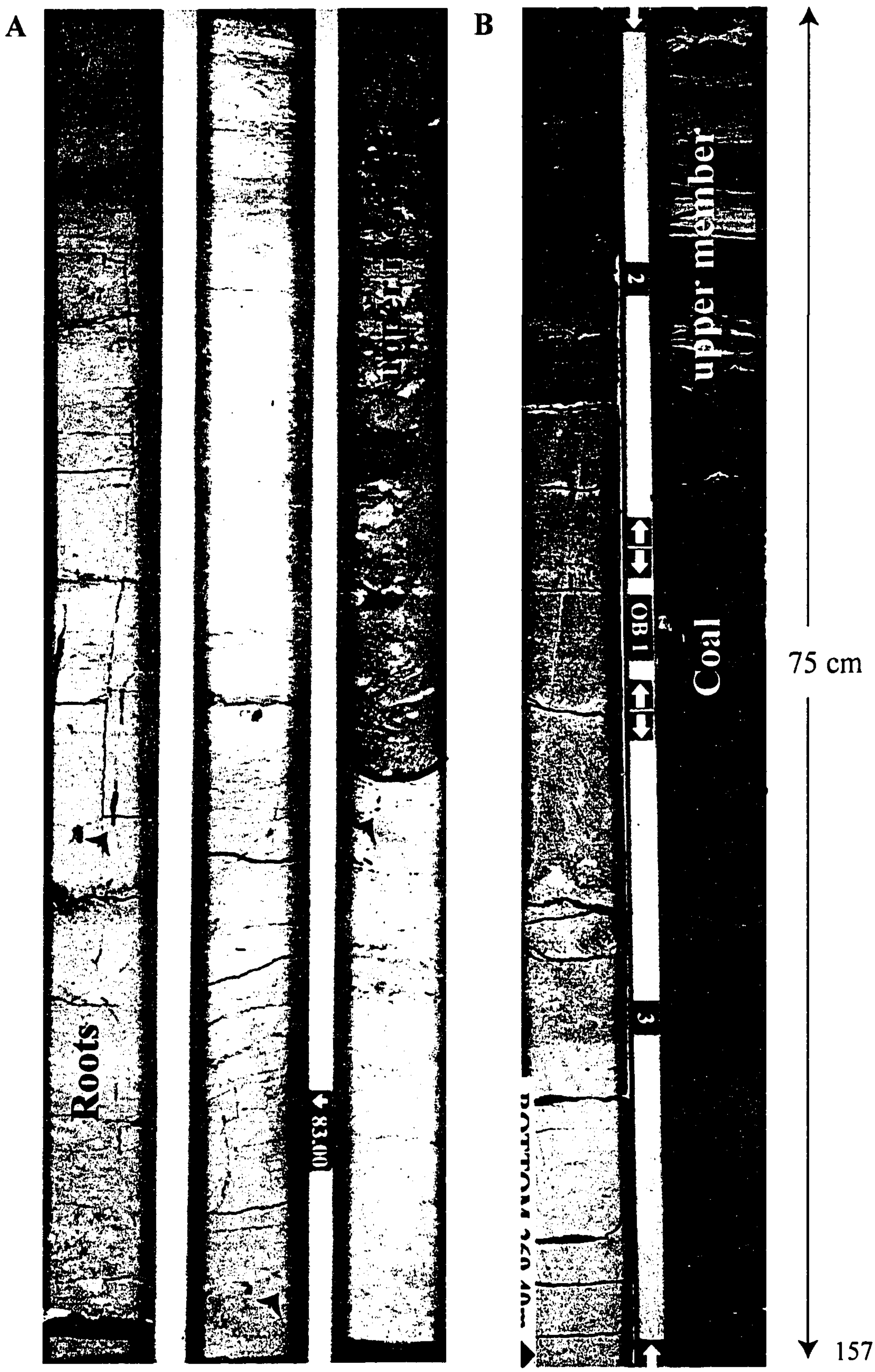


Plate 27

A. Upper middle member paleosol with rooting overlain by the upper marine member of the McMurray Formation. AA/04-02-095-07W4 (181.75 – 184.0 m)

B. Dark gray mud of the upper middle member grades into coal, which is sharply overlain by the upper member of the McMurray Formation. AA/06-21-094-06W4 (268 – 268.5 m)

Plate 27



CHAPTER 4

STRATIGRAPHIC INTERPRETATION

INTRODUCTION

Fifteen facies defined for this study have been grouped into six facies associations. This methodology facilitates comprehension of the depositional environments, accentuated by the high variability of facies within the McMurray Formation and Wabiskaw Member. Interpretation of the vertical succession of the McMurray Formation and Wabiskaw Member as viewed in core, requires careful application of Walther's Law. Walker (1992) succinctly paraphrased the law as "*in a vertical succession, a gradational transition from one facies to another implies that the two facies represent environments that were once adjacent laterally*".

Understanding the discontinuities that bound these facies association units is a requirement for interpretation of the succession. Application of sequence stratigraphic concepts will aid in the interpretation of the facies associations as genetically related units. The interpretation is similar to that of Bechtel (1996) with modifications and simplifications. Table 2 is a summary of facies described and their interpreted depositional environments (chapter 2), including how these facies relate to facies associations (FA) and the informal subdivision into lower, middle and upper members of the McMurray Formation.

SEQUENCE BOUNDARY (SB)

The McMurray Formation unconformably overlies Devonian carbonates. During this hiatus, the top of the Devonian was subjected to several periods of subaerial exposure (Carrigy, 1963; Stewart 1963). The unconformity is a high relief surface, with gradients as high as 70 m/km (Martin and Jamin, 1963). This surface marks the lowermost bounding discontinuity of the McMurray/Wabiskaw succession and represents both the sequence boundary and the lower boundary of the lowstand systems tract (LST).

FA1: LOWER MEMBER – FINING UPWARD SANDY ASSOCIATION (LST)

The lower McMurray succession of facies occurs in a predictable order. Large-scale cross-stratified sand (F1) overlies a sharp erosional lower contact. This facies grades upward into small-scale cross-stratified sand (F3) and apparently structureless sand (F2). Bioturbation is absent. This association is interpreted as a channel succession. The absence of flood basin deposits suggests confinement of channels within topographic lows. Younger channels continually re-incise older channels (Figure 43). Consequently, a larger proportion of large-scale cross-stratified sand (F1) is preserved.

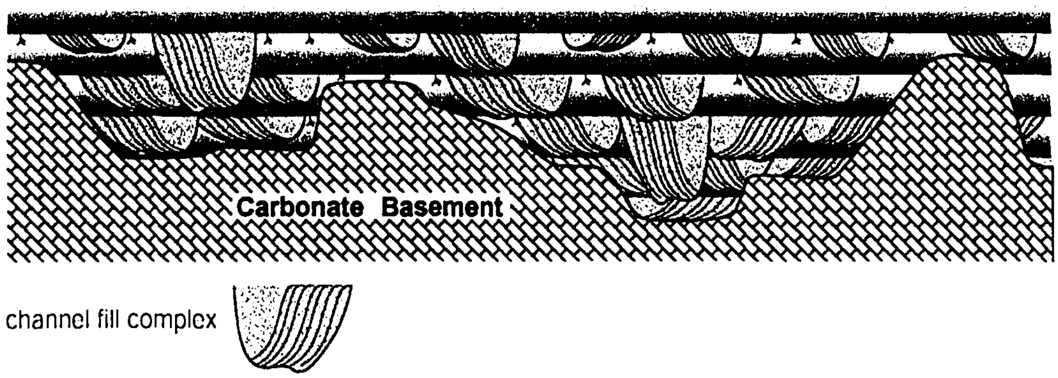


Figure 43
Schematic for preservational bias of channel base sediments confined by the carbonate basement. Younger channels incise pre-existing channels. Stratigraphically upwards, confinement pressures are reduced and channel complexes have increased ability to migrate laterally, and preservation of the upper channel fill is enhanced (modified from Ranger, 1997).

Previous studies have assigned a fluvial interpretation to the lower member of the McMurray Formation (Carrigy, 1971; Stewart and MacCallum, 1978; Flach, 1984; Flach and Mossop, 1985; Rennie, 1987; Fox, 1988; Yuill, 1995; Bechtel, 1996). Most of these interpretations include the muddy intervals with the lower member of the McMurray Formation. However, these muddy intervals are assigned to the middle McMurray in this study (as discussed in chapter 3).

The lower member represents alluvial-fluvial channel deposits constituting the lowstand systems tract (LST), which overlies the sequence boundary (sub-Cretaceous unconformity), and occupies structural lows.

TRANSGRESSIVE SURFACE OF EROSION (TSE)

The contact between the lower and middle members of the McMurray Formation is interpreted as a transgressive surface of erosion (TSE). The contact is sharp and uneven, and separates the coarser sand and conglomeratic facies of the lower McMurray from the sandy facies of the middle McMurray. The contact represents the top of the lowstand systems tract (LST) and the base of the transgressive systems tract (TST).

FA2: MIDDLE MCMURRAY - FINING UPWARD SANDY ASSOCIATION (TST)

The middle McMurray facies within this association occur in a predictable order. Large-scale cross-stratified sand (F1) overlies a sharp erosional lower contact. In contrast to the lower McMurray sediments, the channel sequence includes lateral accretion deposits of sand dominated and/or mud dominated IHS (F4), which commonly overly small-scale cross-stratified sand (F3). Mud clast breccia (F2) is commonly found in the channel deposits. The succession is typically capped by gray muds (F5), and flat-lying, thinly interbedded sand and mud (F6). This succession of facies is repeated vertically over the middle McMurray with both complete and incomplete successions being preserved (Figure 44).

AA/03-26-095-07W4

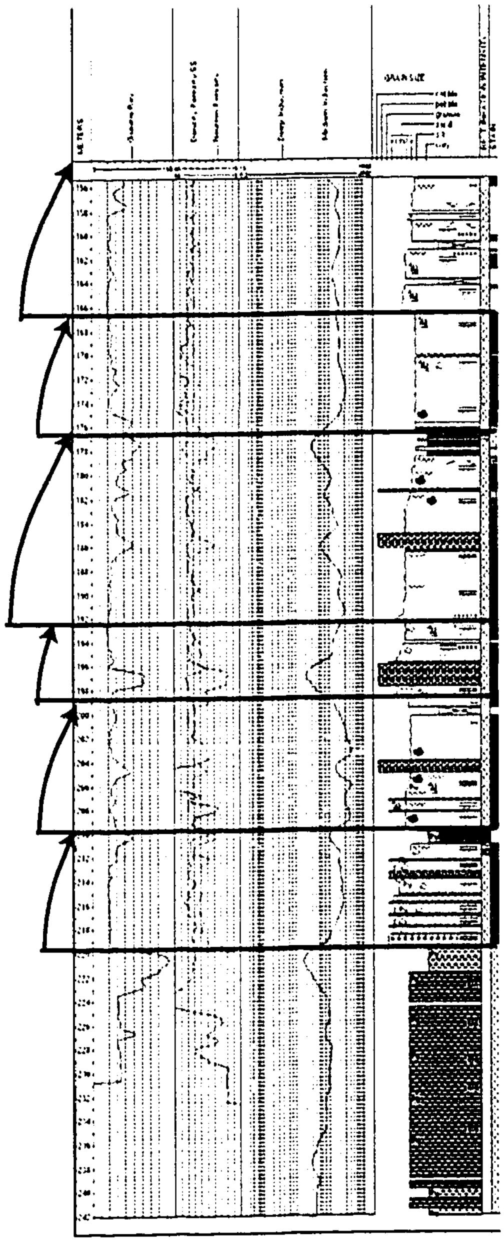


Figure 44
The fining upward succession of facies is repeated vertically within the middle McMurray; both complete and incomplete successions are preserved.

The succession within the middle McMurray indicates deposition within an estuarine channel environment. Estuarine channels are characterized by fining-upward successions, abundance of burrowing indicative of brackish water conditions, and abundance of IHS cycles.

FA3: MIDDLE MCMURRAY - MUDDY ASSOCIATION (TST)

This succession of facies typically lacks a predictable order of facies, as facies are irregularly intercalated with each other. Reineck and Singh (1980) subdivided the channel environment into three major groups: channel deposits, bank deposits and flood basin deposits. The middle member fining upward sandy association, described above, corresponds to the channel deposits. Chaotic, interbedded sand and silty muds (F10) interpreted as crevasse splays correspond to bank deposits of this association. Additionally, flood basin deposits correspond to gray mud (F5), white to light gray mud (F7), dark gray to black carbonaceous mud (F8) and coal (F9).

Flood basin deposits are traditionally well developed within fluvial systems where the channel does not migrate laterally (Reineck and Singh, 1980). The lowermost portion of the middle McMurray Formation is an exception. The low proportion of bioturbated IHS deposits implies that these channels did not migrate significantly. This however, does not suggest that the lowermost channels in the middle McMurray are fluvial. The lack of migration is due to confinement of the lower portions of the middle McMurray within lows on the sub-Cretaceous unconformity. The proportion of IHS deposits increases stratigraphically upwards, indicating that channels did migrate where lateral movement was permitted. Lateral movement of channels occurred more frequently where previous channel sands were easily eroded and Devonian highs played a less significant role on the configuration of the channel patterns (Figure 43).

Through a sedimentological and micropaleontological study, Rennie (1987), interpreted a deltaic marsh environment for the muddy association. In addition to a wide variety of freshwater pollens, including cypress and ferns species, from overbank muds and mud drapes within the channel sediments; Rennie (1987) also recovered algal species and dinoflagellates indicating influxes of saltwater.

The relationship of the middle McMurray fining upward and muddy association is described in chapter 3 as stacked parasequences.

TIDAL RAVINEMENT SURFACE (TR)

The contact between the middle McMurray deposits and the overlying interbedded marginal marine deposits represents a significant stratigraphic horizon. As a result of continued transgression, the contact marks the base of the outer estuary deposits. At this surface, outer estuary deposits overlie the central estuary sediments.

FA4: UPPER MCMURRAY - FLAT LYING, SAND AND MUD ASSOCIATION (TST)

This association is characterized by various flat-lying, interbedded, typically well burrowed, laterally extensive facies. It constitutes the lower portion of the upper member of the McMurray Formation. The flat-lying nature of the upper McMurray is used to distinguish it from the inclined stratification of the middle McMurray (Mossop, 1980; Flach and Mossop, 1985). From outcrop studies, Stewart and MacCallum (1978) reported that the flat-lying upper McMurray beds truncate the inclined middle McMurray stratification.

The constituent facies do not always occur in a predictable vertical order, though some general observations can be made. At the base of the association, flat lying, thinly interbedded sand and mud (F6), is overlain by laminated to interbedded sand and mud with variable bioturbation (F12). The subfacies of F12 include basal laminated to burrowed sand overlain by well burrowed sand and capped by interbedded sand and mud.

Laminated to burrowed sand (subfacies F12a) and interbedded sand and mud (subfacies F12c) represents deposition of an outer estuary sand body characterized by high sedimentation rates. The preservation of physical structures suggests reworking of the substrate by physical processes. The undulatory parallel laminated very fine- and fine-grained sands likely represent HCS, and SCS, which indicate storm deposition (Arnott, 1993). The trace fossil assemblage include escape traces and displays burrows of opportunistic organisms passing into burrows of the fairweather assemblage.

Well burrowed sand (subfacies F12b) also represents deposition of an outer estuary sand body, although in a more sheltered area than the previous subfacies laminated to burrowed sand (F12). Sufficient time and protection from physical processes have resulted in a high intensity of burrowing. As well, flow energies were sufficiently low to allow mud deposition and intense bioturbation of the substrate. Thorough bioturbation of the facies has resulted in muddy sand. The higher diversity of traces reflects more marine conditions.

The three subfacies represent a continuum within facies 12. The dominance of sand or mud and the dominance of biogenic or physical structures reflect the nature of the depositional setting. The relationship revealed between F12 subfacies reflects a continuum based on variations of sedimentary features (mud versus sand deposition and preservation of biogenic versus physical structures) related to the depositional environment (proportion of exposure and sedimentation versus shelter) as depicted in Figure 45.

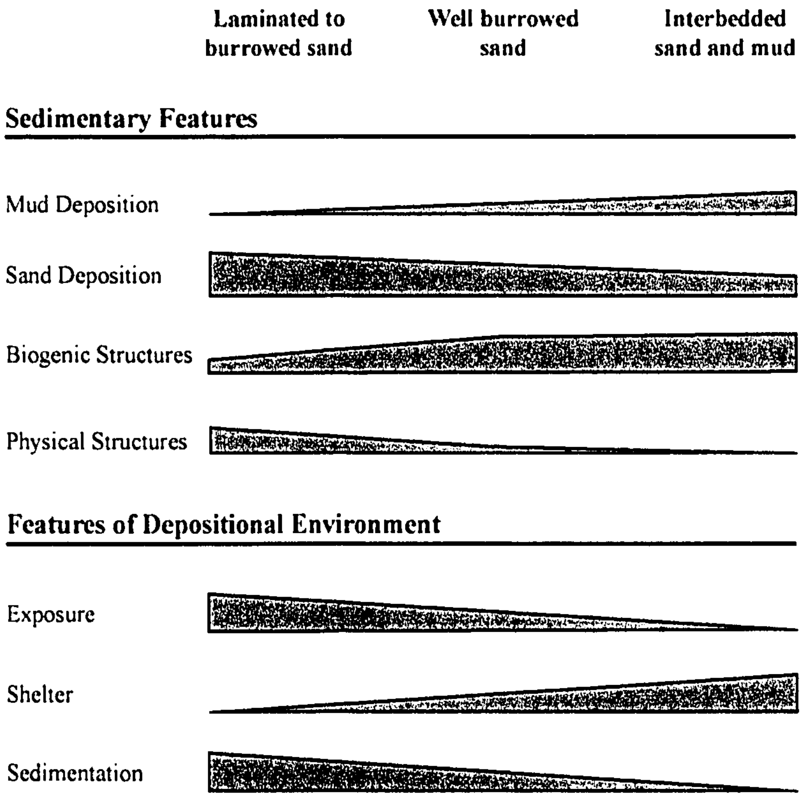


Figure 45
Relationship of subfacies continuum for facies 12 (modified from Bechtel, 1996).

This association represents a continuation of the transgressive systems tract (TST). The tidal ravinement surface was incised and rising sea levels shifted deposition up the paleovalley depositing outer estuarine sediments.

CLASSIFICATION OF THE MCMURRAY ESTUARY

The definition of an estuary varies based on perspective. For example, a geologist may envision a drowned river valley, a hydrogeologist may consider bodies of water to be estuarine if salinity is less than that of sea water, and oceanographers will regard bodies of water as estuarine if river water mixes with and dilutes sea water (Dalyrymple *et al.*, 1992; Boggs, 1987).

As utilized in this study, Dalrymple *et al.* (1992) provided a definition based on criteria recognizable within the geologic record: an estuary is '*the seaward portion of a drowned valley system, which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth.*' In addition, the authors note that estuaries can only form as the result of a relative sea-level rise (transgression).

Dalrymple *et al.* (1992) also provided a schematic representation of the definition of an estuary and the distribution of physical processes operating therein (Figure 46). Estuaries are classified within a continuum that has wave-dominated and tide-dominated estuaries as its end-members (Dalrymple *et al.*, 1992). The classification reflects the dominant energy source (wave or tidal currents) at the marine end of the estuary (Zaitlin *et al.*, 1994).

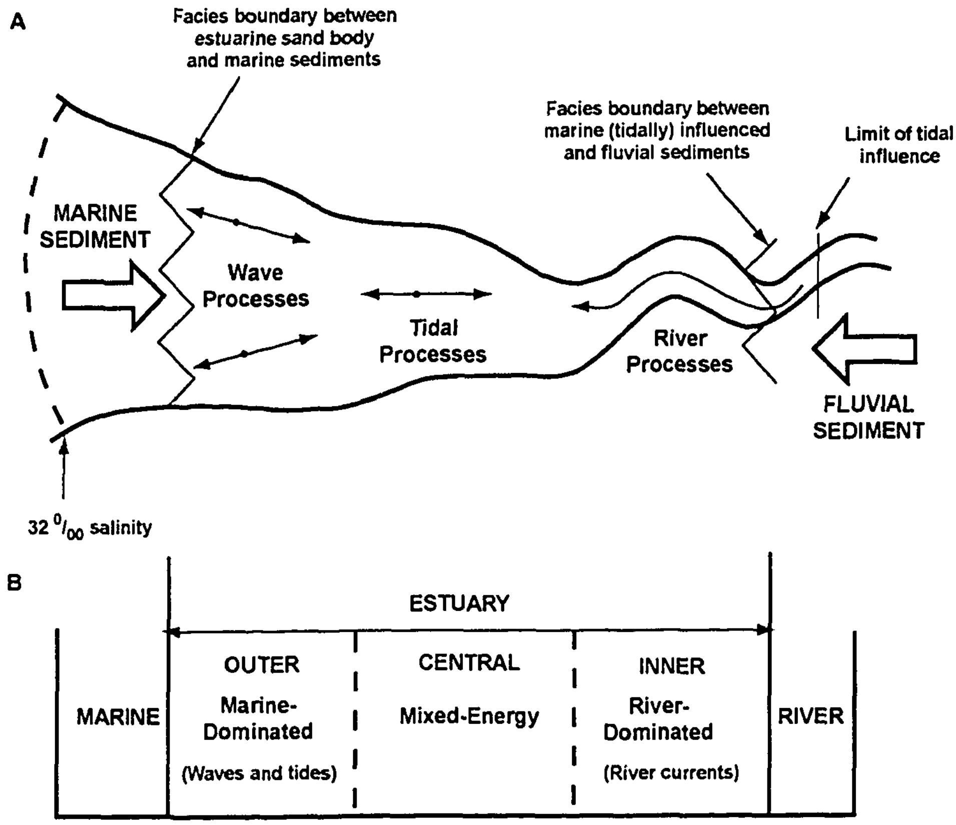


Figure 46

A Schematic representation of an estuary;

B Tripartite zonation of the estuary (modified from Dalrymple *et al.*, 1992).

The McMurray estuary contains features common to both the wave-dominated and tide-dominated models. The estuary is interpreted to have an estuary mouth complex, yet lacks the bay-head delta deposits of the wave-dominated model. The inner and central zones of the McMurray estuary are dominated by channel deposition, yet lack the tidal sand bars and upper flow regime sand flats associated with the tide-dominated model. The presence of fringing tidal flat deposits is consistent with the tide-dominated model. The above evidence suggests that the McMurray represents a mixed tide- and wave-dominated estuary (Bechtel, 1996).

Through comparison with modern analogs Smith (1988a: 1988b) interpreted a mesotidal tidal range for the McMurray Formation. The complete classification of the McMurray estuary would then be: a mesotidal, mixed tide and wave-dominated estuary.

WAVE RAVINEMENT SURFACE (WR)

The contact between the outer estuary flat lying, interbedded association and the overlying coarsening upward association represents a significant stratigraphic horizon. It is sharp and erosional, but unlike the tidal ravinement surface it is a low relief planar surface. As a result of continued transgression, wave erosion associated with shoreline retreat cuts the ravinement surface. The contact marks the boundary between the underlying estuarine deposits and the overlying marine deposits. Wave ravinement surfaces are not present in tide-dominated settings (Zaitlin *et al.*, 1994), which is further evidence that the McMurray is not simply tide-dominated.

FA5: UPPER MCMURRAY - COARSENING UPWARD SANDY ASSOCIATION (HST)

The coarsening upward association is characterized by blue-gray mud, a coarsening-upward profile, and large trace fossils. Where present, it constitutes the uppermost portion of the upper member of the McMurray Formation.

The overall succession represents a thin transgressive sand sheet overlain by a prograding shoreface succession. Poorly sorted fine to coarse sand (F13) represents the transgressive lag associated with erosional shoreface retreat. Interbedded sand and blue gray mud (F14) represents upper offshore to lower and middle shoreface deposits.

Sand interbeds are the result of distal storm event deposition. They are sharp-based and rippled to low angle parallel laminated. The low angle parallel laminated sands are interpreted as HCS and SCS. Oscillation and combined flow ripple laminations represent waning flow conditions. Mud deposition and bioturbation occurred during low energy, fair-weather conditions.

The trace fossil assemblage of this association is distinctively different than underlying estuarine deposits. The trace fossils are larger, (consistent with more marine assemblages), but appear less diverse and are less abundant than the estuarine examples. Strongly storm-dominated lower-middle shoreface complexes can be recognized by amalgamated storm deposits (tempestites) with minimal preserved biogenic structures (MacEachern and Pemberton, 1992a). Insufficient time for colonization and burrowing of a substrate will result in a predominance of physical structures. Another contributing factor to low trace fossil abundances is possibly chemical stresses. These chemical stresses may be due to brackish estuary water, or the shoreface was deposited within a broad embayment rather than an open coastline (Bechtel, 1996).

This association represents the initiation of the highstand systems tract (HST). The shoreface packages coarsen upward and are progradational. HST deposits have a progradational stacking pattern, whereas TST deposits have a retrogradational stacking pattern (Van Wagoner *et al.*, 1990).

WAVE RAVINEMENT (WR)

The low relief, erosive contact between the upper McMurray coarsening upward shoreface and the overlying Wabiskaw Member is another wave ravinement surface.

FA6: UPPER MCMURRAY/WABISKAW - GLAUCONITIC ASSOCIATION (HST)

This thin association is distinctive for its large trace fossils and the presence of glaucony. It represents the lowermost deposits of the Wabiskaw Member of the Clearwater Formation. This association has a sharp, erosive lower contact with all underlying facies. The upper contact is sharp with the overlying shales of the Clearwater Formation.

The constituent facies sand and blue gray mud, forms the base of the association. Well burrowed glauconitic sand mud is found beneath Clearwater shales. Glauconitic sediments are commonly indicators of fully marine offshore deposits (Stewart and MacCallum, 1978; Fox and Pemberton, 1989; Yuill, 1995).

Large *Arenicolites* or *Skolithos* with coarser grained fills are interpreted to belong to the *Glossifungites* ichnofacies. Ravinement is the most favorable process for firmground development and colonization (MacEachern *et al.*, 1992). The *Glossifungites* assemblage indicates a depositional hiatus between the erosional event and sedimentation of the overlying unit (Pemberton and MacEachern, 1995). The stacking of sand and blue gray mud and glauconitic sand and mud represents progradation of the upper offshore over the lower offshore.

This association represents a continuation of the high-stand systems tract (HST). Ranger (1997) demonstrated that stacked, prograding, shoreface parasequences sets could be regionally correlated over the entire south Athabasca deposit. This association represents the distal equivalents of shorefaces to the south. The maximum flooding surface and condensed section occurs stratigraphically higher in Clearwater shales.

SUMMARY OF THE MCMURRAY/WABISKAW SUCCESSION

The McMurray Formation/Wabiskaw Member succession within the study area records the fill of a paleovalley incised into the underlying Devonian carbonate. The sub-Cretaceous unconformity is a sequence boundary and marks the base of the incised-valley. Lower McMurray examples of fining upward sequences represent the lowstand alluvial-fluvial deposits. Above the transgressive surface of erosion, middle McMurray fining upward successions, or parasequences of a mesotidal, mixed tide- and wave-dominated estuary, were deposited. A continued rise in relative sea level resulted in transgression of the outer estuary into the paleovalley.

The tidal ravinement surface resulted from erosion associated with this transgression. A wave ravinement surface was incised during erosional shoreface retreat. Progradation of shorefaces resulted in deposition of the coarsening upward association. Above the second wave ravinement surface, distal equivalents of shorefaces to the south represent the Wabiskaw Member of the Clearwater Formation. The overlying Clearwater shales contain the maximum flooding surface. This succession is schematically represented in Figure 47.

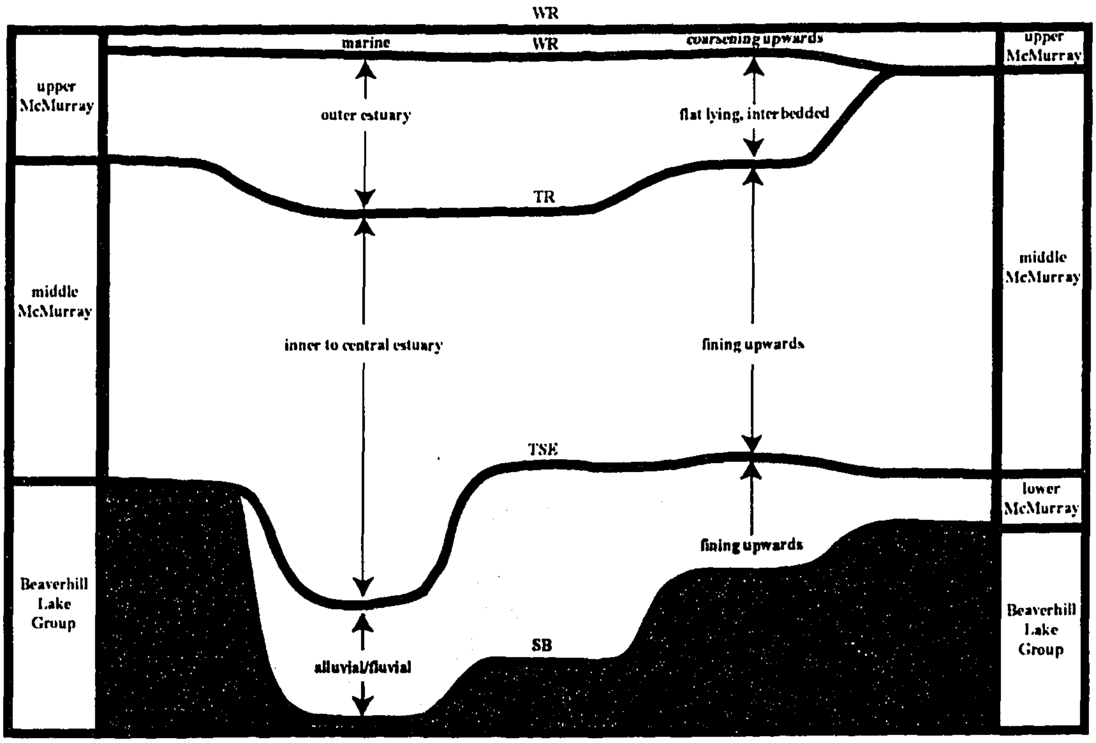


Figure 47
Schematic section summarizing correlation of facies associations, depositional environment, bounding discontinuities and stratigraphic nomenclature.
SB; sequence boundary; TSE; transgressive surface of erosion; TR tidal ravinement; WR wave ravinement
(modified from Bechtel, 1996).

Facies Code	Facies	Environment	Facies Association						Member		
			1	2	3	4	5	6	l	m	u
F1	large-scale cross-stratified sand	channel base	■						■		
F2	apparently structureless sand and mud clast breccia	channel bank collapse	■						■		
F3	small-scale cross-stratified sand	channel floor and point bar surfaces	■						■		
F4	inclined heterolithic stratification	lateral accretion deposits			■						
F5	gray mud	channel abandonment			■						
F6	flat lying, thinly interbedded sand and mud	tidal flats			■						
F7	white to light gray mud	floodplain deposits			■						
F8	dark gray to black carbonaceous mud	marsh deposits			■						
F9	coal	marsh deposits			■						
F10	chaotic, interbedded sand and silty mud	crevasse splay deposits			■						
F11	interbedded sand and mud with gastropods	outer estuary									■
F12	laminated to interbedded sand and mud with variable bioturbation	outer estuary									■
F13	poorly sorted fine to coarse sand	transgressive lag					■				■
F14	sand and blue gray mud	upper offshore to shoreface					■				■
F15	glaucontic sand and mud	upper offshore									

Table 2

Summary of facies, depositional environments, facies associations and informal member subdivision.

facies associations: 1 lower member - fining upward; 2 middle member - fining upward; 3 middle member - muddy; 4 upper member - flat lying; 5 upper member - coarsening upward; 6 Wabiskaw - fining upward

members: l = lower; m = middle; u = upper

CHAPTER 5

KARST BRECCIA

INTRODUCTION

The McMurray Formation consists predominantly of unconsolidated sand and semi-indurated shales, which become brecciated when disturbed. In northeast areas of the Athabasca oil sand deposit, karstification of Devonian carbonates, which subcrop beneath the McMurray Formation, has resulted in collapse structures filled with typically unstratified and often chaotic McMurray sediments. This variability is a complicating factor in identifying hydrocarbon reservoir potential. Karst fill dominated by sand is identified as a potential future exploration play in the McMurray Formation.

KARST FORMATION

Karst is a type of topography formed over limestone, dolomite, or gypsum by dissolution, which is characterized by sinkholes, caves, and underground drainage (Bates and Jackson, 1984). The development of karst terrains occurs primarily when carbonate rocks are hard and relatively free from impurities (i.e. less than 20 % terrigenous material) (Goodman, 1993).

The fundamental karst forming solution process is carbonation, a type of chemical weathering. Carbonation involves the reaction of dilute carbonic acid with a mineral, as summarized by Goodman (1993) in the following equations:

Development of carbonic acid:

$$CO_2 + H_2O \rightarrow H_2CO_3$$

Dissociation of carbonic acid:

$$H_2CO_3 \rightarrow HCO_3- + H^+$$

Acid reaction with calcite:

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3$$

In summary:

$$CO_2 + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3-.$$

Carbonic acid is formed as rainwater percolates through soils, absorbing carbon dioxide from air within the soil. Soil carbon dioxide levels are derived from the atmosphere. The hydrogen ions of mildly acidic rainwater react with calcite, producing calcium and bicarbonate ions. The acidic rainwater becomes progressively weaker through removal of hydrogen ions as this process continues and the residual water becomes progressively saturated with respect to calcium and bicarbonate (Goodman, 1993).

KARST MATURITY

The development of karst topography advances through stages identified as juvenile, mature and old (Goodman, 1993). Juvenile karst terrain has not been appreciably topographically lowered and retains relatively normal surface drainage. Some stream discharge is lost to underground conduits and springs are produced where these flows rejoin the surface (Goodman, 1993). In early maturity, vertical joints in the rock are enlarged by solution to form pinnacles and narrow vertical caverns. Some shallow caves develop, and roof collapse forms sinkholes. In fully mature karst terrain, the land surface is irregular, with numerous small divides between sinkholes and bases at different elevations. Drainage is now focused on sinkholes. The limestone is covered with an extremely variable thickness of residual clay (Goodman, 1993). In old karst terrain, the limestone is virtually leveled or completely removed. It is replaced with a thick deposit of residual clay, consisting of the insoluble residue from calcite and dolomite solution. The topography is irregular (Goodman, 1993). The stages of karst development are illustrated in Figure 48. The sub-Cretaceous unconformity surface overlain by the McMurray Formation in the study area most closely resembles a karst surface between early maturity and late maturity (Figure 48 B or C).

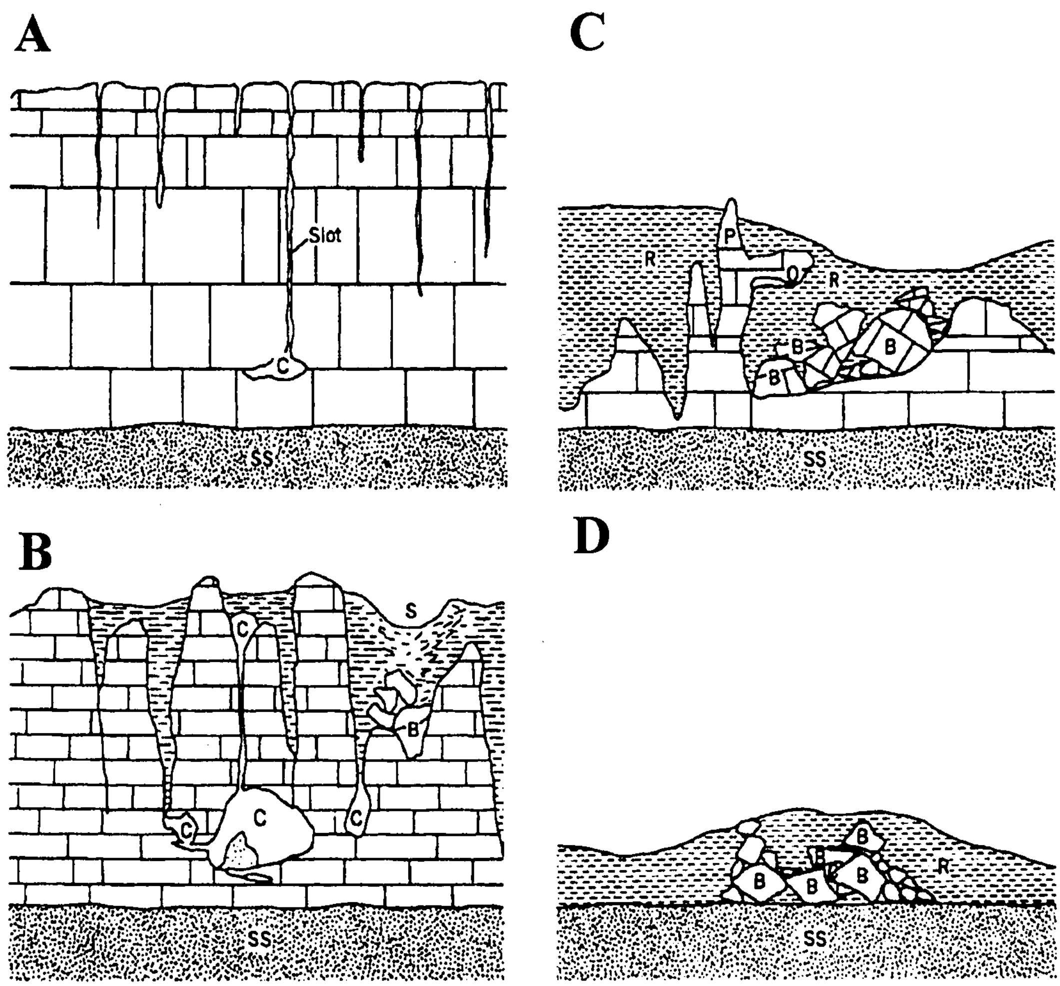


Figure 48
Development of solution cavities and karst features:
A Juvenile
B Early maturity
C Late maturity
D Old
C, cavity; S, sinkhole; SS sandstone; B, block: R residual soil; P, pinnacle; O, overhanging pinnacle (after Goodman, 1993).

DEVONIAN SUCCESSION AND MECHANISM OF COLLAPSE

In the Athabasca Oil Sands area, the Precambrian basement is overlain unconformably by a succession of Devonian evaporites and carbonates. The Devonian strata pinch out against the Canadian Shield to the east and thicken westward (Norris, 1973) as depicted in Figure 49. Devonian strata dip to the west-southwest and the strata that subcrop at the sub-Cretaceous Unconformity become successively younger toward the west (Martin and Jamin, 1963).

In the study area, the Devonian succession includes the Lower Devonian Elk Point Supergroup and the Upper Devonian Beaverhill Lake Group. Of great importance is the Elk Point Supergroup Prairie Evaporite Member (Figure 49). The salt deposits of the Prairie Evaporite extend south to north from North Dakota to the Northwest Territories, and west to east from the northeastern corner of British Columbia, through Alberta, Saskatchewan and Manitoba (DeMille *et al.*, 1964). This large areal extent is illustrated in Figure 50. Dissolution of the Devonian Elk Point Supergroup is evident throughout this area.

In Saskatchewan, features such as the Rosetown Low (covering about 144 sections) and the Hummingbird trough exhibit repeated episodes of salt leaching of the Prairie Evaporite, accompanied by downwarping and compensation in overlying strata (DeMille *et al.*, 1964). To the west, in the Peace River oil sand deposits, Dembicki and Machel (1996) recognized an extensive karst system developed in the Grosmont Formation that is characterized by an irregular erosional surface, metre-size dissolution cavities, collapse breccias, sinkholes, paleosols and fractures. In the Northwest Territories, Park and Jones (1985) noted a distinctive feature where karsting of the Slave Point Formation was filled with remnant Cretaceous sandstones, siltstones and shales comparable to the McMurray Formation. However, the McMurray Formation has been eroded in the area and is absent within the stratigraphic column.

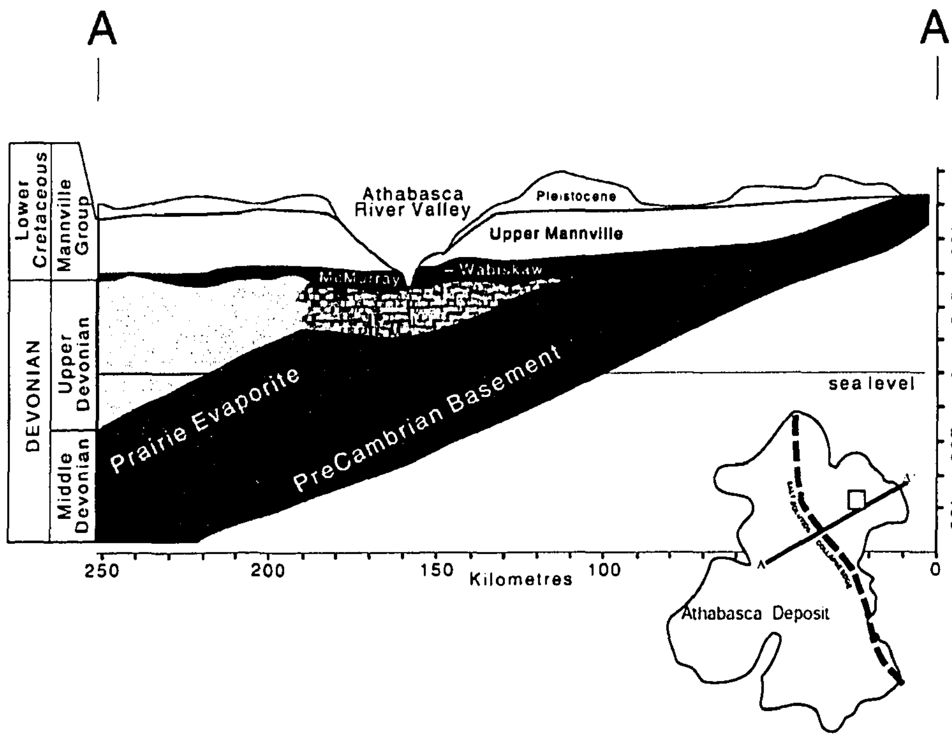


Figure 49
Structural cross-section through the Athabasca reservoir at location A-A'. Structural collapse due to salt dissolution of the Prairie Evaporite caused collapse as indicated by of the overlying upper Devonian rubble (modified from Ranger, 1994). The square on the basemap is the Sunrise Thermal Project area.

In the Athabasca deposit, the Sunrise Thermal Project study area is located east of the dashed line of salt solution collapse edge of Figure 49. In this area, the Prairie Evaporite Member is no longer present due to dissolution. This has immense consequence for the area, as its dissolution caused collapse of the overlying Devonian sediments as indicated by upper Devonian rubble (Figure 49).

Evidence of collapse within the Devonian succession includes breccia and saturation, as deep as 23 m below the sub-Cretaceous unconformity (Plate 28, Photo A), slickensides 5 m above the middle Devonian (Plate 28, Photo B), and faulting 3 m above the middle Devonian (Plate 28, Photo C). The locations are illustrated on the wireline log of Figure 51.

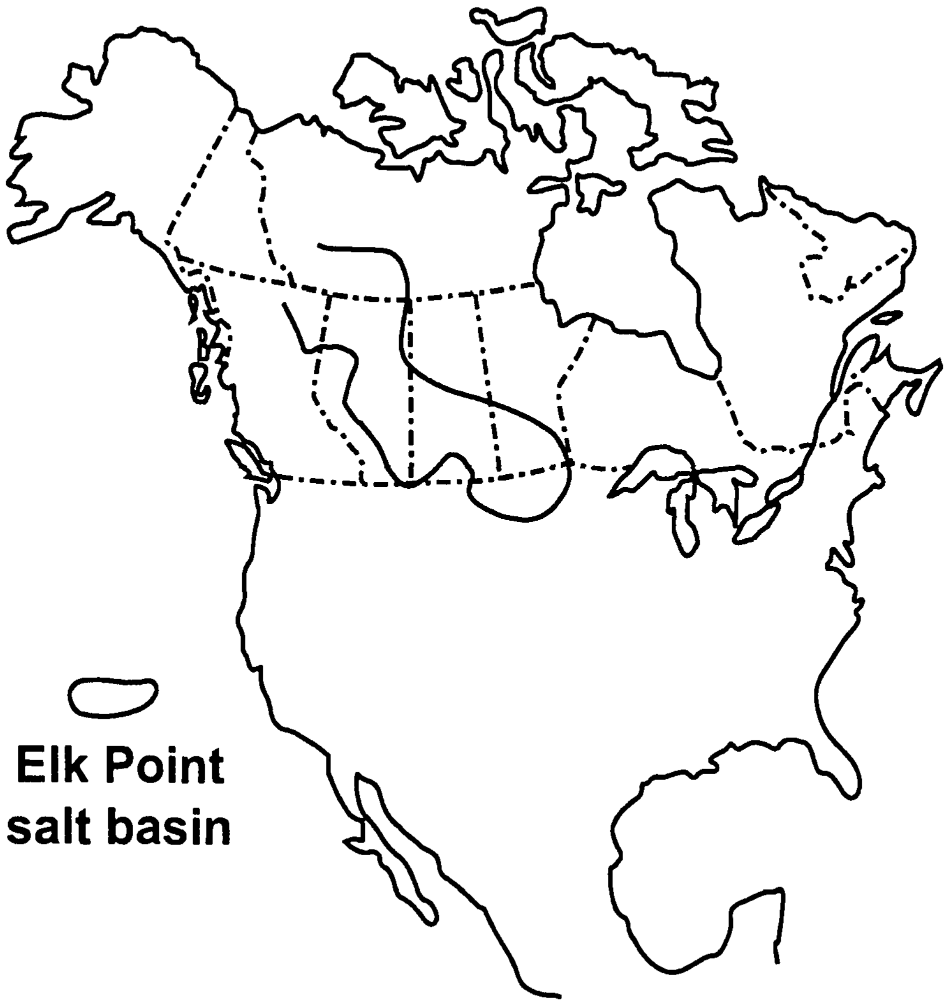


Figure 50
Shaded area shows the extent of the Elk Point evaporites. (from DeMille *et al.*, 1964).

Bell (1885) and McConnell (1893) first noted that Cretaceous sediments unconformably overlie Devonian carbonates in the Athabasca oil sands area. During this extended hiatus (approximately 270 million years), it is probable that the Devonian strata were subjected to several periods of subaerial exposure allowing for dissolution and weathering. Park and Jones (1985) provided evidence for at least three episodes of karsting in the Northwest Territories. Locally observed green calcareous shales (Plate 28, Photo A) directly beneath the McMurray Formation (Carrigy, 1959a; Stewart, 1963) are consistent with long periods of subaerial exposure, as they are interpreted as weathered limestones.

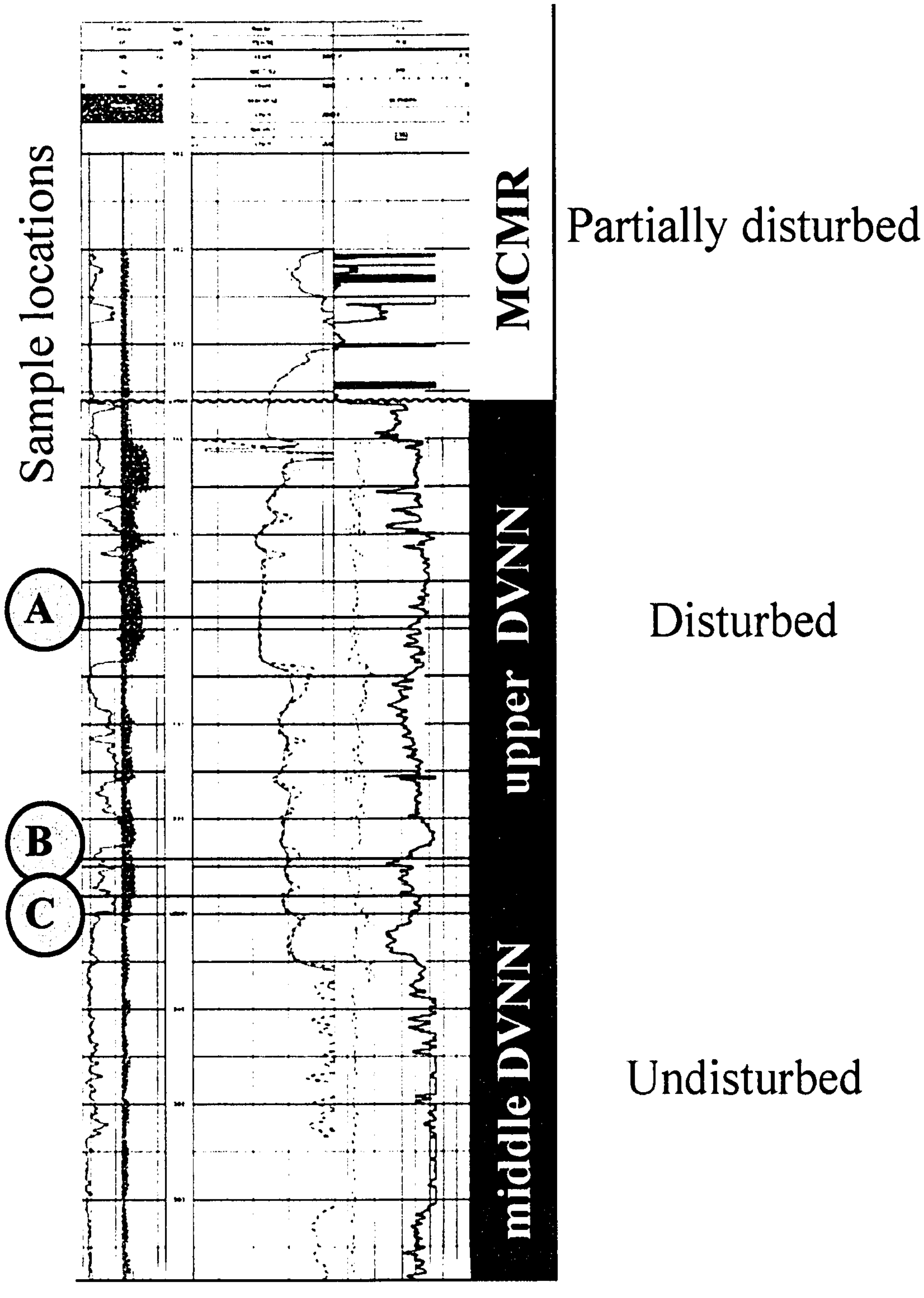


Figure 51
Wireline log from 1F1/14-07-095-07W4 indicating the McMurray Formation, the top of the upper Devonian, and the top of the middle Devonian. This log displays the location of the samples A, B and C from Plate 28.

TIMING OF COLLAPSE

Paleokarst is a typical feature within many foreland basin sequences. They occur in carbonate sequences related to the formation of peripheral bulges. As a consequence of flexural downwarp due to thrust emplacement and loading, uplift occurs in the foreland in conjunction with subaerial exposure (Quinlan and Beaumont, 1984). Paleokarst may be regarded as an integral part of foreland basin development. With propagation of the bulge ahead of the migrating thrust front, extensive karsted areas may form (Wright and Smart, 1994).

Collapse likely occurred as repeated episodes during the long hiatus. Collapse began with the dissolution of the Prairie Evaporite and ended when coal was deposited in the McMurray Formation. Evidence for collapse prior to McMurray sedimentation includes the infilling of Devonian rubble by McMurray sediments with original sedimentary structures preserved (Plate 29, Photos A and B). Evidence for collapse subsequent to McMurray sedimentation includes soft sediment deformation within the fill, such as smeared microfaults (Plate 29, Photo C) and convolute to contorted bedding (Plate 29, Photo D).

At the time of coal deposition, the deformed bedding associated with collapse ceased. Plate 30 illustrates normally inclined bedding above the coal and deformed and oversteepened bedding below the coal. As such, Devonian clasts are absent above the coal.

FILL VARIATION

Collapse fill variation occurs with classes of breccia (Plate 31), cementation and saturation (Plate 32), incorporated McMurray sediments (Plate 33), and structures (Plates 34 and 35).

Cave fill classification by Loucks (1999) identifies three end members of breccias/conglomerates: fracture-dominated, clast-dominated and sediment-dominated (Figure 52). The fracture-dominated examples (Plate 31, Photos A and B) are most closely related to crackle breccias. An irregular network of fractures, which cut the original carbonate rock, is subsequently filled, thereby separating the clasts. The clasts are angular and commonly in place. If clast displacement or rotation is evident, mosaic breccia is the proper term.

The clast-dominated breccia examples (Plate 31, Photos C and D) are most similar to chaotic breccias. During the karstification process, depressions, sinkholes, and caves develop, resulting in collapse of the overlying rocks. Under physical and chemical processes, these collapse blocks break down into breccias that accumulate as a result of gravity. They may be transported for a short distance. Chaotic breccias are characterized by extensive rotation and displacement of clasts.

The sediment-dominated breccia examples (Plate 31, Photos E and F) are entirely composed of sediment fill with little or no original limestone clasts. This classification includes all material deposited in caves and sinkholes. In this type of breccia, deposition occurs as a result of transportation by traction current, mass flow, or debris flow on the surface or underground. These breccias exhibit the most potential as economically viable reservoirs.

Cementation and bitumen saturation within McMurray sand fill varies from absent to partial to pervasive. Well saturated and uncemented examples are most common (Plate 32, Photo A). Partially saturated and partially cemented intervals are least common (Plate 32, Photo B) and occur in two wells for less than 1 m. Unsaturated and cemented sands are also rare (Plate 32, Photo C); they occur in four wells, for less than 1 m. In the McMurray Formation, cemented and unsaturated examples do not have an effect on economics of karst fill reservoirs, due to their low abundance.

Cement in collapse fills is calcareous, indicating that calcite saturated water flowed through a small portion of fractures, precipitating excess carbonate. Incidences of partial cement and partial saturation may suggest one of two possibilities. The first possibility is that low hydrocarbon saturation is due to poor sorting of the sediments, causing constriction of pore throats. This constriction may have prevented hydrocarbon migration and allowed the trapping of carbonate-rich interstitial water (from dissolution at some distance away), producing cementation. Another possibility is, in rare instances, hydrocarbon migration and cementation occurred penecontemporaneously.

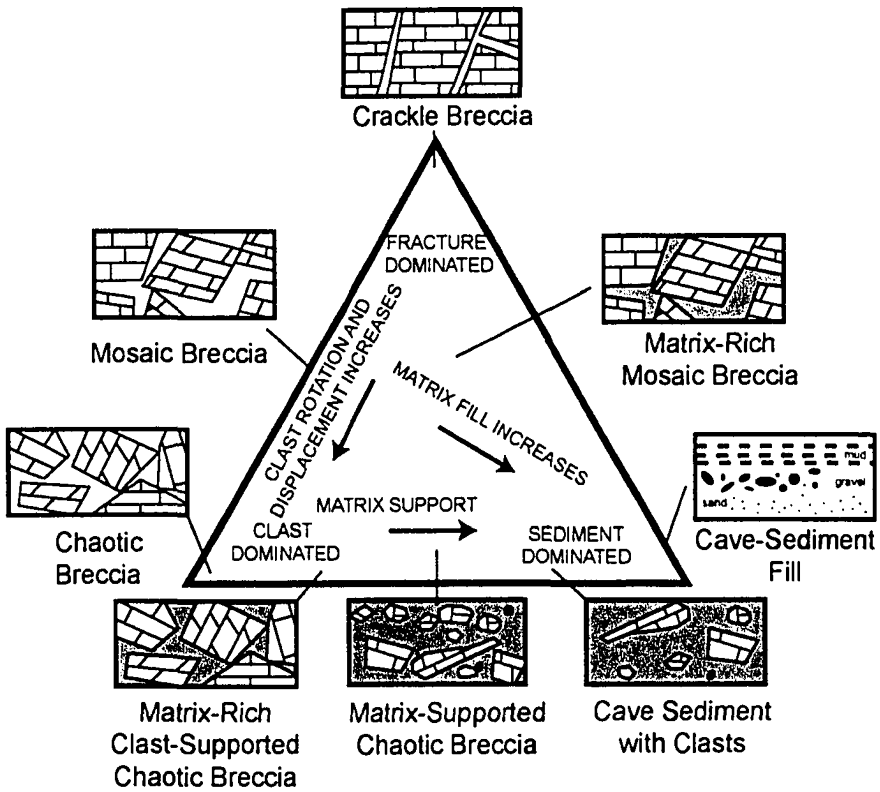


Figure 52
Classification of cave breccias and sediment fills. The triangle displays three end members; fracture-dominated, clast-dominated and sediment-dominated (from Loucks, 1999).

All possible McMurray Formation sediments may be incorporated within sediment fills. This includes quartz granules (Plate 33, Photo A); mud clasts (Plate 33, Photo B) and wood fragments (Plate 33, Photo C). These incorporated clasts suggest that deposition was rapid. A mechanism that could generate such quick deposition is that of cave collapse, producing a sinkhole where sediments were pre-existing on the overlying surface. This would account for the excellent preservation of the large wood fragments and the intact lamination in mud clasts observed (Plate 33, Photo B).

The structures of McMurray sediment fill are variable. Roll structures (Plate 34, Photo A) may suggest that a previous cave fill, with intermixing of McMurray sand and Devonian clasts, was remobilized. Stepped fractures (Plate 34, Photo B) suggest that McMurray sediments were partially indurated prior to movement and that movement was akin to movement in a rift basin, but on a miniature scale. The most common structures are slide planes (Plate 34, Photos C, D and E). Slide planes are interpreted to be sinkhole fills. Near vertical bedding (Plate 35, Photos A and B) may be 6 to 9 m thick, and are also interpreted as sinkhole fill.

Collapse fill may be of McMurray origin (sand- or mud-dominated), Devonian origin, or mixed origin. Well saturated sandy cave fill with Devonian roof sediments and Devonian floor sediments are considered potentially economic reservoirs for future exploration (Plate 36). Devonian origin fills would be Devonian roof rock with little or no reservoir potential.

Fills of mixed origin may have repetitions of various Devonian and McMurray sediments (Plate 37). Devonian sediments that are commonly incorporated include rubble and weathered lime muds as clasts or matrix. McMurray sediments that are commonly incorporated include sand, white paleosols muds, and dark gray organic marsh muds (Plate 37). Due to the lack of well-saturated sand, this example would never be economic.

EXPLORATION OF SINKHOLES

The development of karst dissolution in carbonate rocks by meteoric water during subaerial exposure is an important geologic phenomenon that can lead to the formation of petroleum reservoirs (Fritz *et al.*, 1993; Loucks, 1999). Karst-related reservoirs commonly show great heterogeneity (Kerans, 1988; Hopkins, 1999), which complicates exploration for oil sand gas (Wang and Al-Aasm, 2002).

Loucks (1999) noted that paleocave systems that form large reservoirs are not a product of the collapse of an isolated cave passage, but instead are a product of coalesced, collapsed-cave systems. Internal spatial complexity is high, resulting from the collapse and coalescing of numerous passages and cave-wall and cave-ceiling strata. The more extensive coalesced, collapsed-paleocave systems originated at composite unconformities where several cave systems may overprint themselves during several million years of exposure to karst processes (Esteban, 1991; Lucia, 1995; Loucks, 1999).

The stages of coalesced, collapse-paleocave system development are illustrated in Figure 53. Multiple cave-system development at a composite unconformity may be necessary to produce a high density of passages. As the multiple episode cave system subsides into the deeper subsurface, wall and ceiling rocks adjoining open passages collapse and form breccias that radiate out from the passage and intersect with fractures from other collapse pages and older breccias in the system. Collapsed paleocave systems are the prime exploration targets (Loucks, 1999).

Identification of Athabasca coalesced collapses as exploration targets may utilize the model to predict reservoirs by looking for sag structures. Application of the model will predict the collapse by the sag of the coal (Figure 26).

ECONOMICS

Current steam-assisted gravity drainage (SAGD) technology utilizes 20 m of continuous vertical pay and a horizontal well bore length of approximately 1 km. A sinkhole cross section containing 28 m of continuous collapse pay, and approximately 1 km in length (Figure 26) would suggest that the reservoir is viable economically with current technology. However, it is unlikely that sufficient horizontal well bore length for SAGD exists, as the sinkhole edges have been illustrated to give the maximum appearance of pay. Economics are limited by the ability to image the edges of sinkholes. Additionally, the internal continuity of the pay is suspect due to uncertainty regarding the amount of sand fill and clasts. Economics are also limited by the ability to predict the internal stratigraphy.

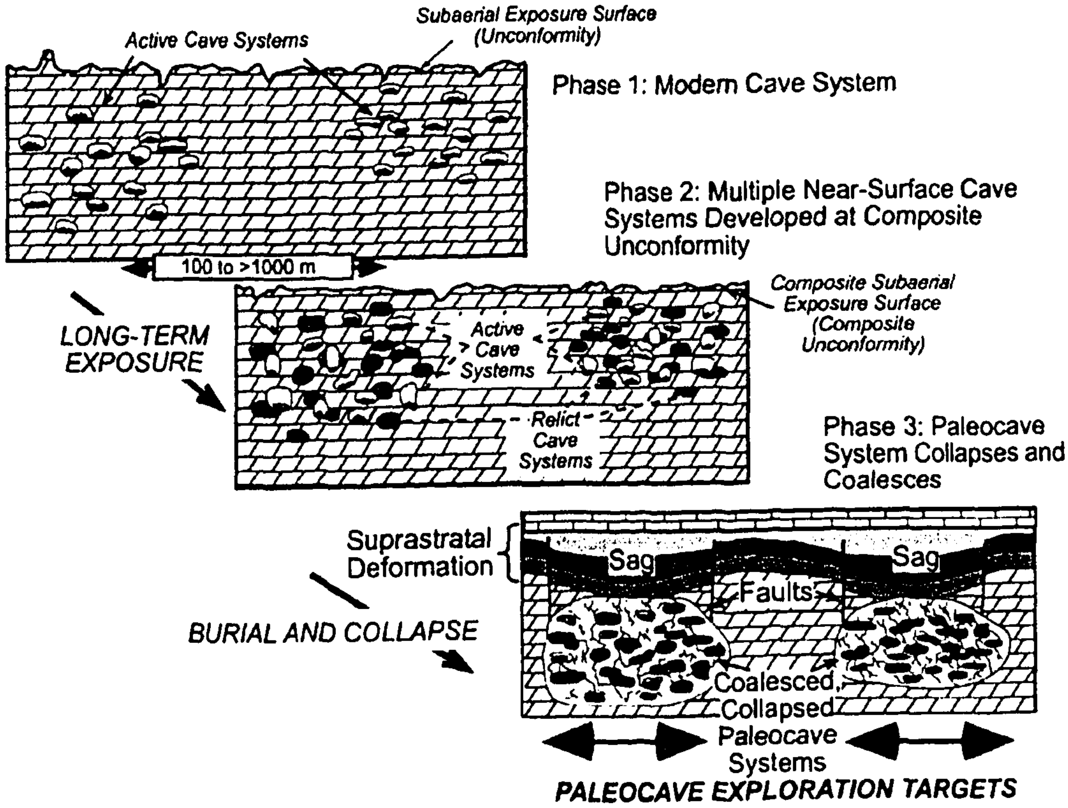


Figure 53
Schematic diagram showing the stages of development of a coalesced, collapsed-paleocave system. Multiple cave-system development at a composite unconformity may be necessary to produce a high density of passages. As the multiple-episode cave system subsides into the deeper subsurface, wall and ceiling rocks adjoining open passages collapse and form breccias that radiate out from the passage and intersect with fractures from other collapsed passages and older breccias in the system. The strata above the collapsed system are characterized by faults and sags termed "suprastratal deformation". The collapsed-paleocave systems are the prime exploration targets (modified from Loucks, 1999).

The internal stratigraphy of collapse fill is complex and the resulting heterogeneous reservoir characteristics cause variable recovery rates (Dembicki and Machel, 1996). Three vertical steam stimulation projects, between 1975 and 1986, attempted to extract bitumen from the paleokarst systems of the subcrop edge of the

Grosmont Formation. The projects encountered variable recovery results, ranging from 20 bbls/day to 500 bbls/day (Vandermeer and Presber, 1980; Harrison and McIntyre, 1981; Harrison, 1982). In order to improve production, it is essential to more fully understand and delineate the geometry of paleokarst systems.

On the Sunrise Thermal Project lease, the sub-Cretaceous unconformity surface has more than sixty sinkholes (Figure 54). Using broad assumptions of; 30% porosity, 80% oil saturation, 30% volume of clasts, 50% recovery factor, and only 50% of collapses as sand-dominated, produces a resource estimate on the order of tens of millions of barrels. This estimate advocates that the volume of oil currently left behind is significant.

In the future, sinkholes in the McMurray Formation may be a new play type. The ability to image the edges of sinks holes and predict internal stratigraphy will be essential. In addition, most sinkholes are not of the required horizontal and vertical economic limit for current technology (Plate 36), and advances in SAGD technology, or VAPEX or new technology will be required to make sinkholes economically viable reservoirs.

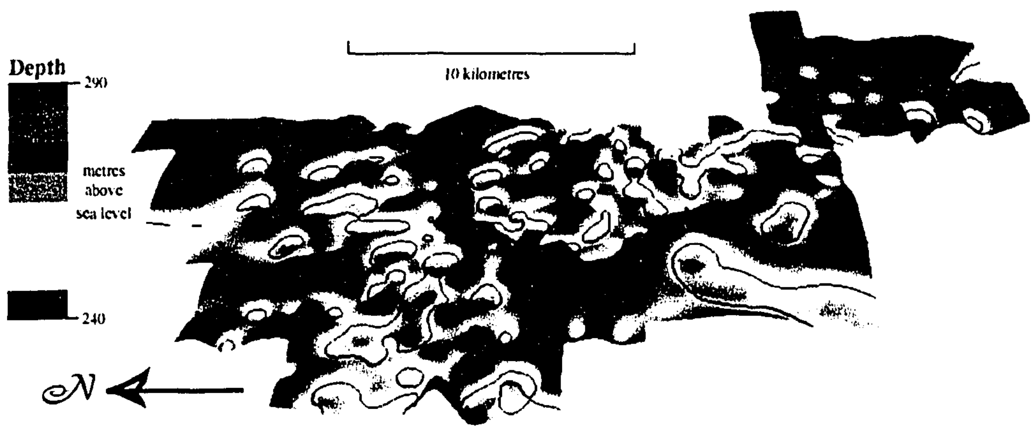


Figure 54
Three dimensional view of the Sunrise Thermal Project sub-Cretaceous unconformity surface exhibiting more than sixty sinkholes. Assuming 30% porosity, 80% oil saturation, 30% clasts, 50% recovery factor, and 50% of collapse as sand filled produces a resource estimate on the order of tens of millions of barrels. Sinkholes are identified as a potential future play type.

SUMMARY

Collapse played a significant role to the east of the Prairie Evaporite solution edge. It occurred as repeated episodes beginning with the dissolution of the Prairie Evaporite and ending at the time of the deposition of the McMurray coal. The variation of paleokarst fills are based on the classification of the breccia, amount of cementation and saturation, incorporated sediments, and structures. This variability produces a heterogeneous reservoir producing a difficult target. Better reservoirs may result from coalesced collapsed systems, and the common sag associated with these collapses may be an exploration tool useful to identification of these reservoirs.

Collapse fills may be an exploitation play in the future, however, the current economics are limited by the ability of current technology to image the edges of collapses, and to predict the complex internal stratigraphy, and to exploit these relatively small-scale reservoirs.

Plate 28

Evidence of collapse within the Devonian succession.

A. Breccia and bitumen saturation from more than 20 m below the McMurray Formation. 1F1/14-07-095-07W4 (198.0 m)

B. Slickensides in three directions, 5 m above the middle Devonian. 1F1/14-07-095-07W4 (224.5 m)

C. Microfaulting located 3 m above the middle Devonian. 1F1/14-07-095-07W4 (227.0 m)

Wireline log with these samples identified in Figure 51.

Plate 28

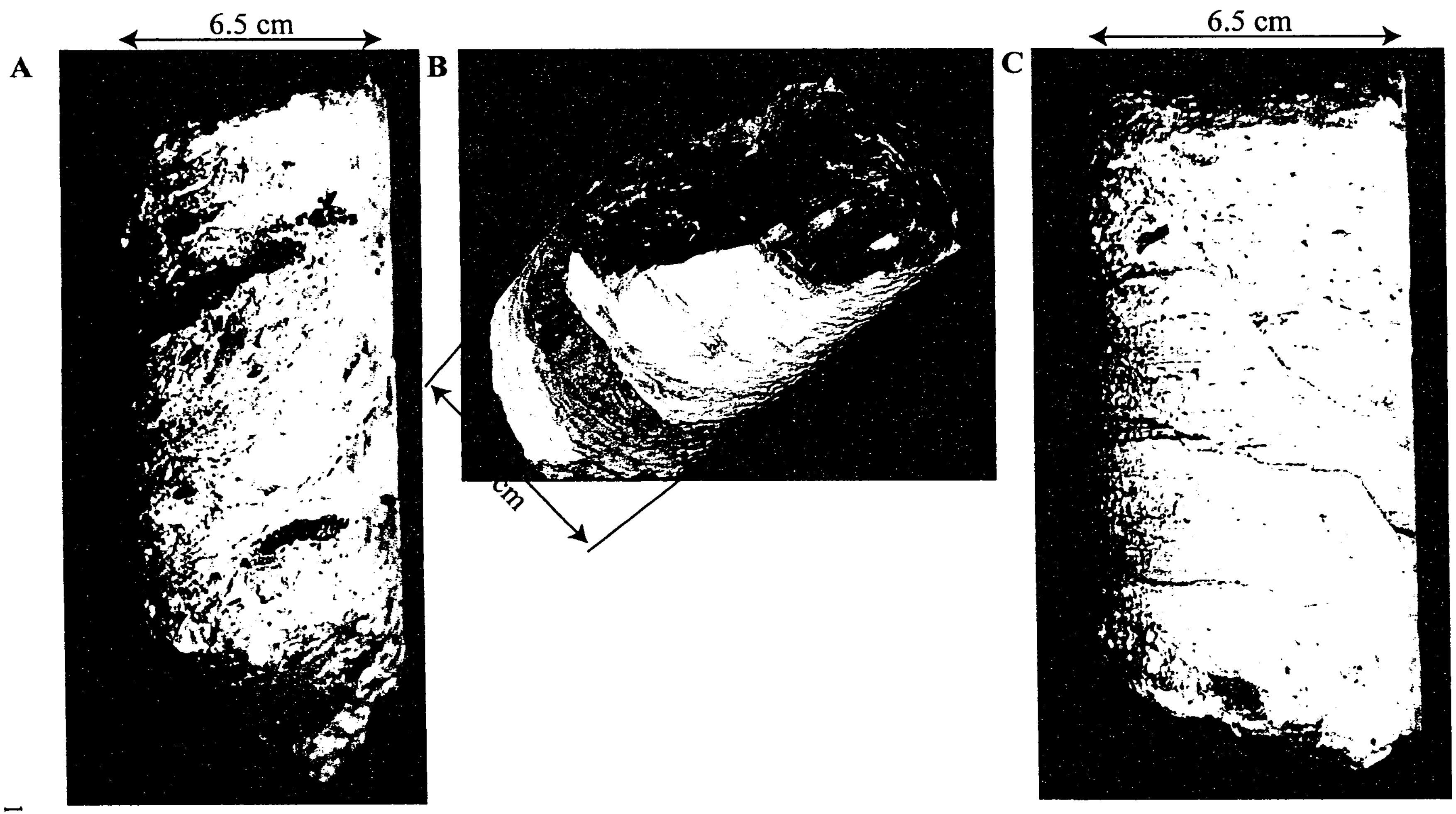


Plate 29

Evidence for collapse prior to McMurray sedimentation.

A. Infill of Devonian rubble by undeformed, saturated cross-stratification. AA/15-16-095-07W4 (229.5 m)

B. Infill of Devonian rubble by undeformed, unsaturated cross-stratification. AA/15-16-095-07W4 (233.25 m)

Evidence for collapse subsequent to McMurray sedimentation.

C. Soft sediment smear fault. AA/05-05-094-06W4 (300.25 m)

D. Soft sediment contorted and convolute laminations. AA/15-16-095-07W4 (225.5 m)

Plate 29

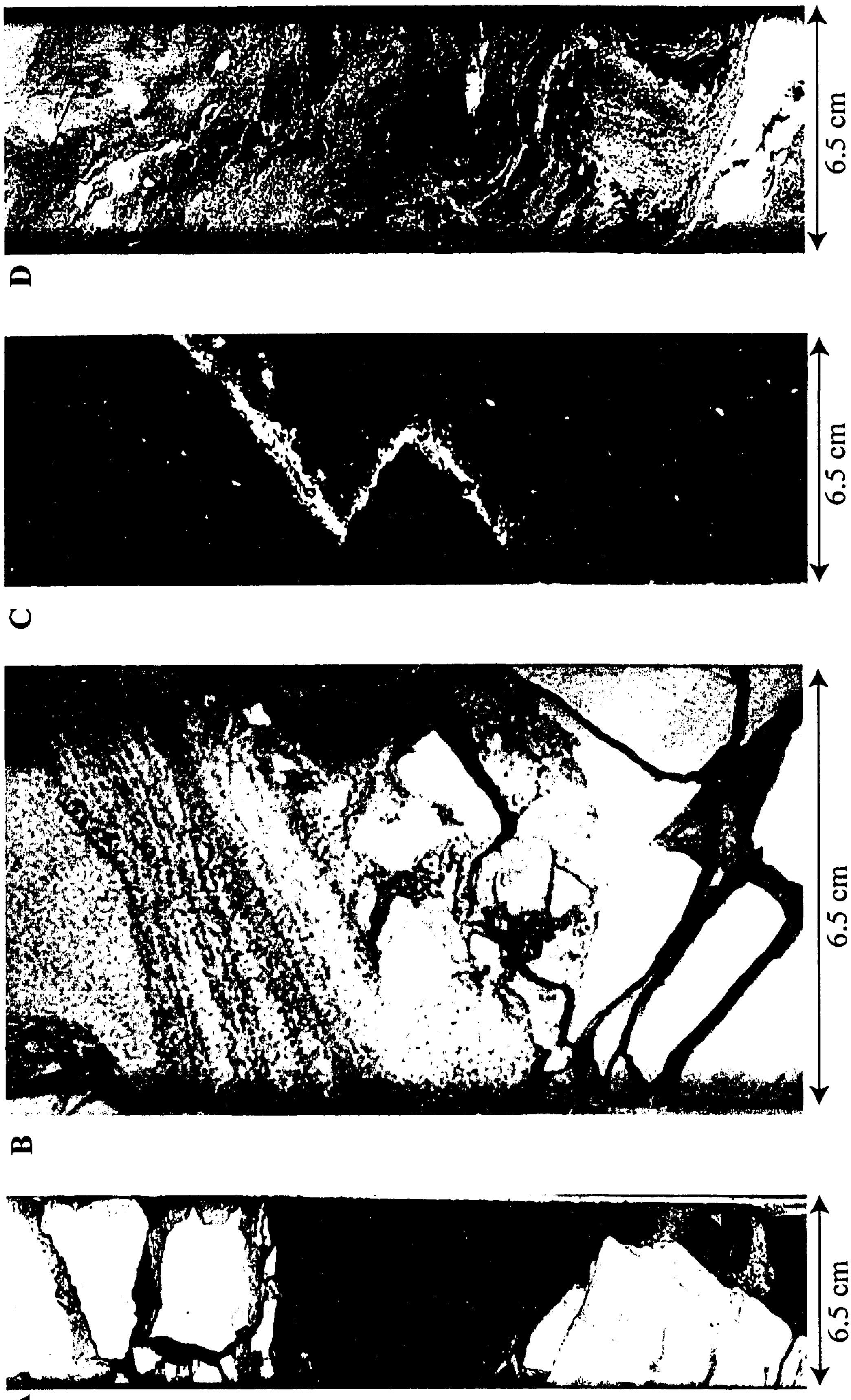


Plate 30

Collapse occurred prior to coal deposition in the McMurray Formation. Normally inclined bedding is evident above the coal, and chaotic and oversteepened bedding is evident below the coal. AA/08-32-094-07W4 (226.0 – 244.0 m)

Plate 30

A

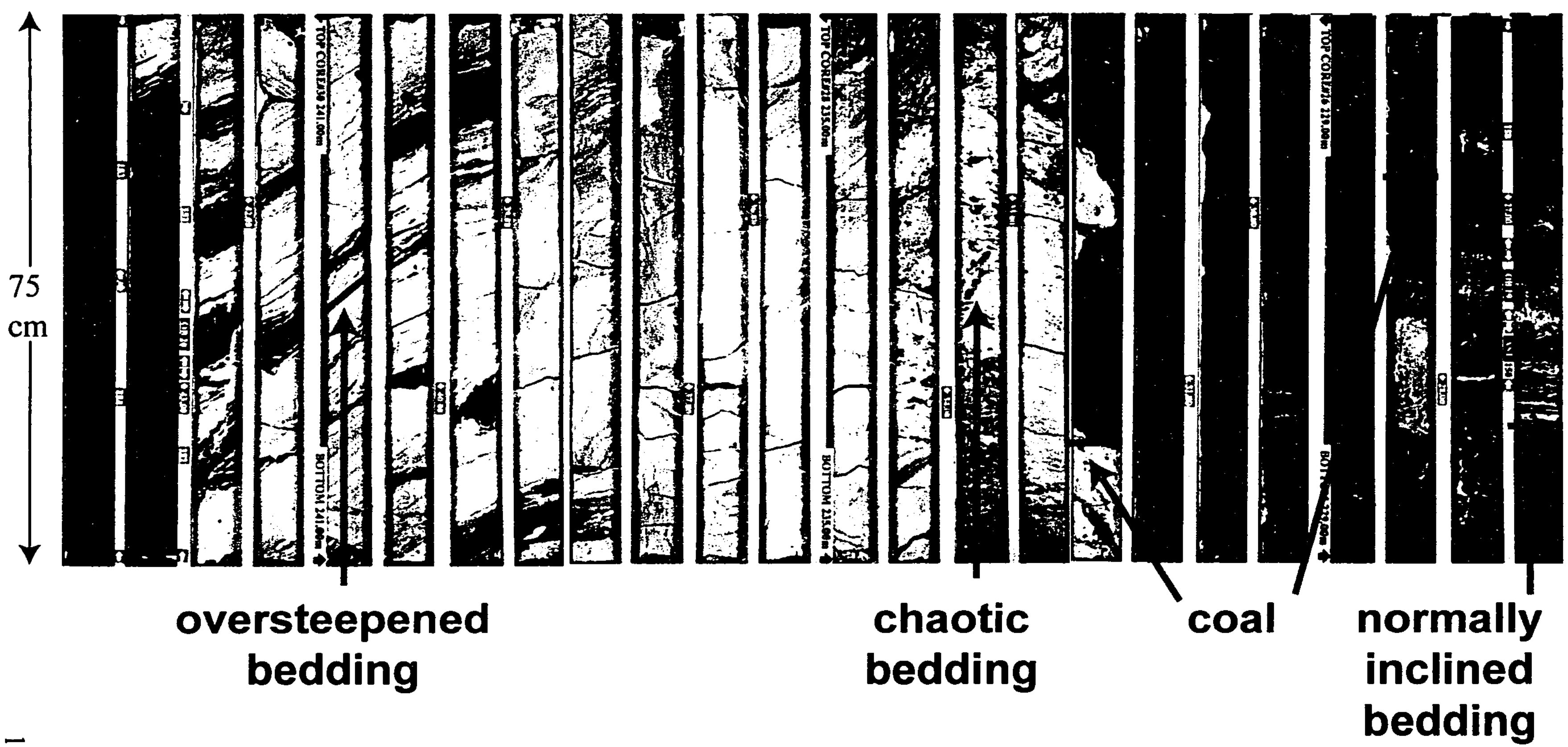

75
cm
oversteepened
bedding
chaotic
bedding
coal
normally
inclined
bedding

Plate 31

Comparison of fracture-, clast- and sediment-dominated breccias from Loucks (1999) classification (Figure 52).

A. Fracture-dominated crackle breccia. AA/12-21-094-07W4 (252.0 m)

B. Fracture-dominated crackle breccia. AA/12-05-095-07W4 (211.5 m)

C. Clast-dominated breccia. AA/09-04-095-07W4 (251.5 m)

D. Clast-dominated breccia. AA/15-16-095-07W4 (233.25 m)

E. Sediment-dominated breccia. AA/ 04-02-095-07W4 (272.0 m)

F. Sediment-dominated breccia. AA/ 04-02-095-07W4 (264.25 m)

Plate 31

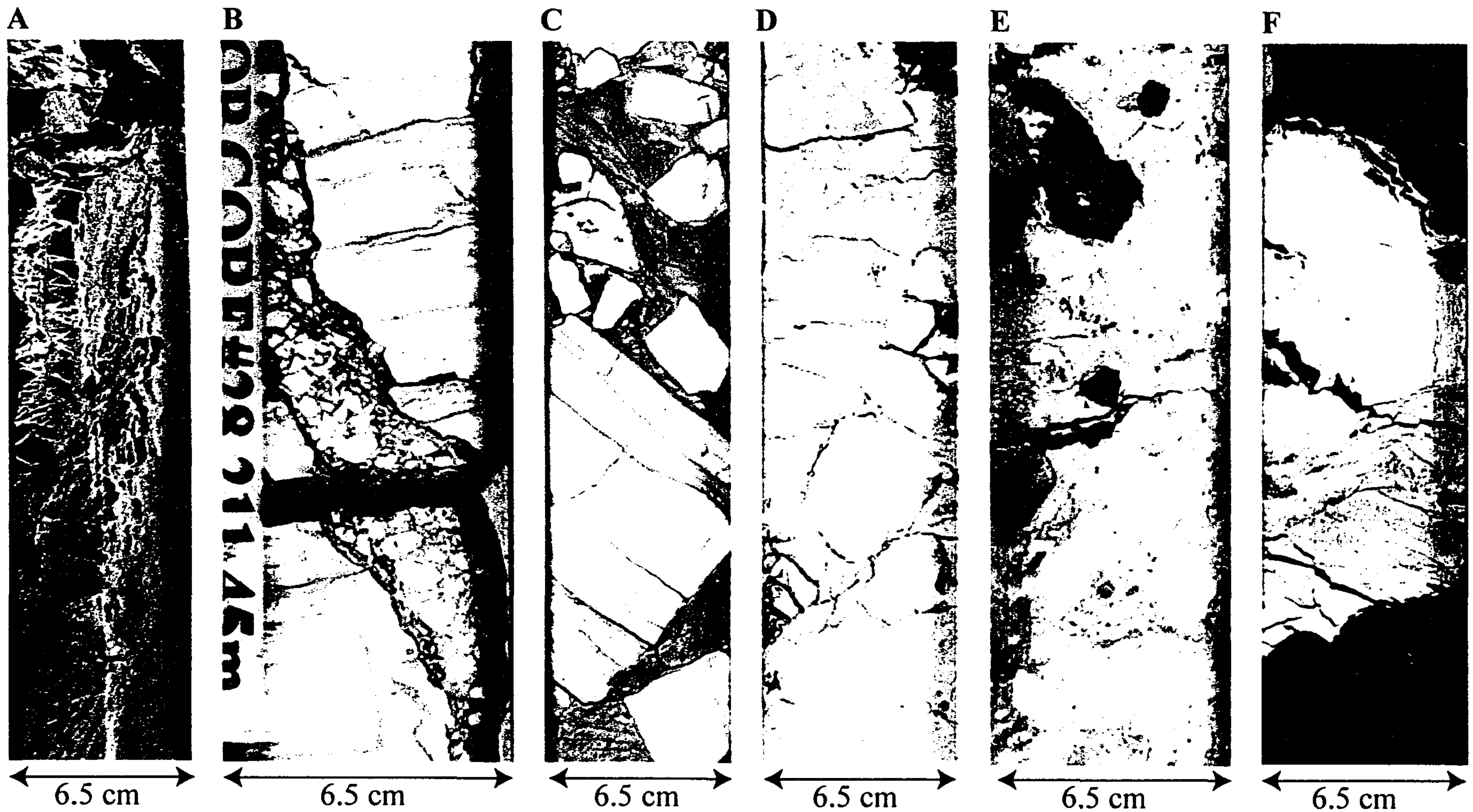


Plate 32

Comparison of cementation and bitumen saturation.

A. Saturated and uncemented sand examples are abundant. AA/09-04-095-07W4 (252.1 m)

B. Partially saturated and partially cemented sand examples are rare. AA/09-04-095-07W4 (254.0 m)

C. Unsaturated and cemented sand examples are rare. AA/15-16-095-07W4 (230.75 m)

Plate 32

A B C

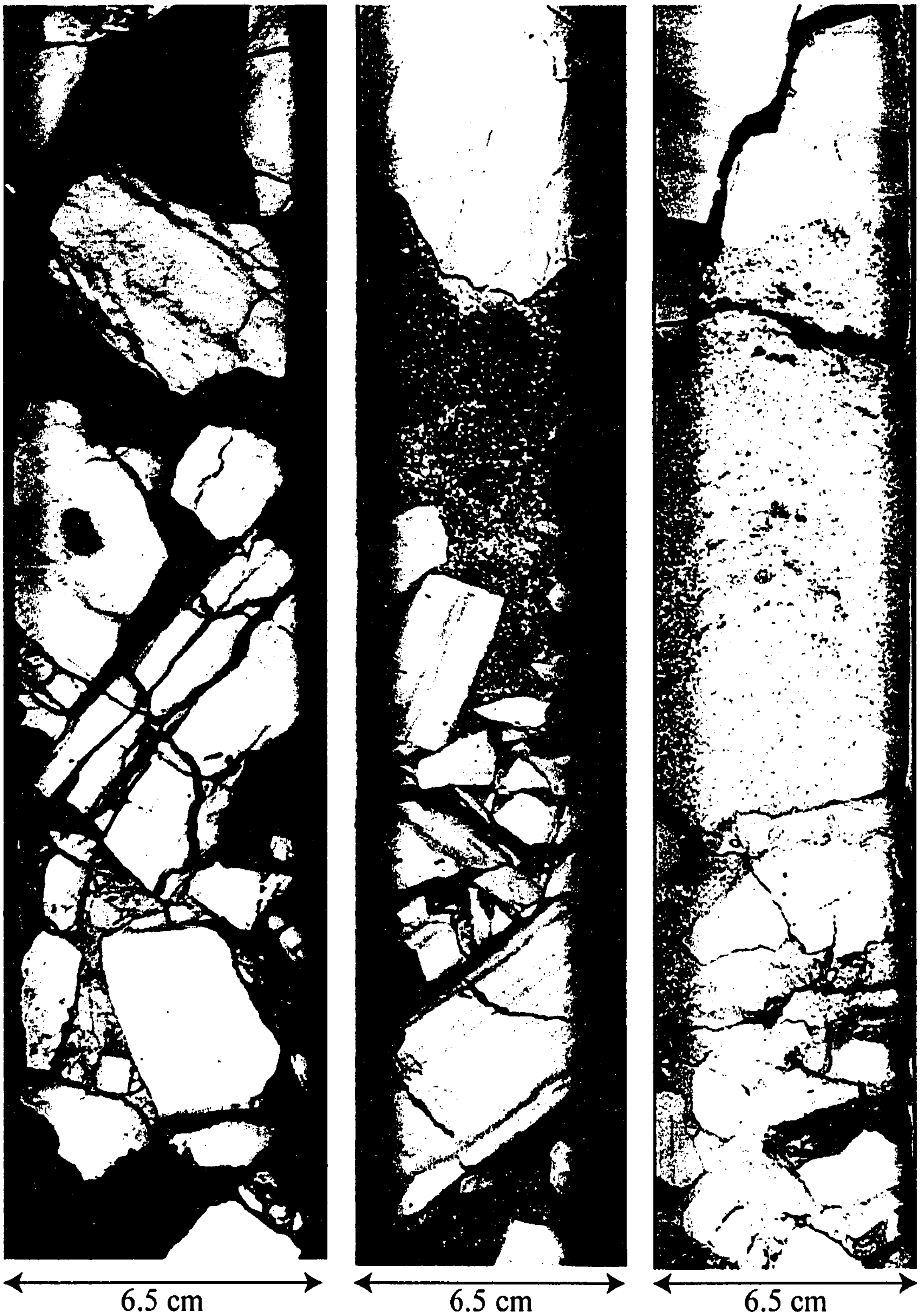


Plate 33

McMurray Formation sediments are incorporated into collapse fill.

A. Pebbles. AA/15-12-095-07W4 (303.75 m)

B. Mud clasts. AA/15-16-095-07W4 (223.5 m)

C. Wood fragment. AA/05-05-094-06W4 (313.25 m)

Plate 33

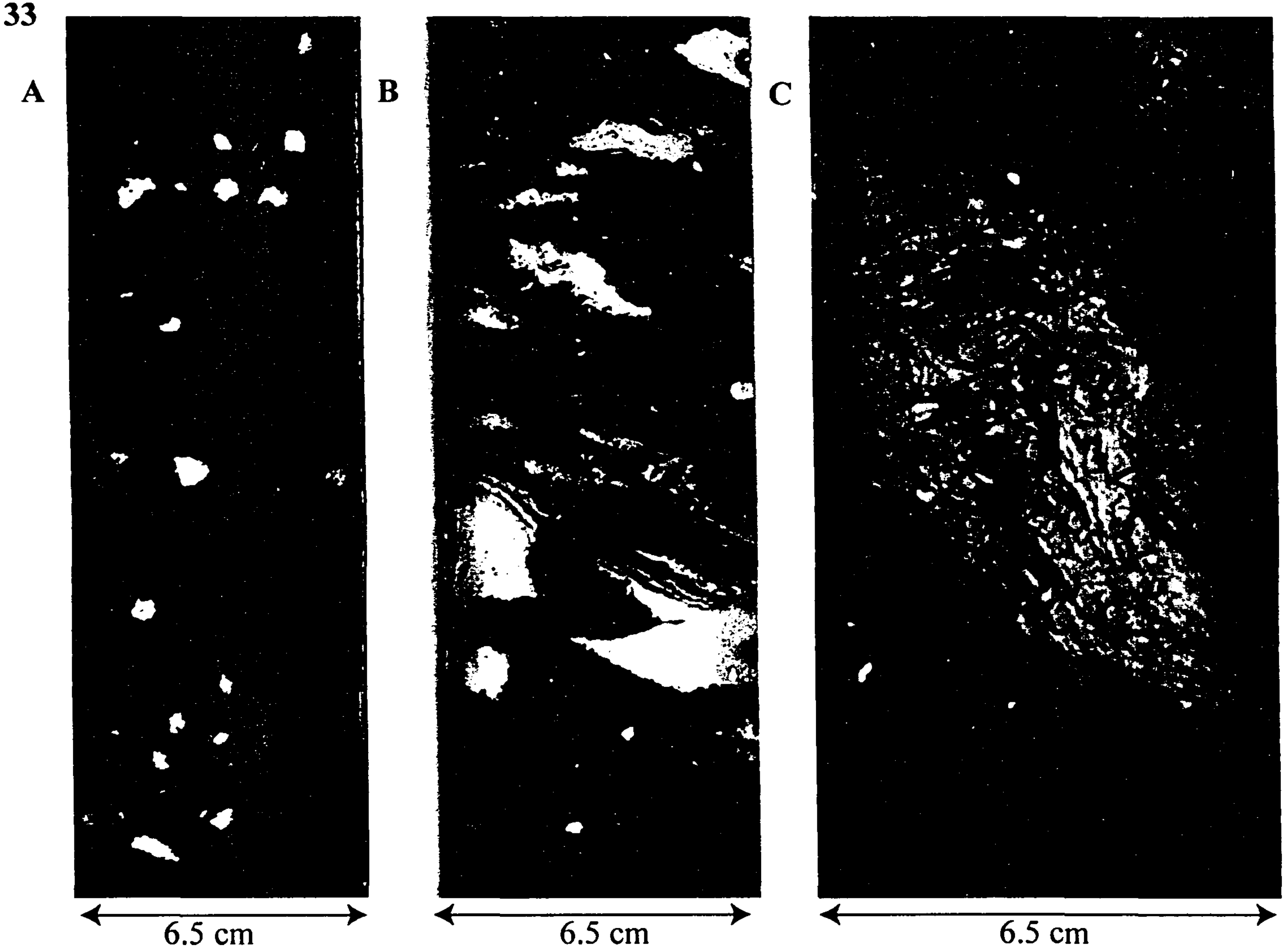


Plate 34

Abundant structures are found in collapse fill.

A. Roll. AA/04-34-095-07W4 (200.5 m)

B. Stepped fractures. AA/12-21-094-07W4 (251.5 m)

C. Slide plane. AA/04-02-095-07W4 (269.0 m)

D. Slide plane. AA/04-34-095-07W4 (180.75 m)

E. Slide plane. AA/04-34-095-07W4 (196.5 m)

Plate 34

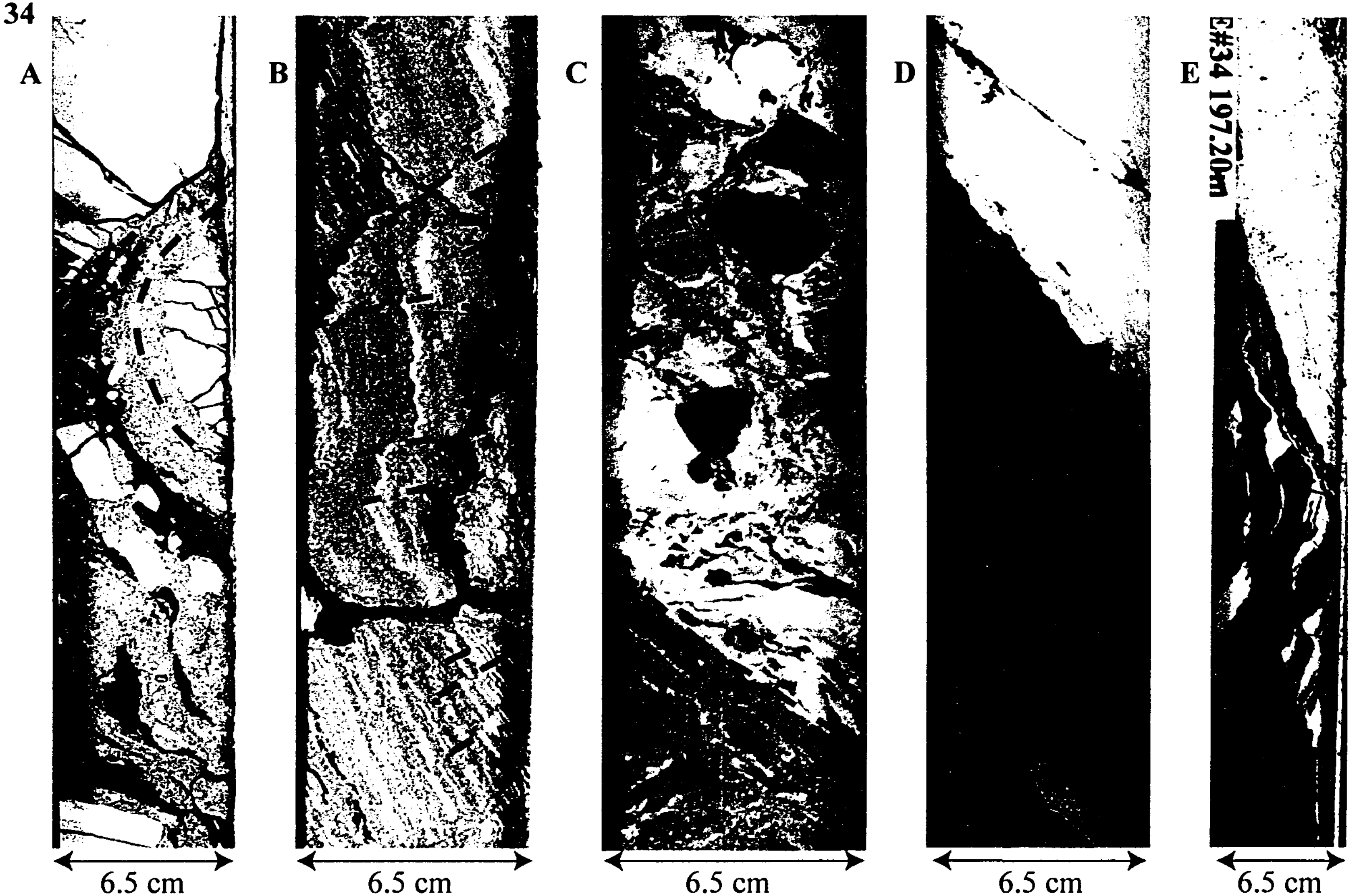


Plate 35

Near vertical bedding in collapse fill is interpreted as sinkhole fill.

A. Near vertical bedding. AA/04-02-095-07W4 (250.0 – 250.75 m)

B. Near vertical bedding. AA/04-34-095-07W4 (191.6 – 192.35 m)

Plate 35

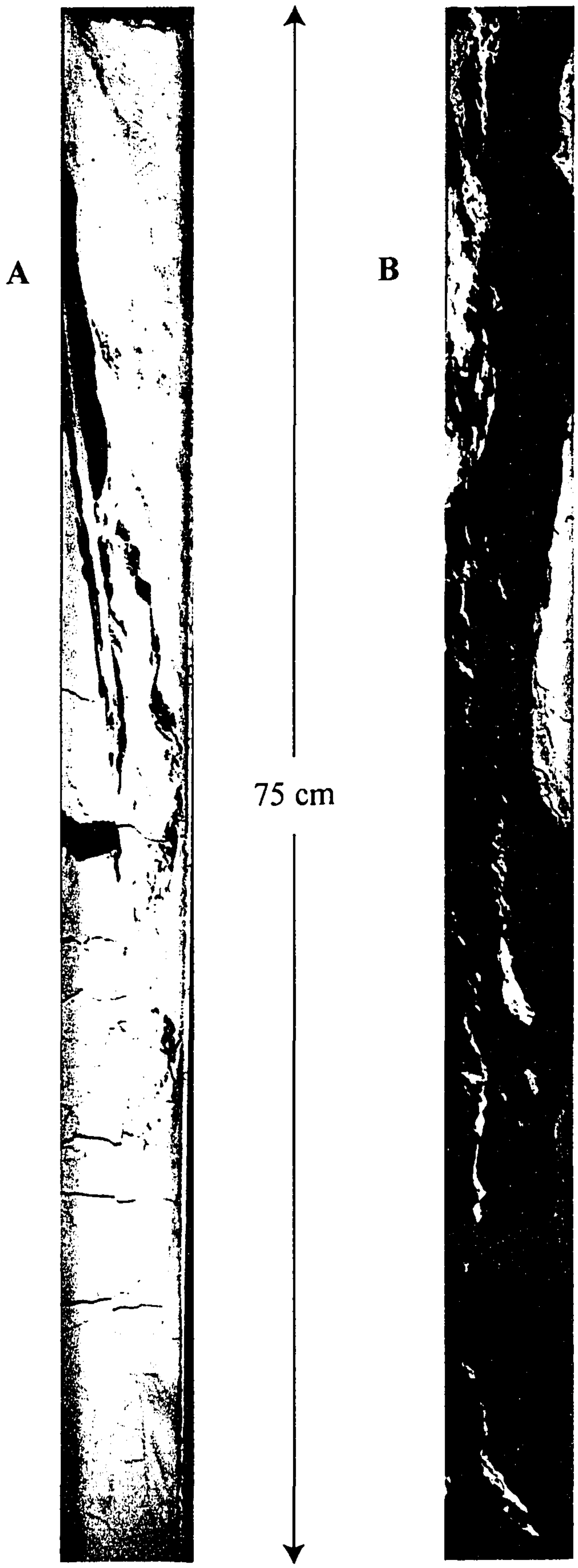


Plate 36

Nine metres of well saturated sand-dominated collapse fill identifiable on wireline logs. This fill is potentially economically viable in the future. AA/07-14-095-07W4 (250.4 – 271.25 m)

Plate 36

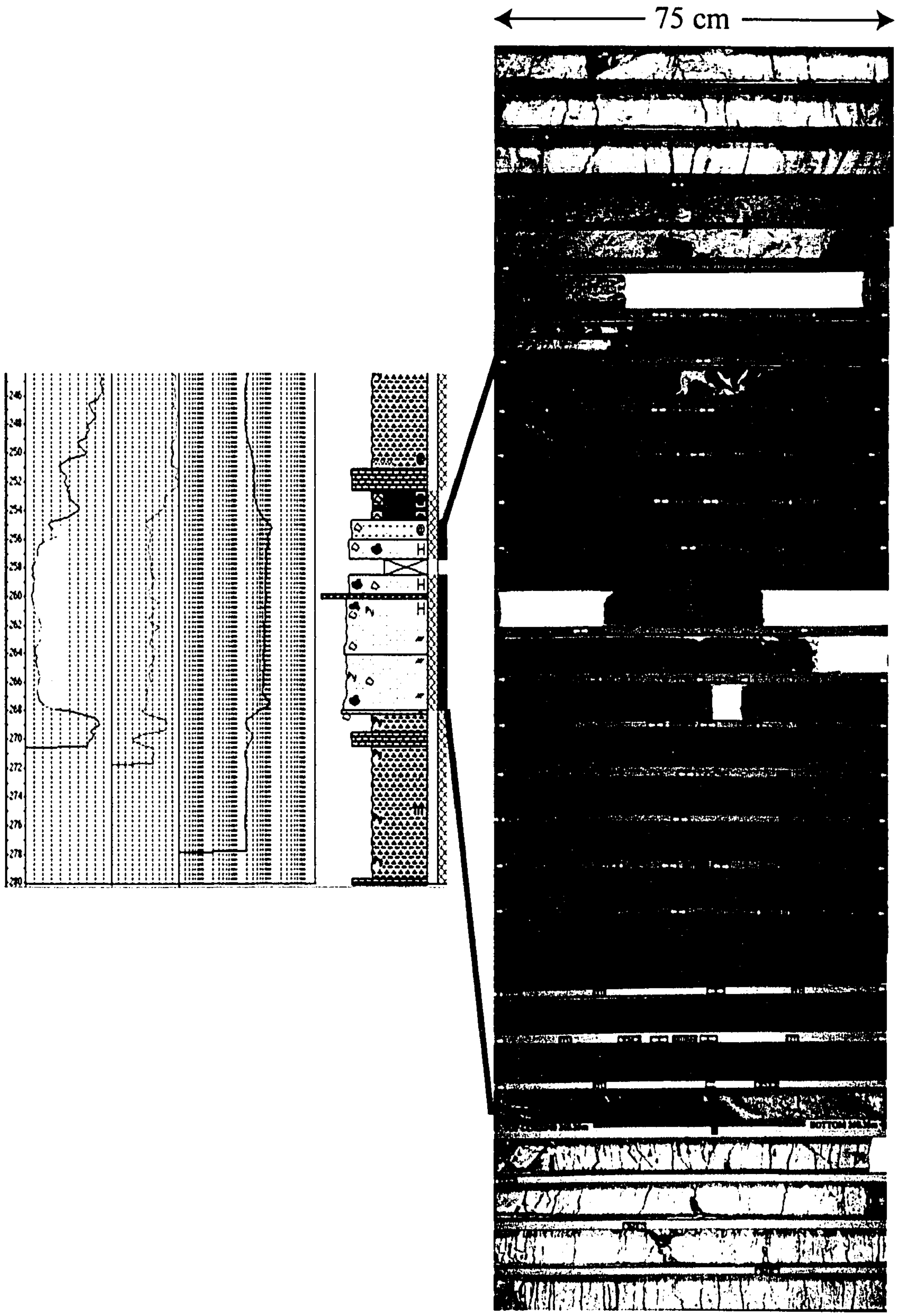
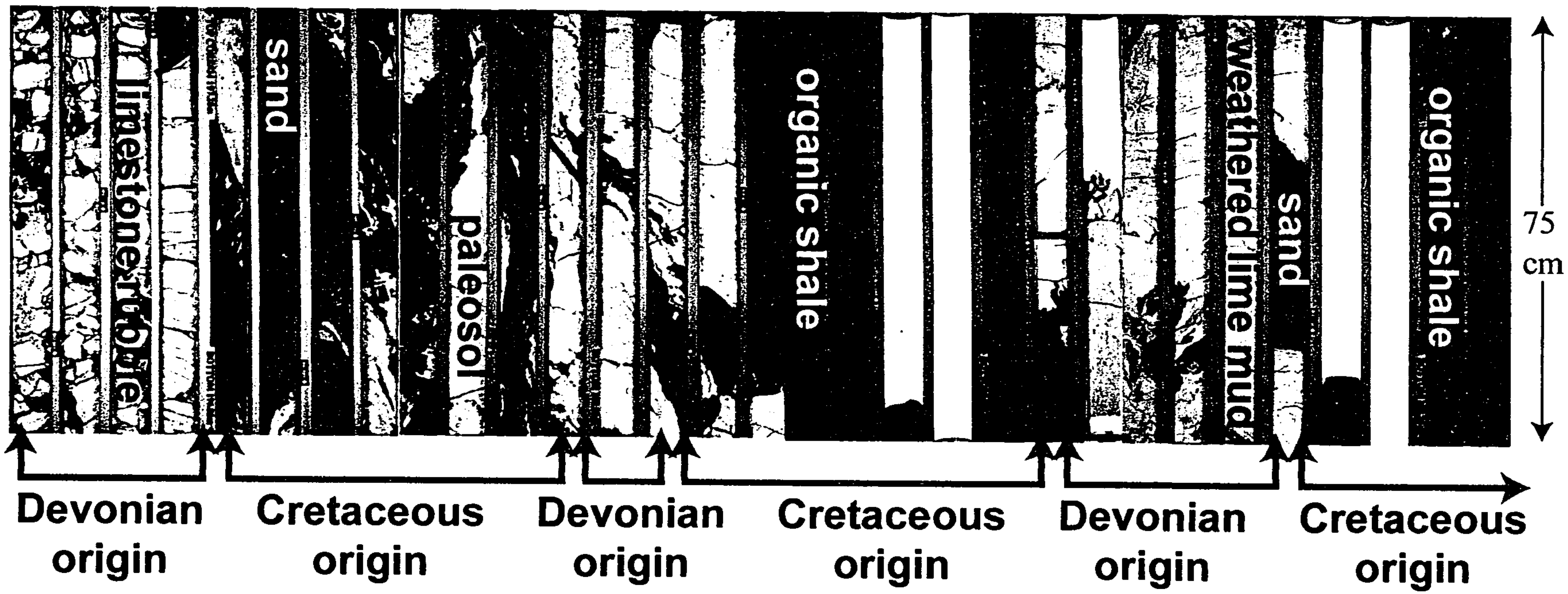


Plate 37

Mixed origin collapse fill with three repetitions of Devonian and McMurray sediments. Due to the lack of well saturated sand, this example would not be economically viable. AA/04-34-095-7W4 (178.8 – 200.15 m)

Plate 37


limestone rubble
sand
paleosol
organic shale
weathered lime mud
sand
organic shale
75 cm
Devonian origin
Cretaceous origin
Devonian origin
Cretaceous origin
Devonian origin
Cretaceous origin

CHAPTER 6

BANK COLLAPSE

INTRODUCTION

Bank collapse breccias are a significant component of McMurray deposition, but the mechanisms generating the facies have not been well studied. The sand matrix of bank collapse breccias commonly possesses excellent bitumen saturation. Incorporated shale clasts increase the gamma ray response and lower the resistivity response on petrophysical well logs. Therefore, localized bank collapse breccias cannot be reliably distinguished from regionally continuous stratified shale intervals using standard well logs alone. This can result in downgrading potential pay. Only visual examination of core (or an FMI log) can differentiate the two facies.

This chapter will review the mechanisms of instability, and collapse, as well as the preservation potential and economic significance of bank collapse deposits. Several possible triggering mechanism have been suggested for slump development, including; seismic shocks, excess loading, oversteepening of slopes by deposition or erosion, and building of pore-fluid pressure as the result of migration of pore-water (Coleman, 1969; Helwig, 1970; Lowe, 1976; Allen, 1984; Jones and Rust, 1983). The complex processes of channel bank failure and erosion are controlled by the interplay of several factors including, but not limited to, discharge flow, bank lithology, stratigraphy, and channel geometry (Youdeowei, 1997).

MECHANISMS OF INSTABILITY

Factors controlling channel formation are complex and interrelated. As these factors change over time, channel systems respond by altering their shape, and/or location. Aspects affecting bank stability include vegetation, current velocity, bioturbation, bank lithology, flooding, and fluctuating water levels.

Vegetation

In general, vegetation reduces soil erodibility; however, its impact on bank stability, with respect to mass failure may be either stabilizing or destabilizing (Langendoen, 2000).

Bank stabilization by vegetation occurs through reduction of flow erositivity and bank erodibility, as reviewed by Gray and Leiser (1982), and Coppin and Richards (1990). They concluded that (a) foliage and plant residue intercept and absorb rainfall energy and prevent soil compaction; (b) root systems physically retain soil particles; the roots and rhizomes bind soil and introduce an 'added' cohesion over the intrinsic cohesion of the bank material; (c) near-bank velocities are retarded by increased roughness and turbulence is dampened to reduce instantaneous peak shear stresses (Kouwen *et al.*, 1969; Lopez and Garcia, 1997); (d) roots and humus increases permeability and reduce excess pore-water pressure; and (e) depletion of soil moisture reduces water-logging, reducing the frequency of occurrence of saturated conditions conducive to bank collapse (Simon and Collison, 2001).

Vegetation may destabilize banks through root invasion creating cracks and fissures in the soil or rock mass, thereby causing local instability by wedging or prying action. The surplus weight of vegetation may also significantly increase motivating forces, causing destabilization of the bank (Langendoen, 2000).

Vegetation during Cretaceous times for the Athabasca region was in the temperate zone (Figure 55), which incorporated seasonal variations in growth and extensive deciduous/semi-deciduous conifer–dominated forests (Saward, 1992). McMurray sediments host transported wood with growth rings. Ells (1931) reported the identification of at least two species of fossil wood, including the genera *Keteloeria* and *Xenoxylon* (the latter being an extinct genus while the former is still found in parts of China and Taiwan today), as well as an identified gymnosperm. Gordon (1932) also noted the presence of large trunks of *Xenoxylon* in the lower McMurray, and it is not unusual for large pieces of fossil tree material to be recovered during mining operations in the Syncrude Mine Site (B. Ryan, Syncrude Geology staff, personal communication 1985; Fox, 1988).

Although the sediments within the McMurray Formation were dominantly estuarine, there are abundant examples of root traces, indicating the existence of brackish tolerant species of plants. Modern grasses such as *Spartina* (Plate 38, Photo A) grow in estuarine environments tolerate variable salinities.

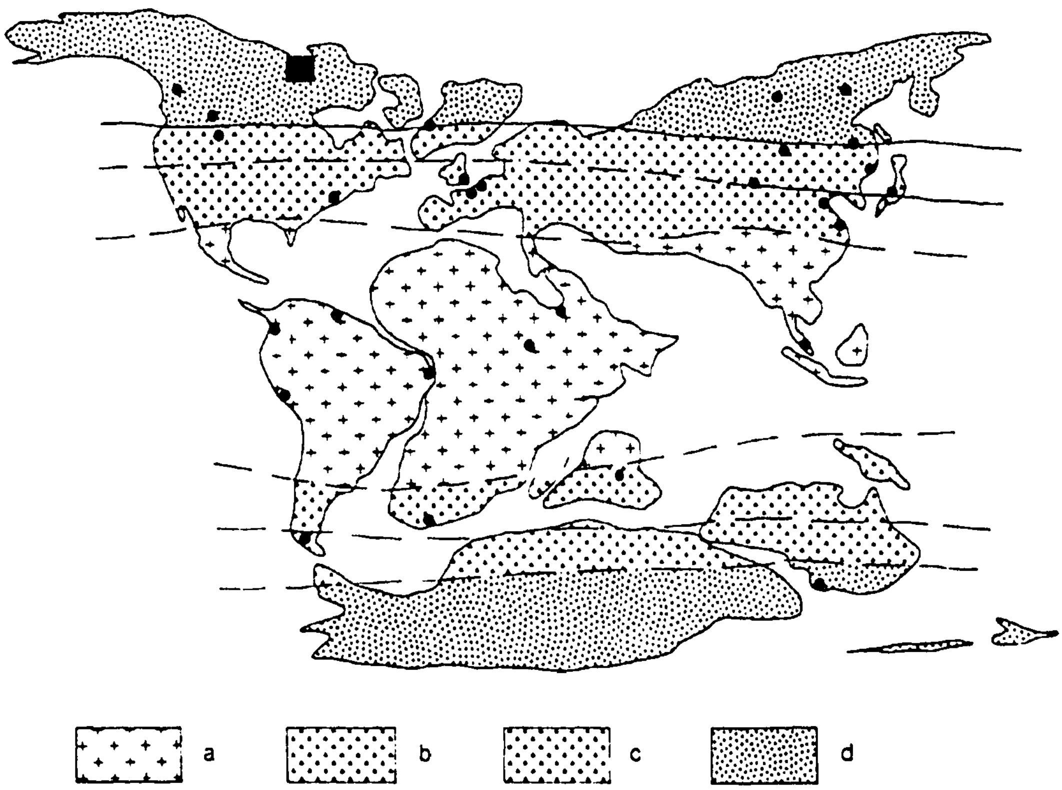


Figure 55
Vegetation distribution pattern for the early Cretaceous. a = Tropical vegetation. b = Paratropical vegetation. c = Paratemperate vegetation. d= Temperate vegetation. Solid circles represent megafloral data points (modified from Saward, 1992). Gray square represents the location of the Athabasca Oil Sand area indicating temperate vegetation was predominant in the study area during the Cretaceous

Current Velocity

Increasing current velocity enhances erosion, effectively increasing of the slope and height of banks causing shear failure or undercut banks (Simon *et al.*, 2000). Changing current velocity is exemplified in McMurray sediments on channel bases. Ripples (small-scale cross-stratification) climb the upper surfaces of dune forms (large-scale trough cross-stratification). Erosion with the subsequent dune set is sometimes demarcated with a pebble lag.

Bioturbation

Bioturbation commonly decreases the cohesion of banks. A modern example from the Willapa Bay estuary, demonstrates this concept. Shrimp that colonize the cutbank of meandering tidal channels form the trace *Ophiomorpha* to compensate for the high energy and instability of the cutbank (Plate 38, Photo B and C). Walking on the bank acted as a trigger for collapse, enhanced by the instability created by the burrows. With the collapse, shrimp were washed into the channel and swept downstream.

An analogous scenario in the fluvial environment is that of muskrat burrows causing bank failure (Helfrich, 1999). Tunnels dug above the water level can decrease structural support of the embankment and increase the risk of washout during flood conditions. These hazards are multiplied in waters where burrowing animals are abundant and where water levels fluctuate. Rising and falling water levels stimulate these animals to dig new burrows (Helfrich, 1999).

Bank Lithology

Bank lithology plays many roles in bank stability. There is a clear contrast in failure mechanics between noncohesive and cohesive materials due to significant differences in soil mechanics. Noncohesive materials usually fail by dislodgment and avalanching of individual particles, or by shear failure along shallow, curved slip surfaces. Deep-seated failures occur in cohesive materials, and typically result in a block of disturbed, but more or less intact, bank material sliding into the channel along a curved failure surface (Langendoen, 2000).

Unconsolidated clays swell and shrink during repeated cycles of wetting and drying which induces cracking. This significantly increases erodibility and reduces soil shear strength (Langendoen, 2000). A cracked mud horizon below a breccia zone (Plate 39, Photo A) in McMurray sediments may be due to such swelling and shrinking of clays.

Unconsolidated sands may be subject to liquefaction which probably plays a significant role in most cases of slumping (Allen, 1984). Coleman (1969) observed failure where bank sediments started flowing on a zone of liquefied sands and silts from the Brahmaputra River. Unconsolidated sands in the McMurray may slump in a contorted roll structure, and as a consequence, are overlain by breccia (Plate 39, Photo B). These sands must be buried quickly to preserve the unconsolidated sand lamination in the roll.

Mixed sediments may cause a change in the exfiltration causing collapse. This will be discussed further in the upcoming mechanism of collapse section.

Flooding

As velocity increases, the erosive power of flowing water also increases and scour may occur. Flooding is directly linked to effects observed with current velocity, increased bank saturations and the production of crevasses (Youdeowei, 1997).

Fluctuating Water Levels

Rising water level in a river can create and unbalanced condition between the bank profile and the river channel. Shear or flow of bank material into the river may result, assuming the river bank profile was in near equilibrium prior to the rise in water. Under these conditions, bank instability may result from (a) increased weight of bank material due to absorption of water, (b) decreased shear strength within bank sediment due to increasing pore-water pressure, or (c) increased depth and intensity of river scouring creating an unstable oversteepened bank profile (Leopold *et al.*, 1964, p. 340).

Collapse normally occurs as banks dry out during periods of falling water level (Gibling and Rust, 1984). For example, river discharge in the Niger delta area is linked with frequent and prolonged precipitation, which induces high current velocities. Maximum bank failure takes place when there is a sharp fall in rainfall. This period of flood recession causes disequilibrium and results in the loss of soil strength and subsequent collapse (Youdeowei, 1997).

The magnitude and frequency of water-level fluctuation are also significant factors in bank collapse (Boe, 1988). In tidal areas, such as the middle member of the McMurray Formation, the frequency of water-level fluctuation is exceptionally high, with semidiurnal, diurnal, bi-weekly and neap-spring cycle tidal variations. The magnitude may vary as well, being highest during offshore storms or fluvial flooding events.

MECHANISMS OF COLLAPSE

Collapse is commonly generated by one of the following mechanisms: planar failure, rotational failure, cantilevered toppling failure or exfiltrating seepage.

Planar failure occurs along steep banks, which characteristically fail along almost planar surfaces. Detached blocks of soil slide downward and outward into the channel (Figure 56A).

Rotational failure commonly occurs in banks with shallow slope angles. The failure surface is curved and the block tends to rotate back toward the bank as it slides in a rotational slip (Figure 56B). McMurray sediments may collapse by rotational failure along curved failure planes (Plate 39, Photo C).

Cantilevered or overhanging banks are generated when erosion of an erodible layer in a stratified or composite bank undermining overlying, erosion-resistant layers (Figure 56C). The strength of cantilevered blocks is significantly increased by root reinforcement (due to riparian and floodplain vegetation) and is decreased by tension cracks. A Pleistocene estuarine outcrop at Willapa Bay demonstrates that overhang can occur in estuaries (Plate 40, Photo A).

Hagerty (1990) described channel bank collapse by exfiltrating seepage, which is also called piping or sapping (Figure 56D 1-3). Outflowing water removes soil particles in the exfiltration zone. Undercut strata located above the zone of soil loss becomes unstable and collapses. Whether bank failure occurs by rotational slip, toppling or cantilever collapse, the primary force tending to move the failure block is the weight of the block. The weight of bank material increases with the moisture content of the soil and failure often follows the change from submerged to saturated conditions (Sands and Kapitzke, 1998).

Meandering tidal creeks often re-incise previous point bar deposits. Tidal point bars are dominantly composed of IHS exhibiting sands of alternating grain sizes. This alternating grain size allows exfiltration of pore water of differing sediments to be common place in McMurray channels cutbanks. In Willapa Bay, sandy meandering tidal channels that incise pre-existing point bars show evidence of slump activity (Plate 40, Photos B and C).

MCMURRAY MUD CLAST DESCRIPTION

McMurray mud clasts are generally comprised of the muddy portions of IHS and/or tidal flat deposits. This is determined by the preserved lamination, and rare bioturbation, dominantly *Planolites* (Plate 41, Photo A). Clasts are typically tabular and define bedding (Plate 41, Photo B), indicating that they were deposited with channel processes. Mud clasts may disaggregate due to high energy transport or through exposure in the thalweg before burial. This disaggregation results in the addition of clay to the sandy matrix and decreased hydrocarbon saturation (Plate 41, Photo C). The mud clasts are semi-indurated and may exhibit internal plastic deformation (Plate 41, Photo D).

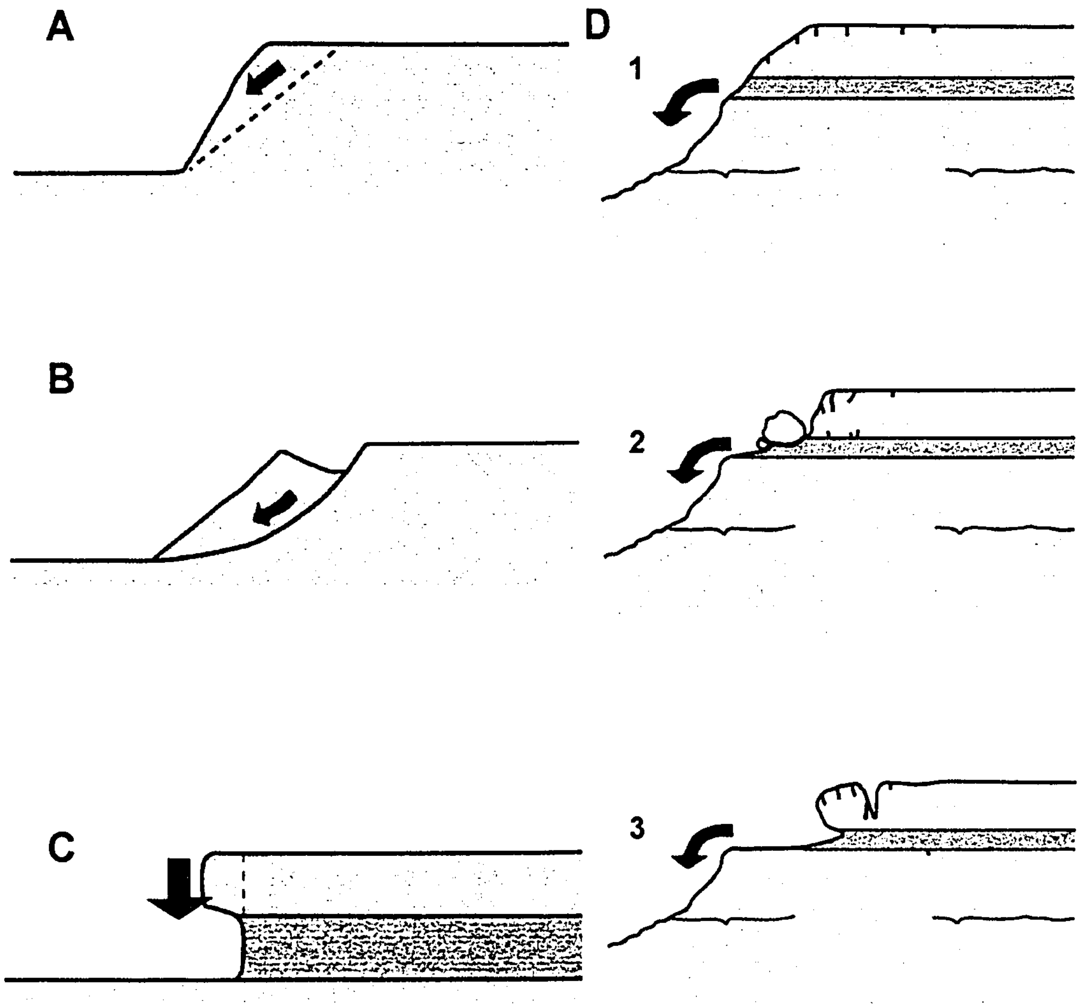


Figure 56
A Planar slip. Steep banks characteristically fail along almost planar surfaces, with detached block of soil sliding downward and outward into the channel in either a planar slip or a toppling failure.
B Rotational slip. In banks with shallow slope angles, the failure surface is curved and the block tends to rotate back toward the bank as it slides.
C Cantilevered or overhanging banks are generated when erosion of an erodible layer in a stratified or composite bank leads to undermining of overlying, erosion-resistant layers.
D Collapse by exfiltrating seepage, which is called piping or sapping
1 Outflowing water removes soil particles in the exfiltration zone.
2 Undercut strata located above the zone of soil loss become unstable and collapse
3 Bank failure occurs by rotational slip, toppling or cantilever collapse, the primary force tending to move the failure block is the weight of the block.
(modified from Langendoen, 2000).

MCMURRAY DISCUSSION

Clasts may be deposited on dune forms defining large-scale cross-stratification bedsets on the bases of channels (Plate 42, Photo A). Migration of dunes and the resultant high deposition rate likely enhance preservation. Deposition in this manner makes the mechanism of collapse difficult to identify.

Clasts may also occur in point bar sediments (Plate 42, Photo B). The mechanism of collapse involves the change from normal flow conditions to flood flow conditions. The increased energy of the flood flow decreases the sinuosity, resulting in straightening of the channel (Figure 57). The flood thalweg runs across the point bars surfaces (Figure 58), ripping up mud clasts. Closer inspection of a bedded example reveals the base of the bed to be erosional (Plate 42, Photo C). It is hypothesized that it is also a clast. This brings into question the validity of the apparent bedding, which may also have resulted from collapse.

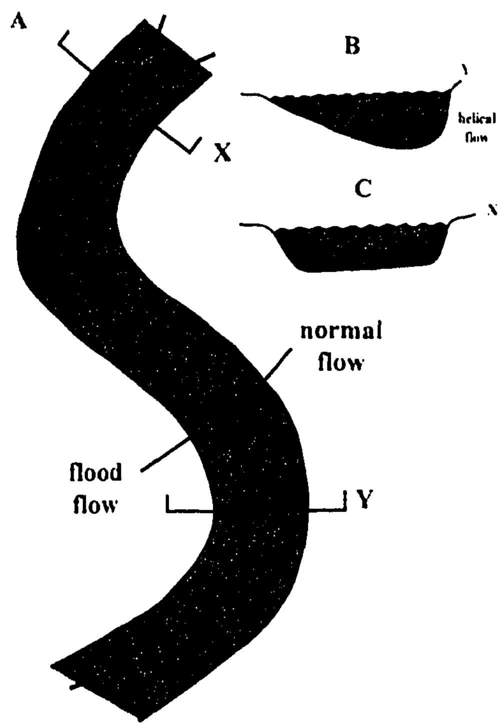


Figure 57
Flow patterns in a meandering stream. Maximum velocity varies between normal to flood flow conditions. Cross profiles X and Y indicate this variance in different reaches of the stream (modified from Galloway and Hobday, 1983).

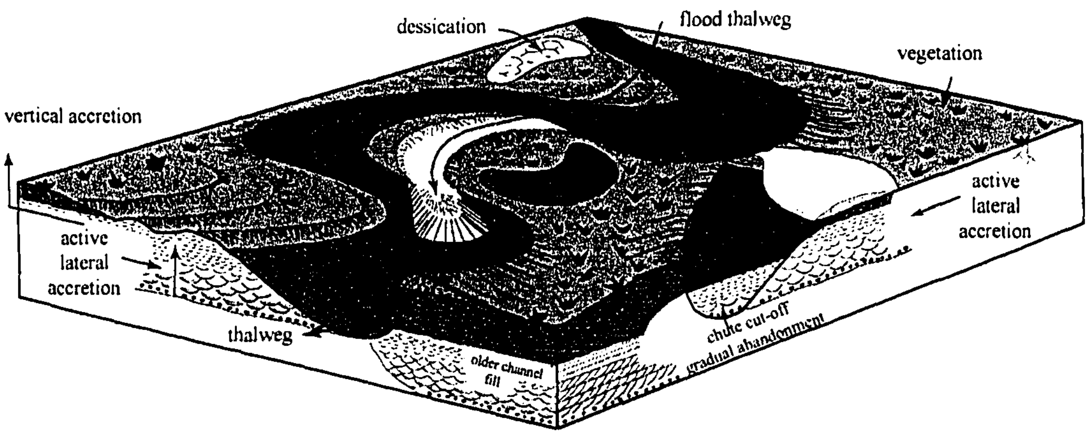


Figure 58
The morphological elements of a meandering channel system. A thalweg is a line connecting the deepest points along a stream channel. It is commonly the line of maximum current velocity (modified from Walker and Cant, 1984).

PRESERVATION

Bank failures deposits most likely to be preserved in the stratigraphic record are those produced by large-scale shear failure, in particular, rotational slumping. Preservation of rotational slumping is most easily accomplished by base failure, rather than slope failure. Base failure, where the surface of failure passes below the local thalweg and therefore, below the active depth of stream scouring, allows slumped masses to be preserved. Areas of active scouring, in which banks and thalwegs are cut in cohesive silt- and clay-rich sediments, favour the occurrence of deep rotational slumping and possibly base failure (Figure 59). Such conditions appear to be more common in low-energy delta plain or tidal flat environments (Laury, 1971).

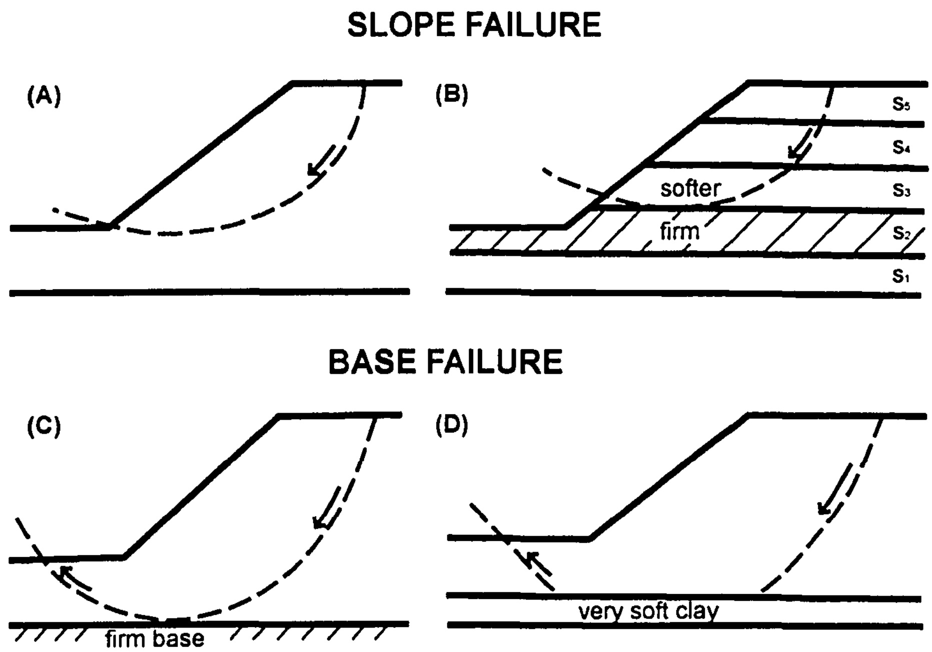


Figure 59
Basic patterns for bank failure by rotational shear. Slope failure: surface of failure intersects slope at (A) the toe of the slope or (B) above its toe. In (B) the cohesion of S_3 is considerably smaller than S_2; hence S_2 acts as a firm base with the shear surface tangential to its top. Normal base failure (C) differs from (B) in that the top of the firm base and maximum depth of shear are well below the toe of slope. Base failure along a composite surface (D) occurs during failure of a slope underlain by a thin layer of very low cohesion (after Terzaghi and Peck, 1967).

Most fossil slump features are preserved in marine compared to nonmarine sequences. This is in opposition to the frequency of occurrence, where slumping in nonmarine areas is much higher than under marine conditions (Laury, 1971). Downstream or lateral migration of the thalweg scour pool away from the locus of failure would also favour preservation (Turnbull *et al.*, 1966; Laury, 1971). Rapid burial prevents further rounding and disintegration. From durability experiments, Smith, (1972) concluded that angular mud clasts indicate little or no transport. Clasts become rounded after transport in the order of tens to hundreds of metres. Further transport leads to complete disintegration.

ECONOMIC SIGNIFICANCE

The economic significance of bank collapse is evaluated using Plate 43 as an example. Evaluation of oil sand pay using wireline well logs applies; a sand cutoff of 60 API gamma units or less, an oil saturation cutoff of 200 Ωm or greater, and a 3 m continuous shale cutoff. In Plate 43, Photo A, 21 m of pay is calculated using these cutoffs. Although low, this pay is within the current limits of economics. However, the AppleCore log (Plate 43, Photo B), indicates the shale above the 'top of pay' based on wireline logs is not 'true shale' but rather a mud clast breccia. The core photos (Plate 43, Photo C) demonstrate high bitumen saturation of the sand matrix, which is contrary to the low resistivity of the wireline log. In the example, visual examination of the core upgrades estimates based on wireline logs from 21 to 35 m of pay.

Breccia units typically have limited lateral extent (a few metres) in outcrop, occurring as thin lenses or less commonly in small cut and fill features (Hein *et al.*, 2000). Mud clast breccias are not barriers to steam flow using SAGD methods. In a pilot study on the Sunrise Thermal Project Lease, oil recovery from breccias was equal to the non-brecciated surrounding sands (Plate 44, Photo A).

SUMMARY

Factors which affect bank stability include vegetation, current velocity, bioturbation, bank lithology, flooding, and fluctuating water levels. These factors are often complex and interrelated. Mechanisms of bank failure include rotational and planar slip failure, undercutting toppling failure and exfiltrating seepage. Exfiltrating seepage may be a common mechanism of bank collapse in the tidal meandering channels due to the frequency of cutbanks eroding into pre-existing point bar deposits. Preservation is enhanced by environment. Marine settings have a preservational bias when compared to nonmarine conditions, even though slumping is more common in nonmarine areas (Laury, 1971).

Localized bank collapse breccias cannot be reliably distinguished from regionally continuous stratified shale intervals using well logs alone, which results in downgrading potential pay. Visual examination of core can differentiate the two facies. Mud clast breccias are determined to be of limited areal extent and are not barriers to steam flow using SAGD methods. Bank collapse breccias must be included in evaluation of pay.

Plate 38

A. Modern example of brackish-tolerant vegetation *Spartina* from Willapa Bay, Washington.

B. Ichnology Research Group members hike along a meandering tidal channel cutbank. The trigger of human weight caused shrimp to be dislodged, swept into the channel and carried downstream. This gained the attention of seagulls that began feeding on the dislodged shrimp.

C. Shrimp were colonizing the above cutbank forming the trace *Ophiomorpha* which compensates for the high energy and instability of the cutbank.

Plate 38

A

B

C

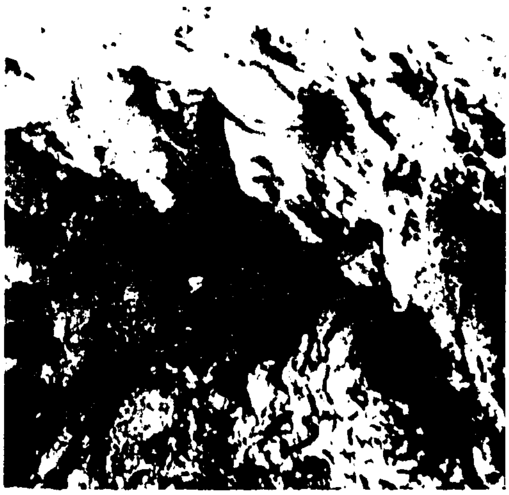


Plate 39

A. A cracked mud horizon, which may be due to swelling and shrinking of clays. AA/16-13-094-07W4 (234.2 m)

B. Unconsolidated sands in the McMurray slump to a contorted roll structure, which is overlain by breccia. These sands must have been buried quickly to preserve the unconsolidated sand lamination in the roll. AA/13-20-095-07W4 (123.0 m)

C. McMurray rotational failure displays curved block lamination. AA/06-27-095-07W4 (162.6 – 163.0 m)

Plate 39

A B C

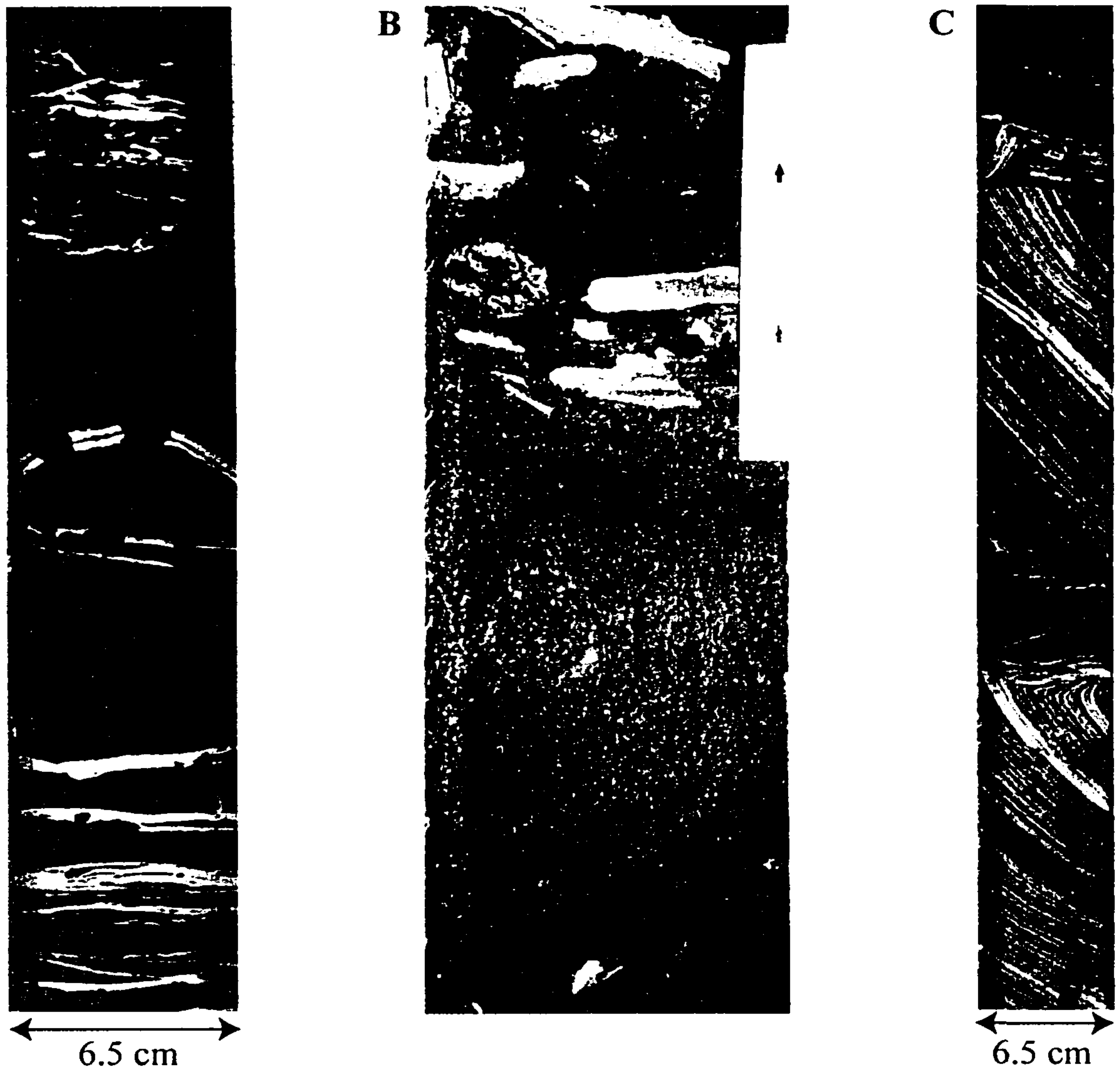
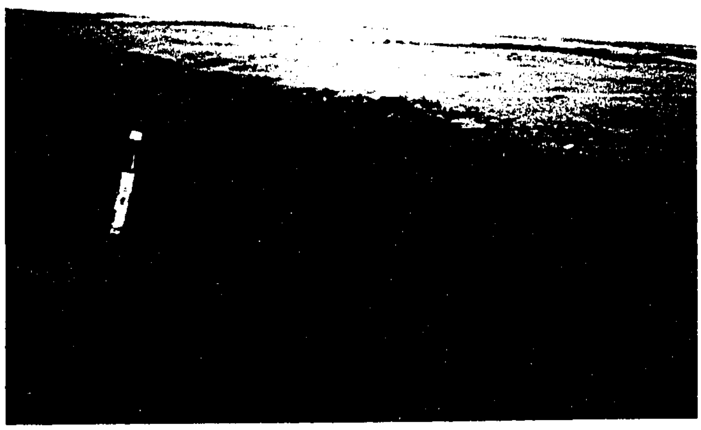


Plate 40

A

B



C

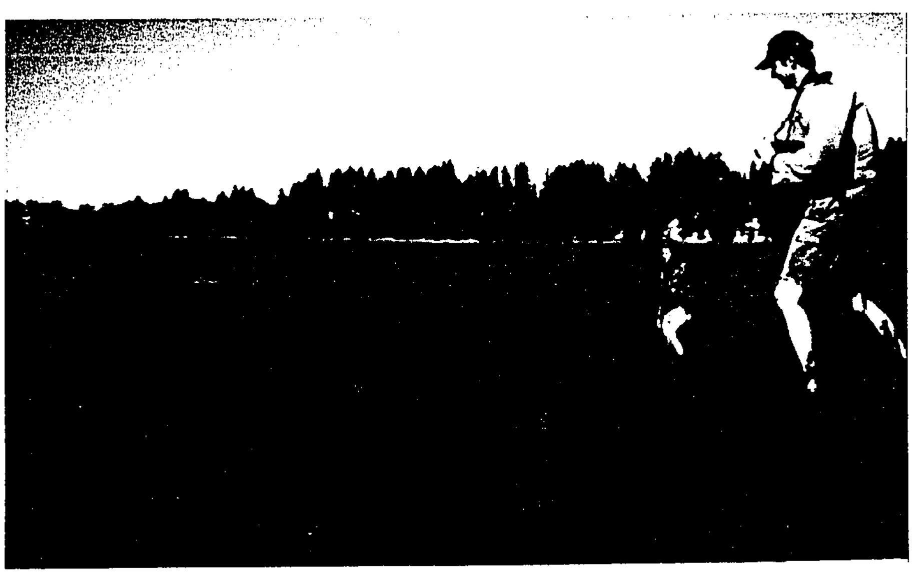


Plate 40

A. Overhang example from estuarine Pleistocene outcrop, Willapa Bay, Washington.

B. Meandering tidal creeks commonly re-incise previous point bar deposits. Tidal point bars are dominantly composed of IHS, exhibiting sands of alternating grain sizes. This alternating grain size allows exfiltration of pore water of differing sediments to be commonplace in McMurray channels. Photo from Willapa Bay, Washington.

C. Slump is evident as a result. Photo from Willapa Bay, Washington.

Plate 41

A. McMurray mud clasts are generally comprised of the muddy portions of IHS and/or tidal flat deposits. This is determined by the preserved laminations and the rare bioturbation (dominantly *Planolites).* AA/12-05-095-07W4 (169.0 m)

B. Clasts are typically tabular and define bedding. AA/07-34-095-07W4 (146.2 m)

C. Mud clasts may disaggregate due to high energy transport or exposure in the thalweg before burial. This disaggregation results in the addition of clay to the sandy matrix and decreased hydrocarbon saturation. AA/07-33-094-07W4 (214.19 m)

D. The mud clasts are semi-indurated and may exhibit internal plastic deformation. AA/14-26-094-06W4 (196.2 m)

Plate 41

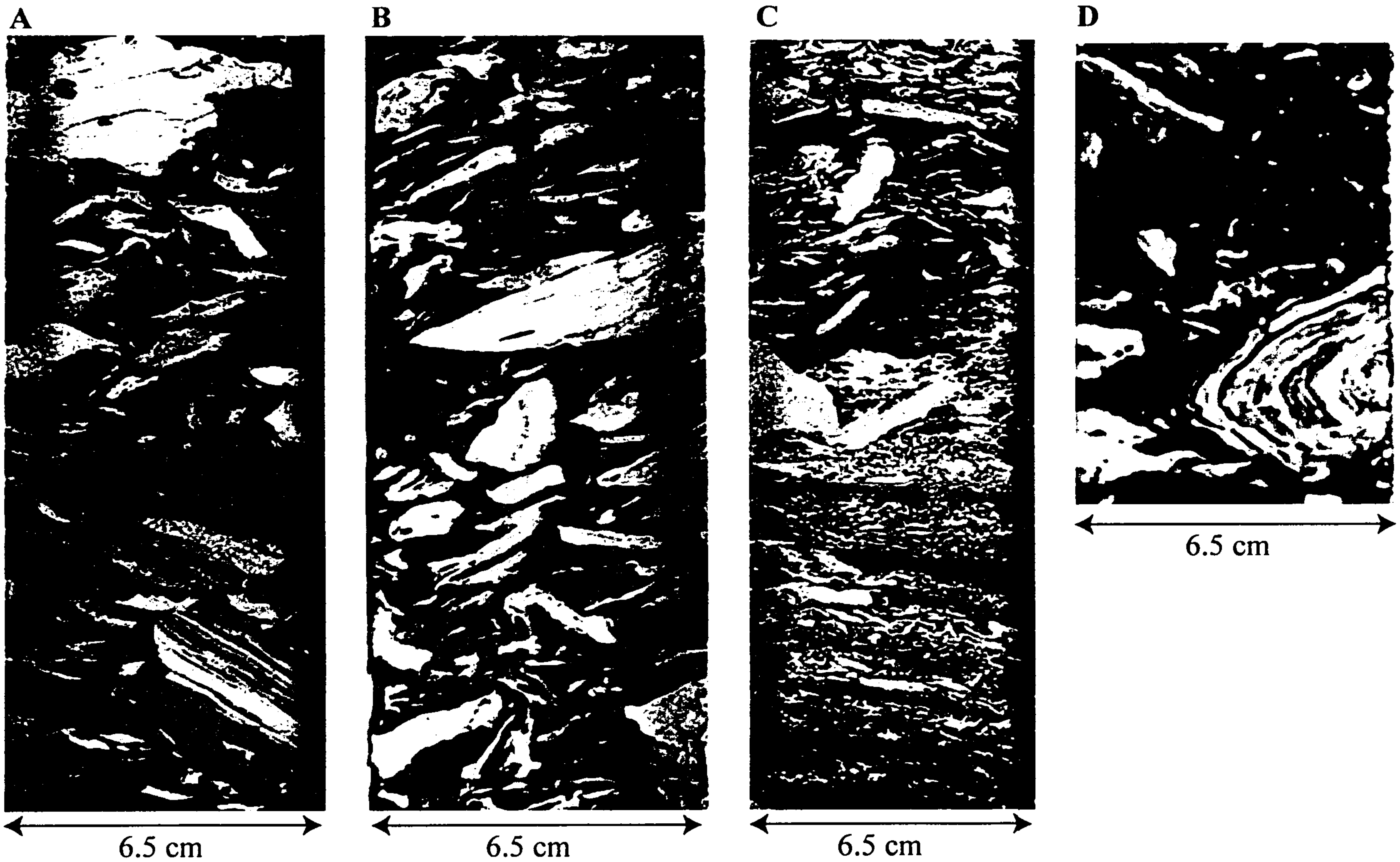


Plate 42

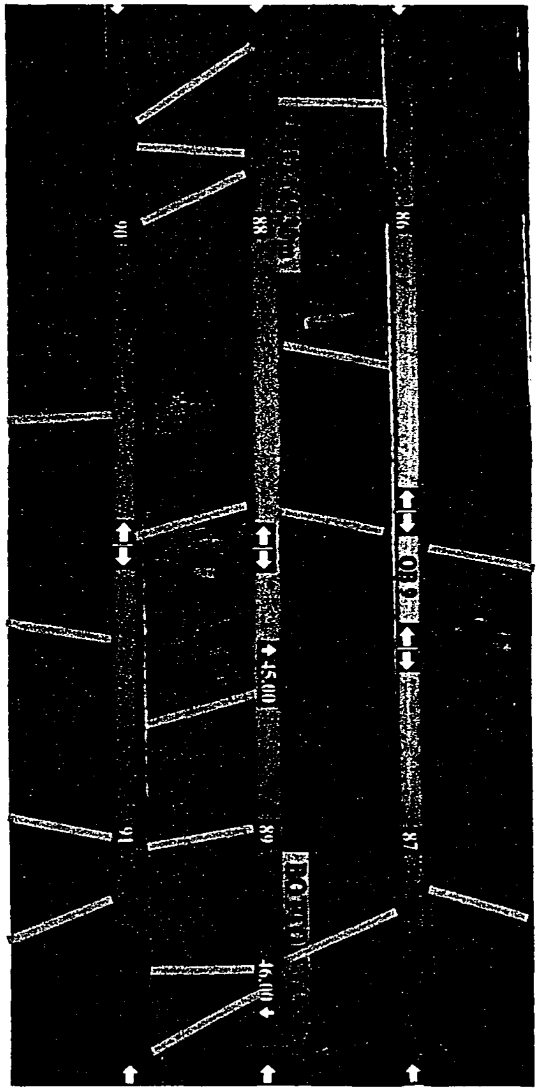
A. Clasts may be deposited in the base of channels on dune forms defining large-scale cross-stratification bedsets. AA/07-34-095-07W4 (143.75 – 146.75 m)

B. Clasts may occur in point bar sediments. The mechanism of collapse involves the change from normal flow conditions to flood flow conditions. The increased energy of the flood flow decreases the sinuosity, resulting in the straightening of the channel. The flood thalweg runs across the point bars surfaces (Figure 58) ripping up mud clasts. AA/15-05-095-07W4 (190.75 – 194.5 m)

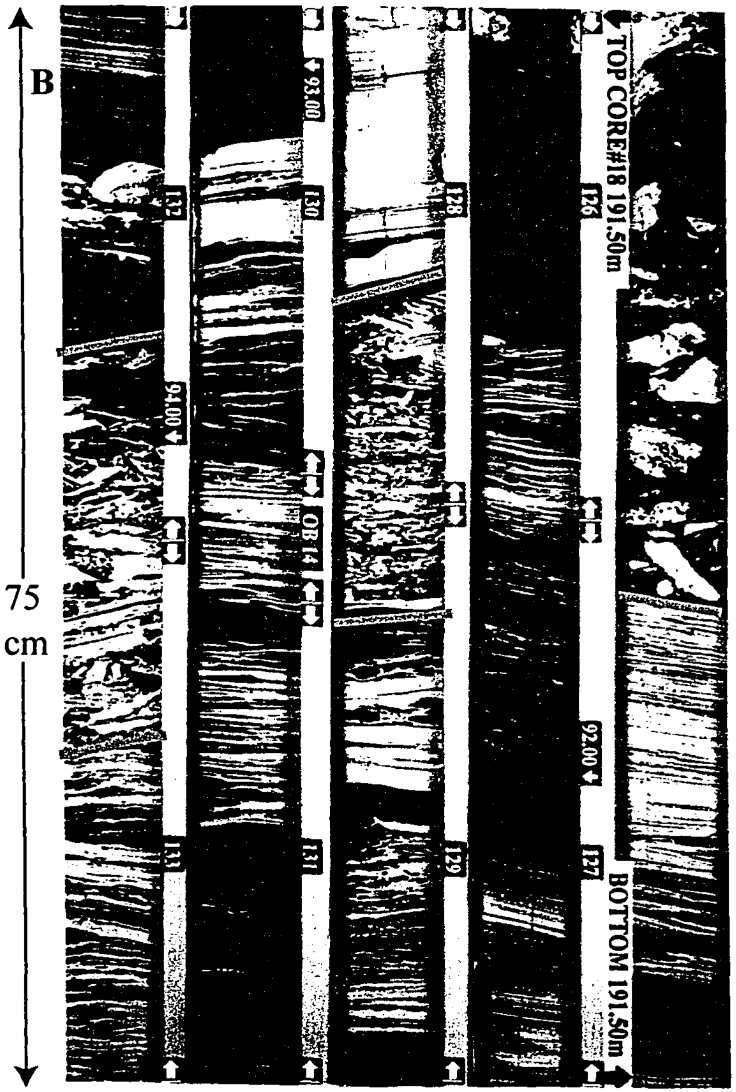
C. Closer inspection of a bedded example reveals the base of the bed to be erosional. It is hypothesized that the bedding above is also a clast. This brings into question the validity of apparent bedding, which may also have resulted from collapse. AA/15-05-095-07W4 (171.0 m)

Plate 42

A


86
OB 9
87
88
45.00
89
46.00
90
91

B


75 cm
TOP CORE#18 191.50m
BOTTOM 191.50m
126
92.00
127
128
129
93.00
130
OB 14
131
132
94.00
133

C


6.5 cm

Plate 43

Economic significance

A. Wireline log. AA/02-21-095-07W4.

Evaluation of this log using a sand cutoff of 60 API gamma units or less (yellow) and oil saturation cutoff of 200 Ω m or greater (green), and a pay continuity cutoff of 3 m shale; 21 m of pay is determined. Although low, this is within the current limits of economics.

B. AppleCore log from AA/02-21-095-07W4.

The AppleCore log indicates that the shale above the top of pay is not 'true shale', but rather a mud clast breccia.

C. Core photos from AA/02-21-095-07W4 (154.0 – 166.5 m).

High saturation of the matrix sand is observed in core photos. This upgrades the pay in this well from 21 m to 35 m.

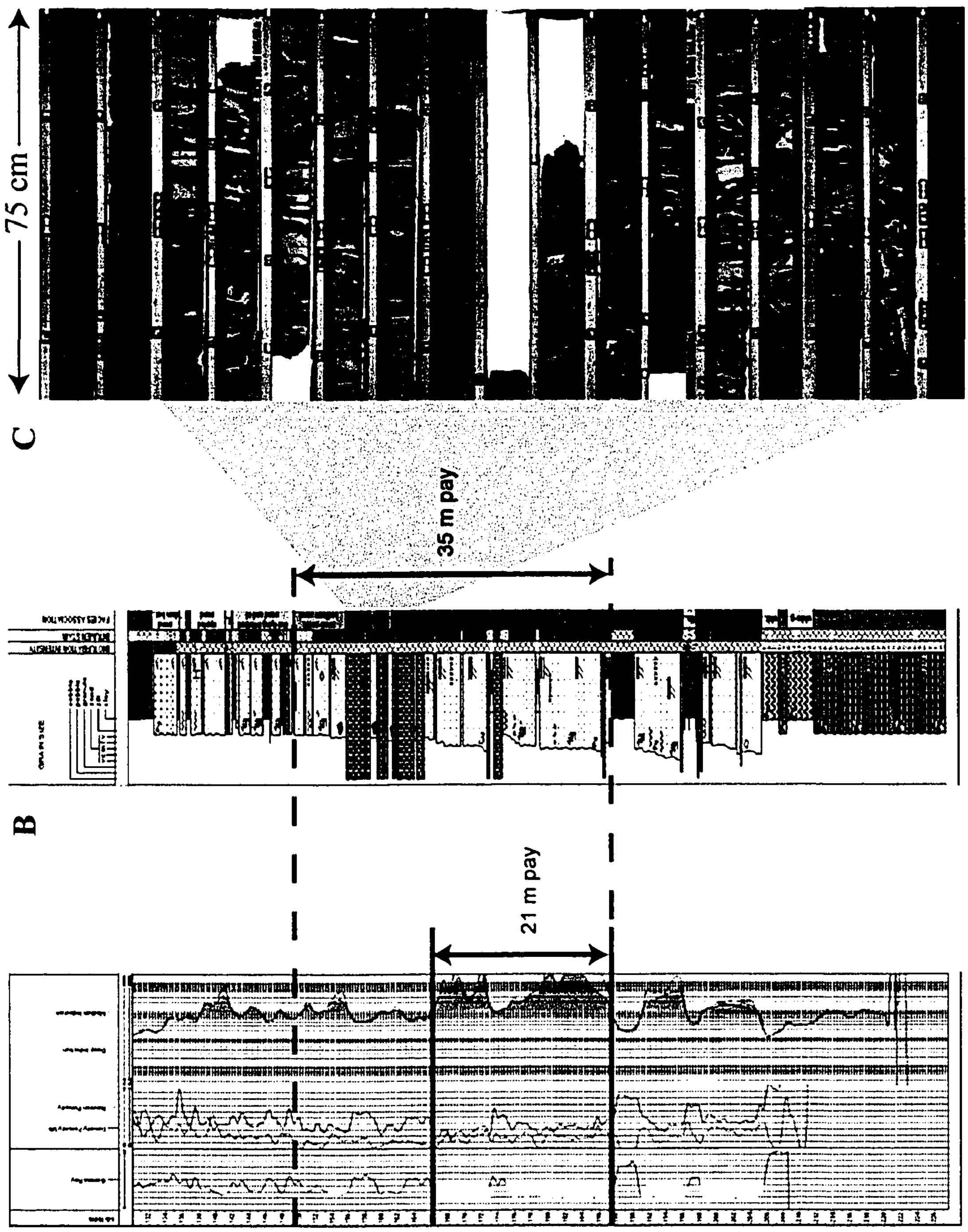


Plate 43

Plate 44

A. Post-steam mud clast breccia exhibiting almost complete oil recovery between closely spaced clasts, proving that breccias are not barriers to steam flow using SAGD methods. AY/01-16-095-07W4 (178.6 m)

Plate 44

A

CHAPTER 7
CONCLUSIONS

The McMurray/Wabiskaw succession within the Sunrise Thermal Project and the Muskeg River Mine study areas record a Lower Cretaceous transgression of paleovalleys incised on the sub-Cretaceous unconformity. The nature of the unconformity significantly influenced McMurray deposition.

Dissolution of the Prairie Evaporite caused collapse of overlying sediments. Many episodes of collapse occurred beginning with the dissolution of the Prairie Evaporite and ending at McMurray coal deposition. The variation of fill within collapse structures produces a heterogeneous reservoir, generating a challenging exploitation target for the future. The economic potential of sinkholes is limited by the ability of current technology to image karst edges and predict complex internal stratigraphy of these relatively small reservoirs.

The sub-Cretaceous unconformity is a sequence boundary and marks the base of the incised-valley. Lower McMurray examples of fining upward sequences represent the lowstand alluvial-fluvial deposits.

The boundary between the lower and middle members of the McMurray Formation has been historically incorrectly defined. Ichnological and sedimentological characteristics within, and below the coal assign it to the middle member. The true boundary between the lower and middle members is represented by a mineralogical change with the inclusion of potassium feldspar.

Parasequences in the middle McMurray comprise fining upward successions capped by coal or coal equivalents which define a pulsed transgression. The McMurray estuary can be classified as mesotidal, with mixed tide- and wave-dominance.

Bank collapse breccias are recognized as a significant component of middle McMurray deposition. Factors which affect bank stability include vegetation, current velocity, bioturbation, bank lithology, flooding, and fluctuating water levels. These factors are complex and interrelated. Localized bank collapse breccias cannot be reliably distinguished from regionally continuous stratified shale intervals using wireline logs. Visual examination of core differentiates the two facies, and may upgrade potential pay. Mud clast breccias are determined to be of limited areal extent and are not barriers to steam flow using SAGD methods.

A continued rise in relative sea level resulted in transgression of the outer estuary up the paleovalley, producing a ravinement surface. Overlying the outer estuarine sediments is a wave ravinement surface, which was incised during erosional shoreface retreat. Progradation of the shoreface resulted in deposition of a coarsening upward association. Above the shoreface lies a second wave ravinement surface. The overlying Clearwater shales contain the maximum flooding surface.

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APPENDIX

AppleCore Legend

Applecore Legend

Lithology

sand	organic shale	silty shale	mud clast breccia
silty sand	coal	sandy shale	limestone
shaly sand	conglomerate	shale	calcareous shale
silt	breccia	lost core	

Physical Structures

current ripple	high angle	flaser	convolute
climbing ripple	low angle	lenticular	faulted
wave ripple	planar	wavy	chaotic
trough-cross strat	homogenous	scour	syneresis
large-scale strat	xxxxxx cemented	double mud drape	

Lithologic Accessories

sand lamina	coal fragments	mud clast	Py pyrite
silt lamina	organic shale lamina	carbonate clast	Sid siderite
shale lamina	coal lamina	quartz/chert pebble	Gl glauconite
pebble horizon	carbonaceous material	rip up clast	Fld feldspar
	shell fragments	Palsl paleosol horizon	S sulfur

Ichnofossils

Asterosoma	churned	Bergaueria	Gyrolithes
Teichichnus	Skolithos	Rosselia	Cylindrichnus
Ophiomorpha	rootlets	Planolites	Diplocraterion
Chondrites	Fugichnia	Paleophycus	Arenicolites
Thalassinoides	undifferentiated burrow		

Bioturbation

- abundant
- common
- moderate
- rare
- barren

Stain

- excellent
- very good
- good
- fair
- poor
- nil

Fossils

- gastropods
- crinoids
- brachiopods