UNIVERSITY OF ALBERTA

SEDIMENTOLOGY, STRATIGRAPHY, AND ICHNOLOGY OF THE MCMURRAY FORMATION, NORTHEASTERN ALBERTA

BY

CATHERINE NICOLE YUILL ©

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ABSTRACT

Twenty-five cores and two hundred well logs from TWP 93, 94, RGE 7 W4, within the Athabasca Oil Sands Deposit, were studied to determine the depositional environment of the McMurray Formation. Sedimentology, stratigraphy, and ichnology were used. Recognition of a brackish water trace fossil assemblage provided good evidence of a marine influence on most of the McMurray Formation deposits.

Structure on the surface of the pre-Cretaceous unconformity was important for McMurray deposition. The lower McMurray was deposited in the lowest valleys, within meandering fluvial channels. As sea level rose, the Boreal Sea flooded the fluvial valleys, forming estuaries. The middle McMurray represents deposition in meandering estuarine channels. Inclined heterolithic stratification indicates tidal influence. Continued transgression resulted in nearshore marine sand bars in the upper member. The upper McMurray also contains off-channel deposits related to the latest estuarine channels.

The McMurray Formation records an overall transgression with deposits ranging from fluvial to estuarine to nearshore marine.

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CHAPTER 1 - INTRODUCTION

INTRODUCTION

The Athabasca Oil Sands Deposit in northeastern Alberta (Fig. 1) is the single largest accumulation of bitumen in the world (Demaison, 1977), with over 209 billion cubic metres (1.3 trillion barrels) of bitumen in place. The Wabiskaw and McMurray formations contain the majority of the bitumen, with 142 billion cubic metres (893 billion barrels) in place (ERCB, 1990). The deposit pinches out to the east against the Canadian Shield and to the west against the Nisku-Grosmont high (Stewart, 1963). To the northwest, the McMurray reservoir sands grade into marine shales; to the north and northeast, the oil sands are limited by glacial erosion (Stewart, 1963). The southern limit of the deposit is poorly defined (Carrigy, 1959; Stewart, 1963).

The heavy oil in this deposit has API (American Petroleum Institute) gravities of 7-10^{o} (Rennie, 1987). Normal light oils, such as those found in the western part of the Alberta basin, have API gravities of 35-40^{o} (Selley, 1985). The viscous nature of the bitumen precludes the use of conventional extraction methods; specialized extraction techniques are required to take advantage of this huge resource. Surface mining is currently being used at the Syncrude and Suncor mine sites near the city of Fort McMurray. *In situ* recovery methods are being tested at various pilot sites in northeastern Alberta where the oil-bearing formation is too deep for surface mining to be economical.

In situ methods involve the heating of the bitumen to reduce its viscosity, enabling the oil to move more freely to a production well (Kendall, 1977; Towson, 1977). Steam injection is often used to heat the bitumen. Two steam injection methods are steam stimulation and steam drive. Steam stimulation is a method in which production occurs through the injection well, after a shut-in period. Steam drive, on the other hand, involves steam injection occurring through a number of wells in a certain pattern, and oil being produced from separate offsetting wells (Doscher *et al.* 1963; Towson, 1977). The injected steam supplies the driving force in both cases (Towson, 1977).

The sediments of the McMurray Formation have undergone little post-depositional modification (cementation, quartz diagenesis, clay authigenesis, etc.) and therefore the porosity, permeability, and bitumen saturation are related to the original depositional environment and facies distributions (Mossop, 1980).

A thorough knowledge of the lateral and vertical continuity of the sand bodies is of fundamental importance when designing an *in situ* recovery scheme for an oil sands deposit. Knowledge of the extent of the sand bodies is necessary for the positioning of injection and production wells. It is also important to ascertain if the sand bodies contain any thick shales that might either hinder extraction, or, in some cases, help some recovery operations by dividing a thick reservoir into smaller units (Kendall, 1977). The interpretation of an environment of deposition might provide insights into how extensive the sands are and the composition of the sands present (Kendall, 1977). Knowledge of the location and continuity of the oil saturated sand bodies and intervening shales is of economic importance, particularly for *in situ* areas (present study area), as well as surface mineable areas (Syncrude and Suncor), where recovery techniques depend on a thorough understanding of the geometry of the sands and shales (Mossop, 1980). With that in mind, the objectives of this study are: 1) to determine, using both sedimentology and ichnology, what processes were responsible for the facies associations found in the McMurray Formation, and 2) to interpret the overall depositional system.

Study Area

The study area (Steepbank, Oil Sand Lease #49) is approximately 45 km north-northeast of Fort McMurray, Alberta. It is an area of almost 200 km^2 comprising Townships 94, 93, and the northeast corner of Township 92, Range 7 west of the Fourth Meridian (the Alberta-Saskatchewan border) (Fig. 2). It is outside the surface mineable area of the oil sands deposit (Fig. 3). The top of the McMurray is 150 m below the surface throughout most of the study area, requiring *in situ* methods to extract the bitumen. A total of 25 drill cores and approximately 200 well logs were examined to determine facies associations and depositional environments, as well as hydrocarbon distribution in the McMurray Formation.

Methods

(1) Drill core

The 25 drill cores were examined at the Energy Resources Conservation Board core research centre in Calgary. They were logged using the APPLECORE logging program created by M. J. Ranger of the University of Alberta. Features of the drill core described in detail include:

1) lithology
2) grain size and sorting
3) biogenic structures and relative degree of bioturbation
4) sedimentary structures
5) nature of bedding contacts
6) bedding styles and bed thickness
7) lithologic accessories
8) relative degree of bitumen saturation.

The main problem in studying oil sands core is that the heavy bitumen saturation can completely obscure any sedimentary structures, making the sands appear massive. X-ray radiography has been used, with variable success, to reveal stratification in apparently massive sands (Fox, 1988), but was not used in the present study. It was found that alternations in grain size can commonly reveal the nature of the stratification.

Another problem is that the oil sands are unconsolidated sediments with the bitumen providing only partial cohesion. For this reason, oil sand cores are commonly drilled using PVC (polyvinyl chloride) pipe as a core barrel liner. In this way, the cores are easily recovered and do not fall apart when handled. The pipe is then frozen and slabbed in half to permit viewing of the core. Only a two-dimensional view of a narrow (6.5 cm - 9 cm wide) strip of core can be observed, making the interpretation of sedimentary structures very difficult. The cut face may be smeared by the cutting tool and the edges of the core distorted by drilling. Drilling mud may also be present, obscuring the edges of the core. Sections of the core may rotate in the tube due to drilling, making it difficult to determine, for example, if inclined bedding is due to rotation or to actual sedimentary processes.

Some sands in the lower part of the McMurray Formation are water sands; they have little or no bitumen saturation. These sands disaggregate very easily and, at times, little is recovered in the PVC tube except a small amount of sand. The unconsolidated nature of these sands makes it difficult to observe any sedimentary structures.

(2) Well logs

The approximately 200 well logs examined in this study consist of gamma ray, resistivity, and density logs. The logs supplement the core observations and fill in the gaps where no core was examined. The well logs were used to create cross-sections across the study area to display the relationships and distributions of the facies described from the drill cores. The well log cross-sections were also used to illustrate the present day structure of the strata in the study area. The well logs were used in combination with the core logs to determine the extent of the hydrocarbon distribution, and therefore the extent of the potential reservoir.

Previous Work

Exploration of northern Alberta began in 1778 when Peter Pond, a fur trader, became the first white man to enter the area. The first mention of the tar sands was by Sir Alexander MacKenzie in the early 1790's. Other early explorers such as David Thompson, Sir John Franklin, and Sir John Richardson passed through the area in the early to middle 1800's, making surveys and notes of the rivers and their features. It wasn't until the late nineteenth century, however, that detailed geological study of the area began. Bell (1885) conducted a reconnaissance survey of the strata along the Athabasca and Clearwater Rivers, as well as other rivers in the area, for the Geological Survey of Canada. He came to the conclusion that the tar sands had great economic significance. McConnell (1893), also of the Geological Survey of Canada, conducted a more detailed study of sections along the Athabasca River, its tributaries, and other rivers in the area. He described the tar sands in detail and correlated them with the Dakota sandstones in Minnesota (McConnell, 1893).

McMurray was the name proposed by McLearn (1917) for the strata containing the tar sands. He stated that "tar sands" was a lithological term and, therefore, not appropriate as a formation name. McLearn (1917) felt that Dakota was not appropriate either, as the exact age of the tar sands was not known. He did not attempt to establish an age for the McMurray Formation tar sands.

Studies in the early part of the twentieth century centred on the extent and tonnage of the oil sand deposits, as well as possible commercial development (Ells, 1914, 1926; Clark and Blair, 1927). Ells and Clark concentrated on the physical and chemical properties and possible commercial value of the oil sands, such as using the oil sands as a paving material (Ells, 1914, 1926; Clark and Blair, 1927). Ells and Clark were also interested in recovering bitumen from the oil sands (Ells, 1926), and in 1923 K.A. Clark and S.M. Blair built the first hot water extraction pilot plant at the University of Alberta (Carrigy, 1973a).

In the middle of the twentieth century, researchers on the Athabasca Deposit became very interested in the origin of the bitumen in the oil sands (Ball, 1935; Sproule, 1951; Link, 1951; Hume, 1951). These researchers also proposed possible depositional environments for the sand, but with no corraborating evidence provided to prove their interpretations.

A paper by Kidd (1951) began a new era in the study of the McMurray Formation that was continued and expanded upon by Carrigy (1959, 1962, 1963a, 1963b, 1963c, 1966, 1967, 1971, 1973b), who produced much of the early key work on the McMurray Formation. By using detailed stratigraphy, mineralogy, paleocurrent analysis, and sedimentary structures, Carrigy produced a depositional model, that of a deltaic complex, for the McMurray Formation (Carrigy, 1966, 1967, 1971), which survived until the middle 1970's.

In the 1970's, and early 80's, researchers concentrated on local detailed studies of the McMurray Formation, rather than regional studies (Flach, 1977; James, 1977; Benthin and Orgnero, 1977; Nelson and Glaister, 1978; Mossop, 1980; Knight *et al.*, 1981). The study done by James (1977) covers Township 93, Range 7 W4, which is the southern portion of the present study area. These workers employed the principles of facies analysis to construct depositional models of the McMurray Formation. From this work, two main depositional models of the McMurray Formation were developed: the estuarine model (MacCallum, 1977; Stewart and MacCallum, 1978; Stewart, 1981; Pemberton *et al.*, 1982; Ranger and Pemberton, 1992) and the fluvial model (Flach, 1977, 1984; Mossop, 1978, 1980; Mossop *et al.*, 1982; Mossop and Flach, 1983; Flach and Mossop, 1985). Smith (1987) proposed a merger of these two models by developing three lithofacies models for different meandering river conditions (Fig. 4). He stated that all three point bar styles could be present in one fluvial-estuarine system (Smith, 1987).

STRATIGRAPHY

Local - Fort McMurray Area

Pre-Cretaceous succession

In the Athabasca Oil Sands area, the McMurray Formation unconformably overlies a succession of Devonian evaporites and carbonates, which, in turn, unconformably overlie the Precambrian basement (Carrigy, 1973c). The Devonian strata pinch out against the Canadian Shield in the east and thicken westward to about 350 m near Fort McMurray (Norris, 1973). The Devonian rocks dip to the west-southwest and strata become successively younger towards the west (Martin and Jamin, 1963).

The dolomite, anhydrite, gypsum, and halite of the Lower to Middle Devonian Elk Point Supergroup are overlain by limestone and dolomite of the Middle Devonian Slave Point Formation, which is overlain by limestone and dolomite of the Upper Devonian Beaverhill Lake and Woodbend Groups (Carrigy, 1959; Norris, 1973). The Waterways Formation of the Beaverhill Lake Group is in direct, unconformable contact with the overlying McMurray Formation. More specifically, the Moberly Member of the Waterways Formation underlies the McMurray Formation (Carrigy, 1959; Norris, 1973). A subcrop map (Fig. 5) shows the distribution of Devonian strata at the pre-Cretaceous unconformity (Devonian-Cretaceous boundary).

Pre-Cretaceous unconformity

Bell (1885) and McConnell (1893) first noted that Cretaceous sediments unconformably overlie Devonian carbonates in the Athabasca oil sands area. During this major break in deposition, the rocks in the area were probably subjected to periods of subaerial exposure, as evidenced by the calcareous shales rarely observed directly beneath the McMurray Formation (Carrigy, 1959; Stewart, 1963). There is no evidence of any deposition between Devonian and Early Cretaceous time in northeastern Alberta (Carrigy, 1959; Stewart, 1963; Park and Jones, 1985).

Cretaceous succession

The Cretaceous succession in the Fort McMurray area of the Athabasca oil sands consists of the (from base to top) (Fig. 6): McMurray, Clearwater, Grand Rapids, Joli Fou, Pelican, and La Biche Formations (Carrigy, 1959).

Only the McMurray Formation and Wabiskaw Member of the Clearwater Formation were examined in the present study.

McLearn (1917) placed the top of the McMurray "at the base of a bed of green sandstone" (p. 147). Carrigy (1959) 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 is limited in areal extent, as it was deposited in deep valleys on the pre-Cretaceous unconformity surface. The middle McMurray is found throughout the study area, as is the upper McMurray. In some areas, however, the upper McMurray is not present due to erosion. The boundaries between members are usually quite distinct, except in some cases where the contact between the middle and upper members is difficult to recognize. The lack of body fossils in the McMurray Formation makes it difficult to determine an exact age for the formation. Ages from Neocomian (Barremian) to Albian have been suggested for the McMurray (Fox, 1988). The consensus seems to be that the McMurray is Aptian, possibly up to early Albian, in age (Burden, 1984; Flach and Mossop, 1985; Ranger and Pemberton, 1992).

The Clearwater Formation (McConnell, 1893) conformably overlies the McMurray Formation, with its base defined as the bottom of a well-defined glauconitic sand bed (McLearn, 1917; Carrigy, 1959), known as the Wabiskaw Member (Badgley, 1952). The appearance of glauconite is what distinguishes the Clearwater Formation from the McMurray Formation. In the present study, the contact between the McMurray and Clearwater is recognized by the appearance of glauconite, the distinct colour change in the shales from brownish gray in the McMurray to dark gray in the Wabiskaw, and the increase in trace fossil size and diversity in the Wabiskaw (Fig. 7). The age of the Clearwater Formation has been established as Albian (Carrigy, 1959).

Regional Stratigraphy

Nauss (1945) first used the term "Mannville" for the succession of Lower Cretaceous strata lying between the pre-Cretaceous unconformity and the base of the Joli Fou Formation (Badgley, 1952), in the Vermilion area. The "Mannville Formation" was found to extend into western Saskatchewan (Wickenden, 1948). Badgley (1952) elevated the Mannville to group status and divided the Mannville Group into, in ascending order, the McMurray, Clearwater, and Grand Rapids Formations. The McMurray Formation has been correlated to the lower part of the Mannville Group (Ellerslie or Basal Quartz) in central Alberta (Badgley, 1952; Williams, 1963; McLean and Wall, 1981); the Dina Formation in the Lloydminster area (Nauss, 1945; Glaister, 1959); the Gething Formation (of the Bullhead Group) in the Peace River area of northwestern Alberta; the Gladstone Formation (of the Blairmore Group) of the Alberta Foothills (McLearn, 1945; Williams, 1963; Mellon, 1967; McLean and Wall, 1981); and the Sunburst Sandstone in southern Alberta (Williams, 1963; Mellon, 1967) (Fig. 6).

STRUCTURE

Regional Structure

The deposition (and therefore the thickness and extent) 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 west-southwest at about 4 m/km (Carrigy, 1959; Norris, 1973). The Devonian strata dip to the southwest at a very small angle and are roughly parallel to the slope of the Precambrian surface (Carrigy, 1959). Post-Cretaceous tilting was approximately 1 m/km to the southwest over most of the Athabasca area (Martin and Jamin, 1963).

The McMurray Formation was deposited in a north-northwest trending trough or syncline bounded by the Canadian Shield to the east and a resistant ridge of Nisku-Grosmont carbonates to the west, the "Wainwright Ridge" (Stewart, 1963; Vigrass, 1965; Ranger and Pemberton, 1988). The McMurray sedimentary basin (Carrigy, 1967) developed in the Devonian limestones parallel to the edge of the exposed Precambrian Shield as a result of the leaching of Elk Point Supergroup (Prairie Formation) evaporites (Stewart, 1963; DeMille *et al.*, 1964). This low, formed by the subsidence of Beaverhill Lake carbonates due to salt solution of the Prairie evaporites, localized a major trunk drainage system, the "McMurray channel valley" (Ranger and Pemberton, 1988). It was in this valley, and its tributaries, that most of the McMurray sediments accumulated (Stewart, 1963; Carrigy, 1967). Salt solution also occurred during and after deposition of the Cretaceous sediments, forming closed depressions around Bitumount and Fort McMurray (Stewart, 1963; Martin and Jamin, 1963; Norris, 1973). In the

Bitumount Basin (TWP 96, RGE 10) for example, the McMurray and Clearwater Formations have collapsed by approximately 60 m (Stewart, 1963; Jardine, 1974). Salt solution is continuing today as indicated by the saline springs commonly found in the Fort McMurray area (Carrigy, 1959; Jardine, 1974).

The main control on the deposition of the McMurray Formation was the structure of the pre-Cretaceous unconformity surface. The McMurray Formation tends to fill in the valleys and depressions on the unconformity surface and thin over the hills and ridges (Stewart, 1963). The unconformity surface is very uneven and displays considerable relief, 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 of erosion-resistant Devonian strata (Martin and Jamin, 1963; Norris, 1973). The two main ridges are the Grosmont Ridge (which is the northern extension of the Wainwright Ridge of Ranger, 1994), which forms the western boundary of the Athabasca Oil Sands Deposit, and the Beaverhill Lake Ridge, which formed as a result of the salt solution of underlying beds to the east of the ridge (Martin and Jamin, 1963; Stewart, 1963; Stewart and MacCallum, 1978). Between the ridges are valleys that 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). Fractures or faults on the pre-Cretaceous surface may have influenced the formation of these tributary valley systems (Martin and Jamin, 1963).

Local Structure

The structure of the pre-Cretaceous unconformity surface (Fig. 8) shows a fairly flat surface with minor highs throughout the southern and central portion of the Steepbank study area. Across the northern portion, and to the east, there are some significant lows. A comparison of the McMurray isopach map (Fig. 9) and the map of the unconformity surface (Fig. 8) indicates that the thickest sections of the McMurray Formation occur within the lows on the unconformity surface. The maximum thickness of the McMurray Formation occurs in the well at 10-12-94-7 W4 (99.4 m) and is coincident with the lowest elevation on the unconformity surface (234.4 m above sea level). The high in the southern portion of the map area, at 4-2-93-7 W4 (292.5 m above sea level) is coincident with the minimum thickness of the McMurray Formation (33.4 m). There may be some evidence of post-Cretaceous salt collapse in the northwest portion of the study area, where there is a low on the unconformity surface but no evidence of thickening of the McMurray Formation.

GEOLOGICAL FRAMEWORK

In Middle to Late Jurassic time, the collision of exotic terranes with the North American craton, along with the development of the Rocky Mountain fold and thrust belt, caused the development of a foreland basin, the Western Canada Sedimentary Basin (Leckie and Smith, 1992; Beaumont *et al.*, 1993; Stott, 1993). The foreland basin was filled with sediments derived from the erosion of the rising Cordillera to the west and the Canadian Shield to the east (Cant, 1989; Beaumont *et al.*, 1993).

There were two main pulses of clastic sedimentation in the Rocky Mountain Foothills during the Columbian Orogeny (Late Jurassic to Early Cretaceous) (Stott, 1984, 1993). The first clastic wedge consisted of Jurassic and earliest Cretaceous sediments of the Fernie Formation and the Minnes and Kootenay Groups (Stott, 1984). The sediments are found only in the western part of the foreland basin, indicating that sedimentation occurred only in the Foothills (Cant, 1989). Unconformably overlying these sediments are the sediments of the second clastic wedge, the Lower Cretaceous Blairmore Group of the Foothills, the Bullhead and Fort St. John Groups of northwestern Alberta, and the Mannville Group of central and northeastern Alberta (Williams, 1963; Stott, 1984; Cant, 1989).

The Blairmore, Bullhead, and Mannville Groups were deposited on an unconformity surface deeply incised by three main northwest trending drainage systems separated by topographic ridges (Fig. 10): the Spirit River Valley system, the Edmonton Channel valley, and the McMurray Valley system (St. Paul Channel of Williams, 1963) (Ranger, 1994). The Spirit River Valley trends northward along the western edge of the basin and probably drained much of western Alberta and the western United States (Ranger, 1994). The Edmonton Channel flowed toward the north-northwest from southeastern Alberta and southwestern Saskatchewan (Williams, 1963; Ranger, 1994). The Edmonton Channel may have emptied into the Boreal Sea to the north or it may have been a tributary of the Spirit River valley

(Ranger, 1994). The Wainwright Ridge (Grosmont High in northeast Alberta) is a major axial ridge system present on the east side of the Edmonton Channel (Williams, 1963; Ranger, 1994). Between the axial ridge and the western margin of the Canadian Shield, the McMurray valley developed due to subsidence caused by the dissolution of Middle Devonian evaporites (Prairie Formation) along the eastern edge of the Alberta Basin (Stewart, 1963; Ranger, 1994). It was into the McMurray Valley system, and the McMurray sedimentary basin, that McMurray Formation sediments were deposited (Carrigy, 1967; Ranger, 1994).

Southward incursions of the Boreal Sea flooded the major valley systems, developing estuaries that eventually became arms of the sea (Williams, 1963; McLean and Wall, 1981). At the end of McMurray time (Early Albian), the Boreal Sea transgressed southward into Alberta, depositing the Clearwater Formation shales (Williams, 1963; McLean and Wall, 1981). This transgression occurred because of the subsidence of the Alberta Basin due to crustal loading during the Columbian Orogeny; the subsidence of the McMurray sedimentary basin due to salt solution; and the global eustatic sea level rise that was occurring during the Lower Cretaceous (Caldwell, 1984; Fox, 1988; Leckie and Smith, 1992). The rising sea level inundated the ridges separating the valleys and the Boreal Sea pushed into southern Alberta (Fig. 11) (McLean and Wall, 1981). At the end of Mannville time, the Boreal Sea had joined with the Gulfian Sea from the south, forming a shallow, epicontinental sea, the Western Interior Seaway, into which Upper Cretaceous marine sediments were deposited (James, 1977; Caldwell, 1984).

Figure 1. Location of Cretaceous oil sand deposits in Alberta (modified from Mossop *et al.* 1982).

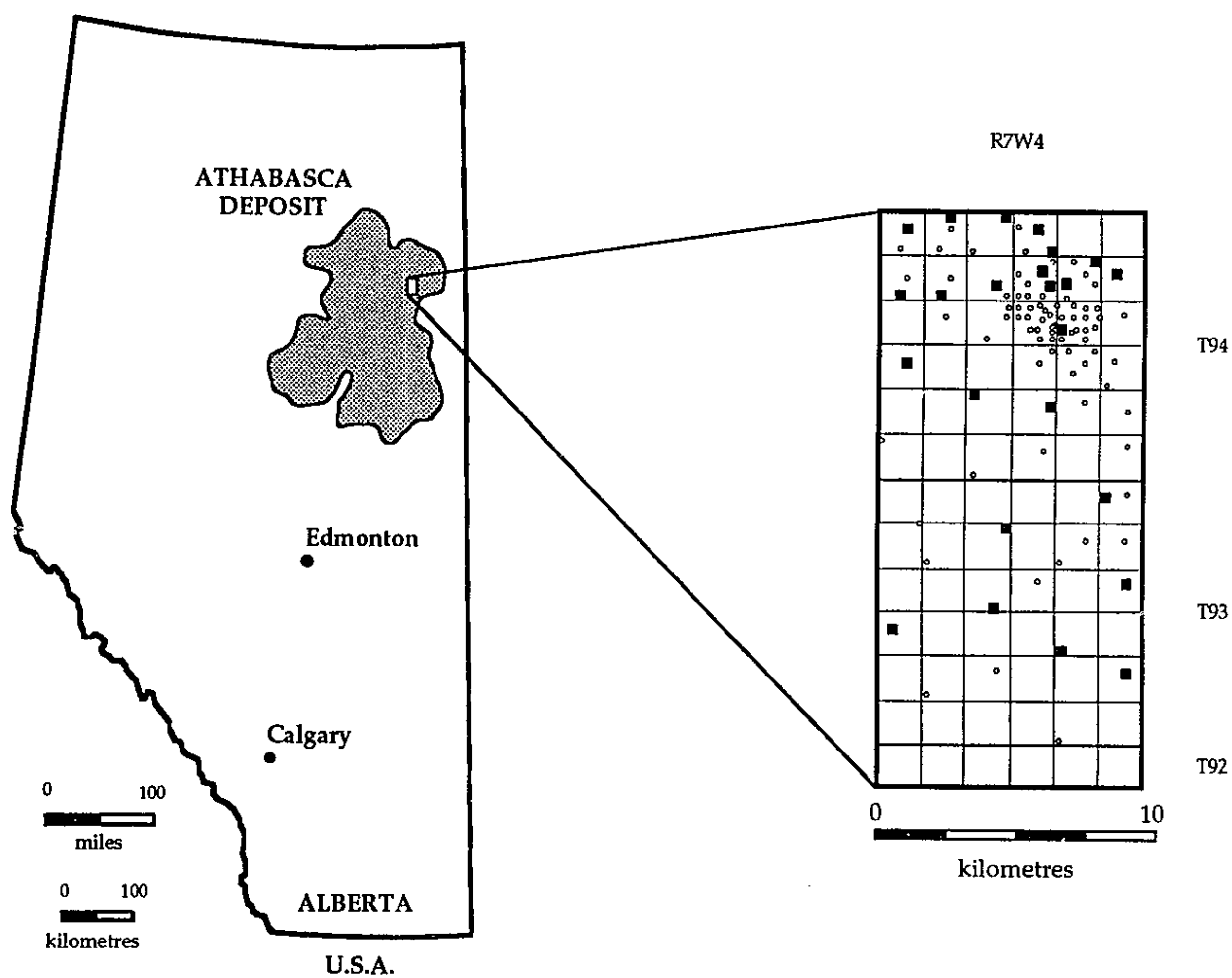

Figure 2. Location map of study area (Steepbank/Oil Sand Lease 49). Black squares are locations with logged core.

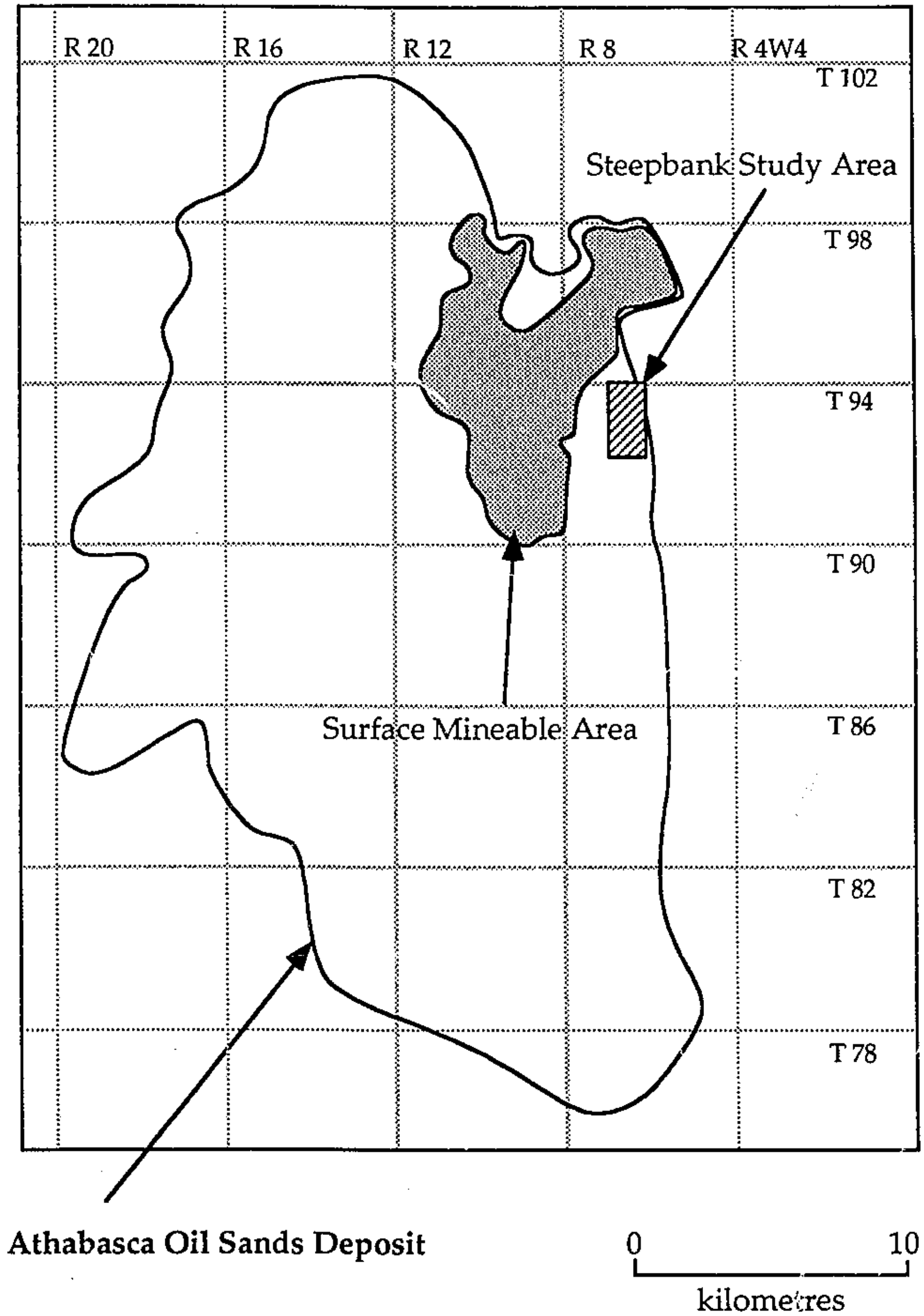

Figure 3. Surface mineable area of the Athabasca Oil Sands Deposit (modified from Govier, 1974).

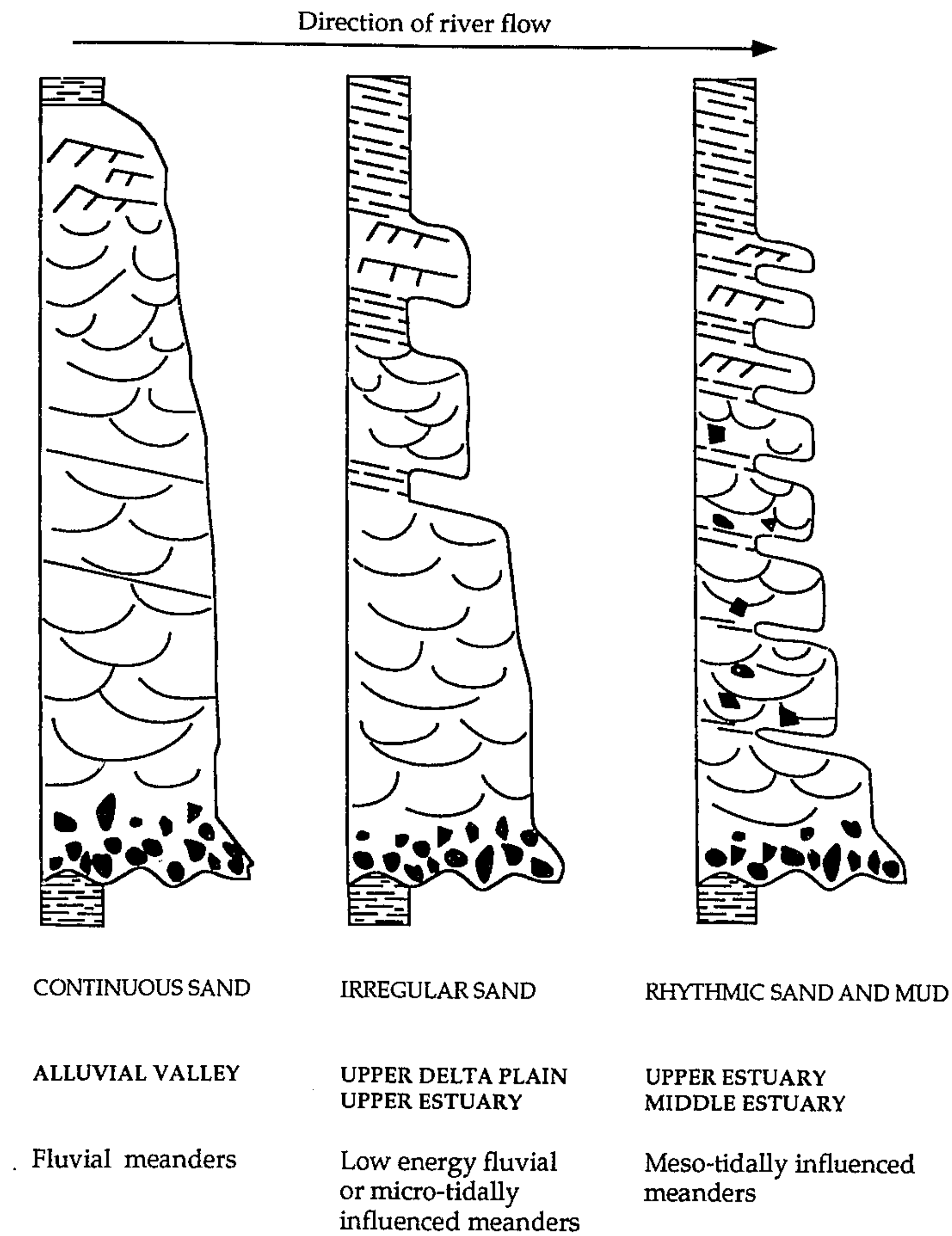

Figure 4. Lithofacies models for meandering river-estuarine point bar deposits (modified from Smith, 1987).

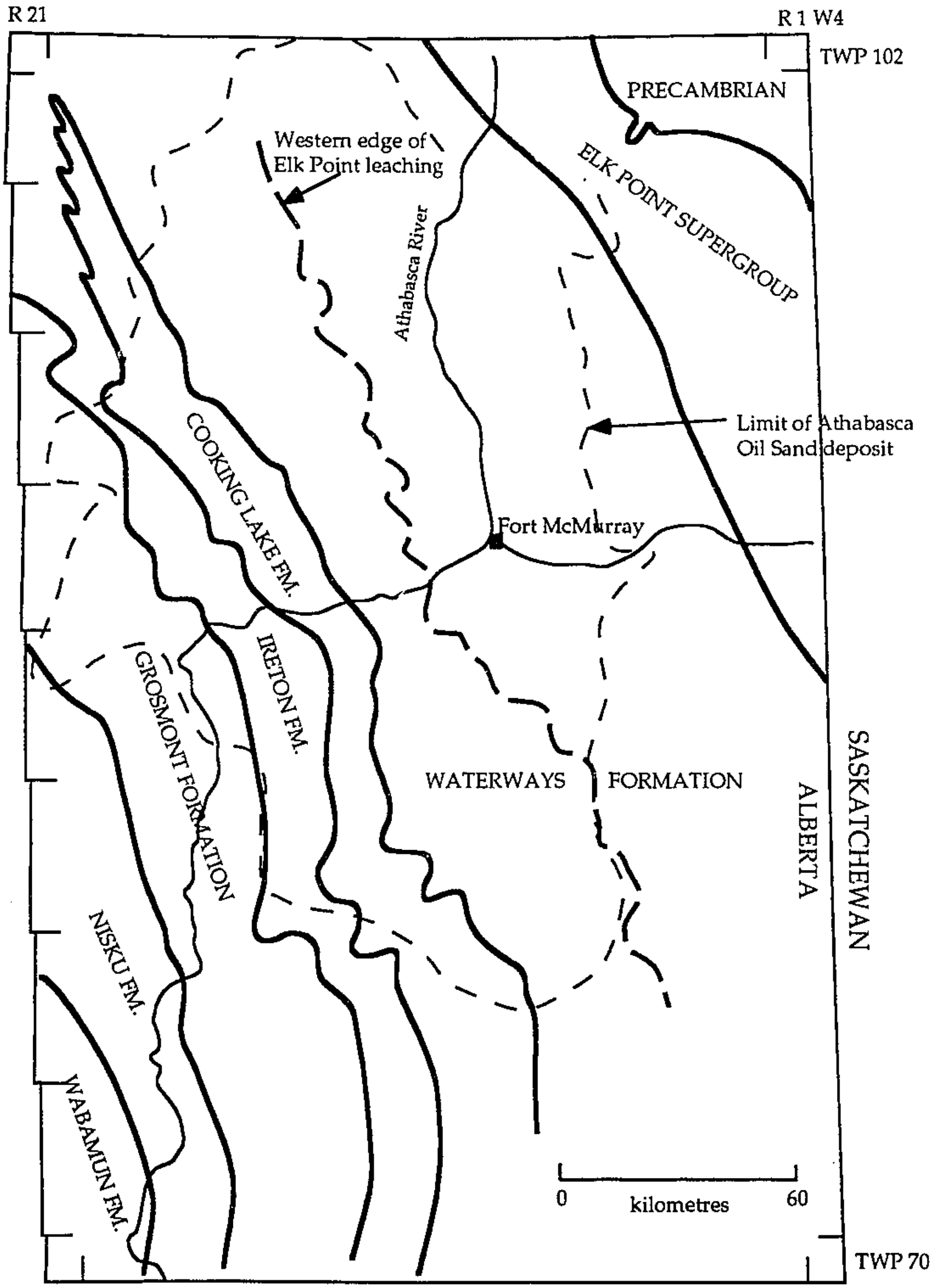

Figure 5. Subcrop map of Devonian strata at the pre-Cretaceous unconformity (modified from Stewart, 1963; Norris, 1973).

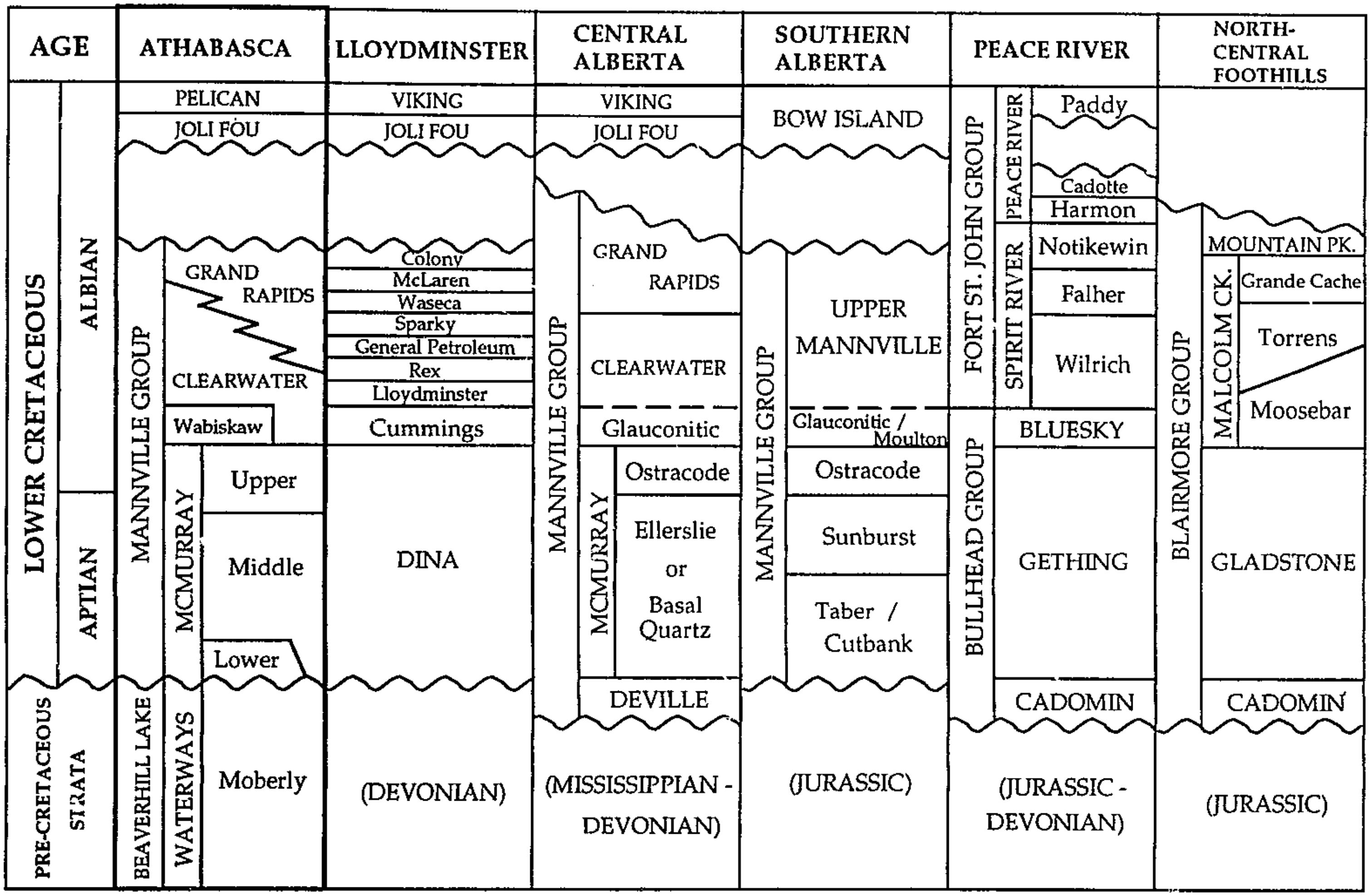

Figure 6. Stratigraphic correlation chart of the Lower Cretaceous in Alberta (from McLean and Wall, 1981; Williams, 1963; Glaister, 1959; Carrigy, 1959; AGAT, 1987).
Parentheses indicate ages, not formation names.

Figure 7. Contact (arrow) between the McMurray Formation, below, and the Wabiskaw Member of the Clearwater Formation, above. Note colour change in shales from brownish gray in the McMurray to dark gray in the Wabiskaw.


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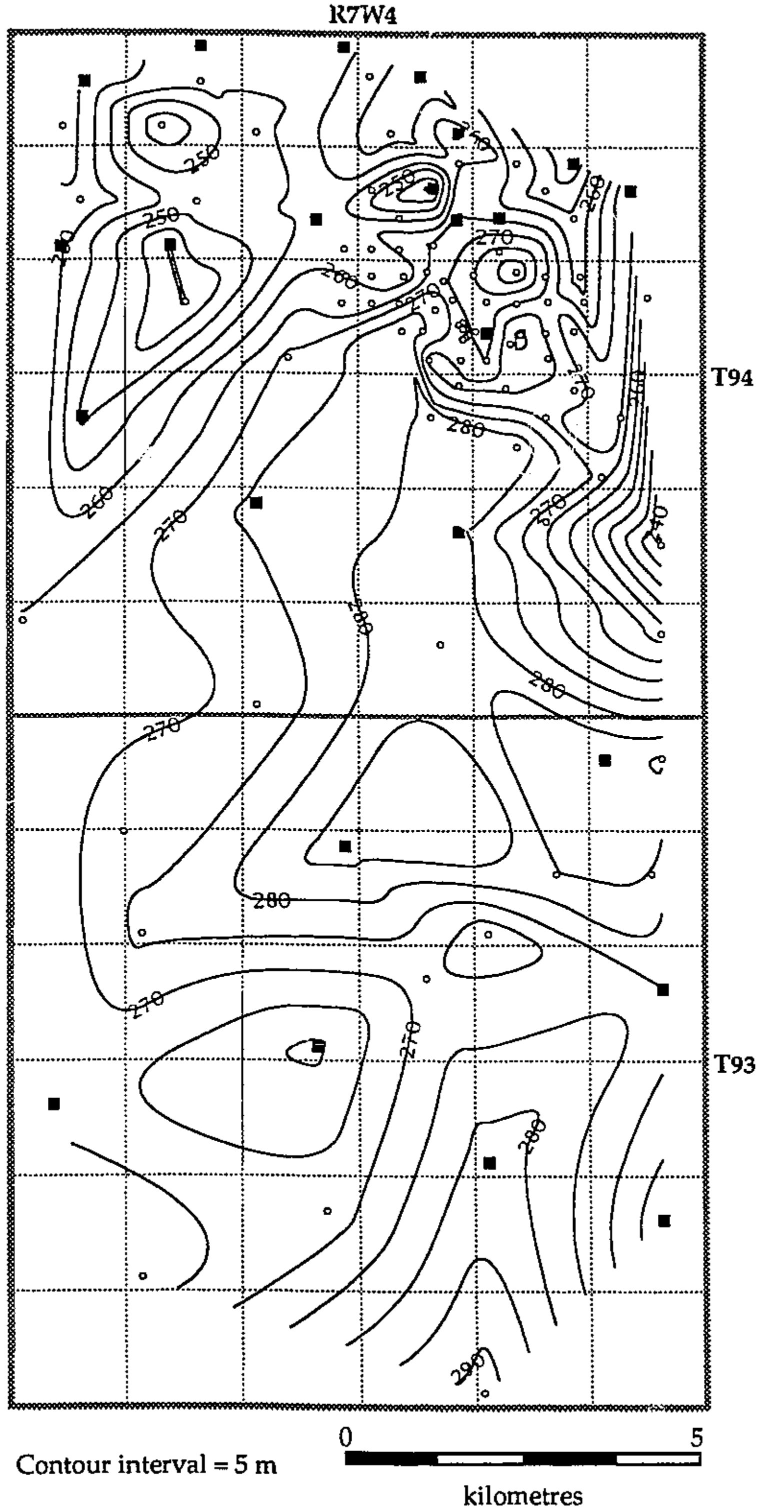

Figure 8. Structure on the pre-Cretaceous unconformity. Black squares are well locations with logged core.

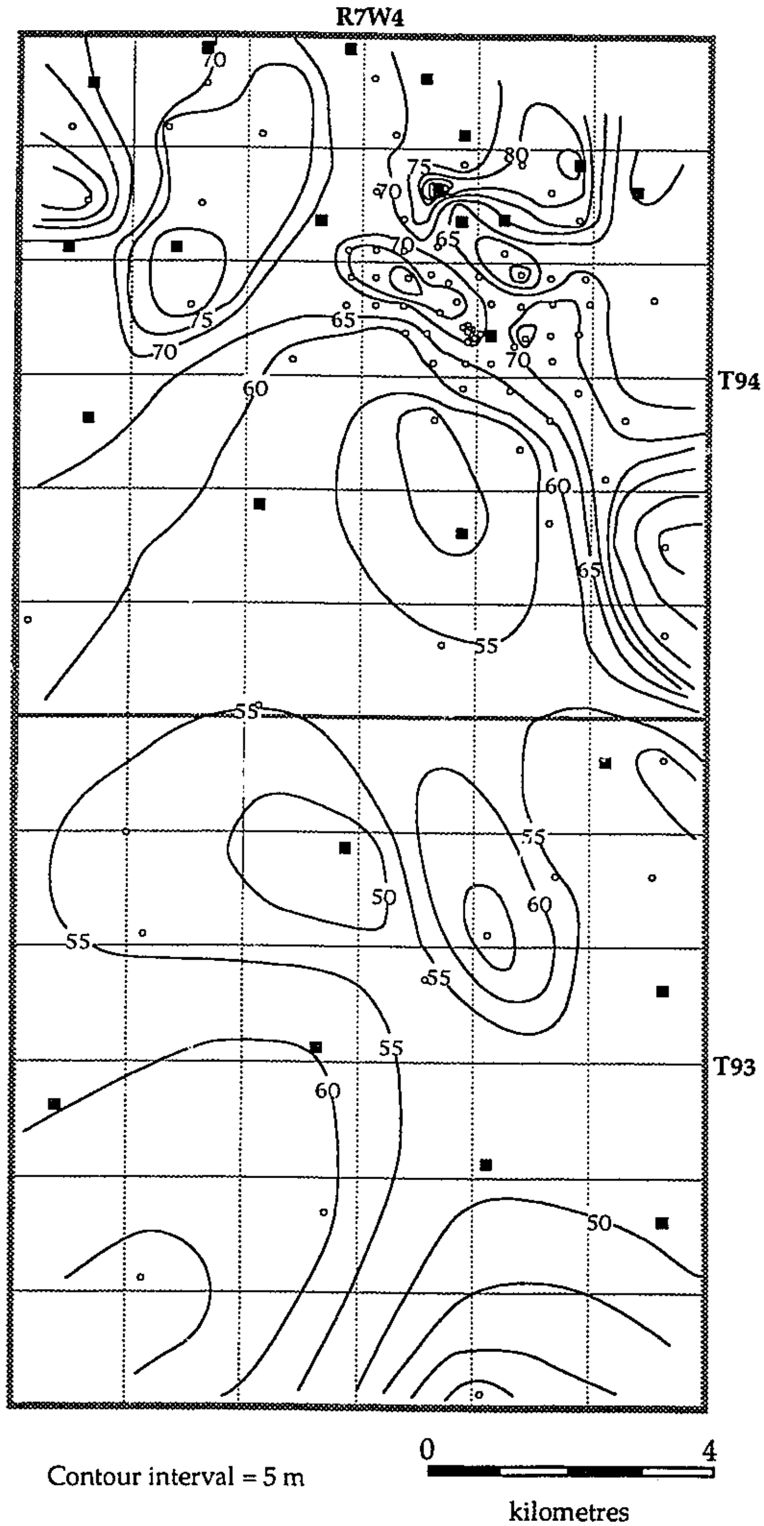

Figure 9. Isopach map of the McMurray Formation. Black squares are well locations with logged core.

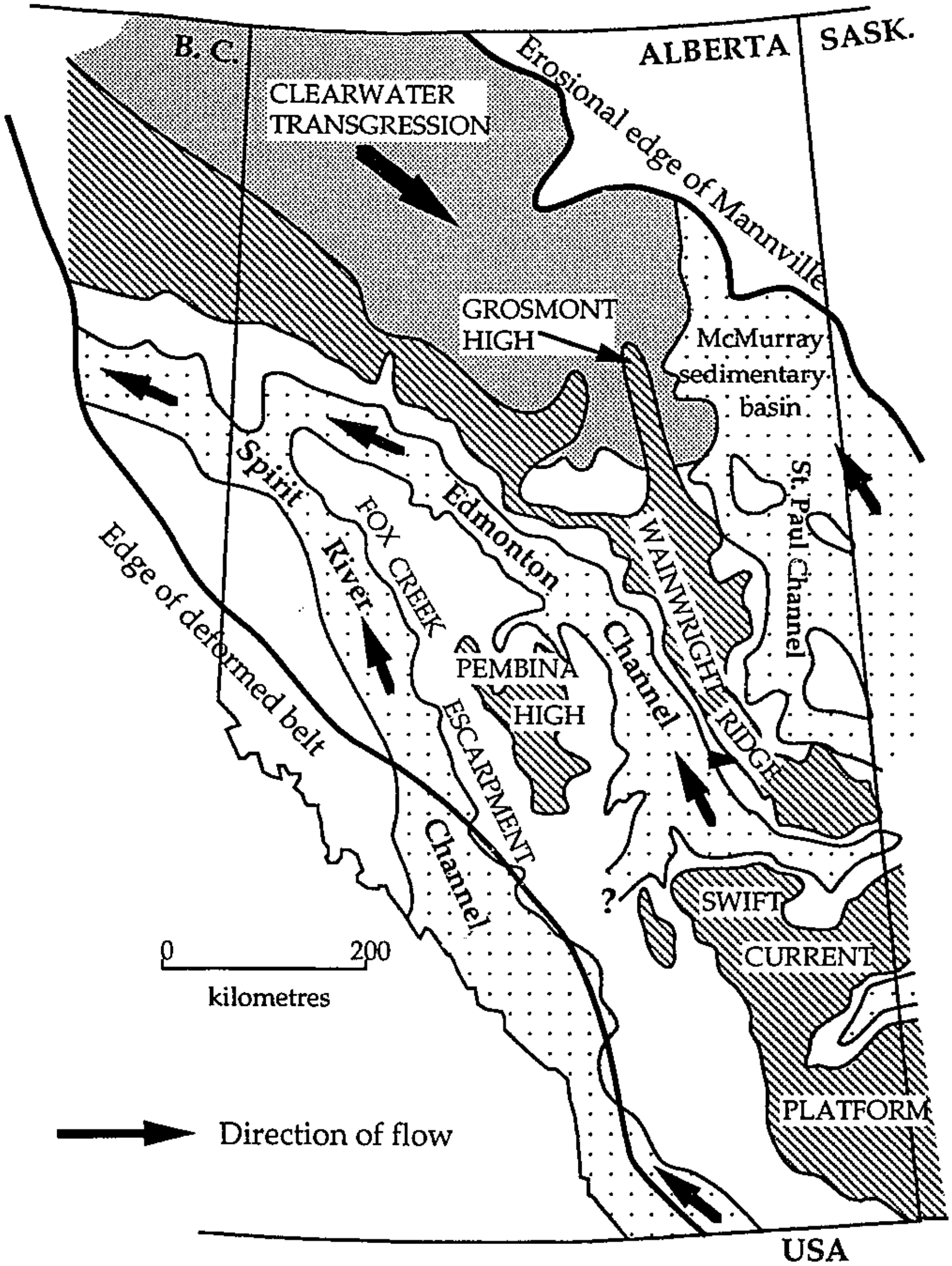

Figure 10. Lower Cretaceous paleotopography prior to deposition of the Mannville, Bullhead, and Blairmore Groups, showing major drainage systems and topographic ridges (modified from Fox, 1988).

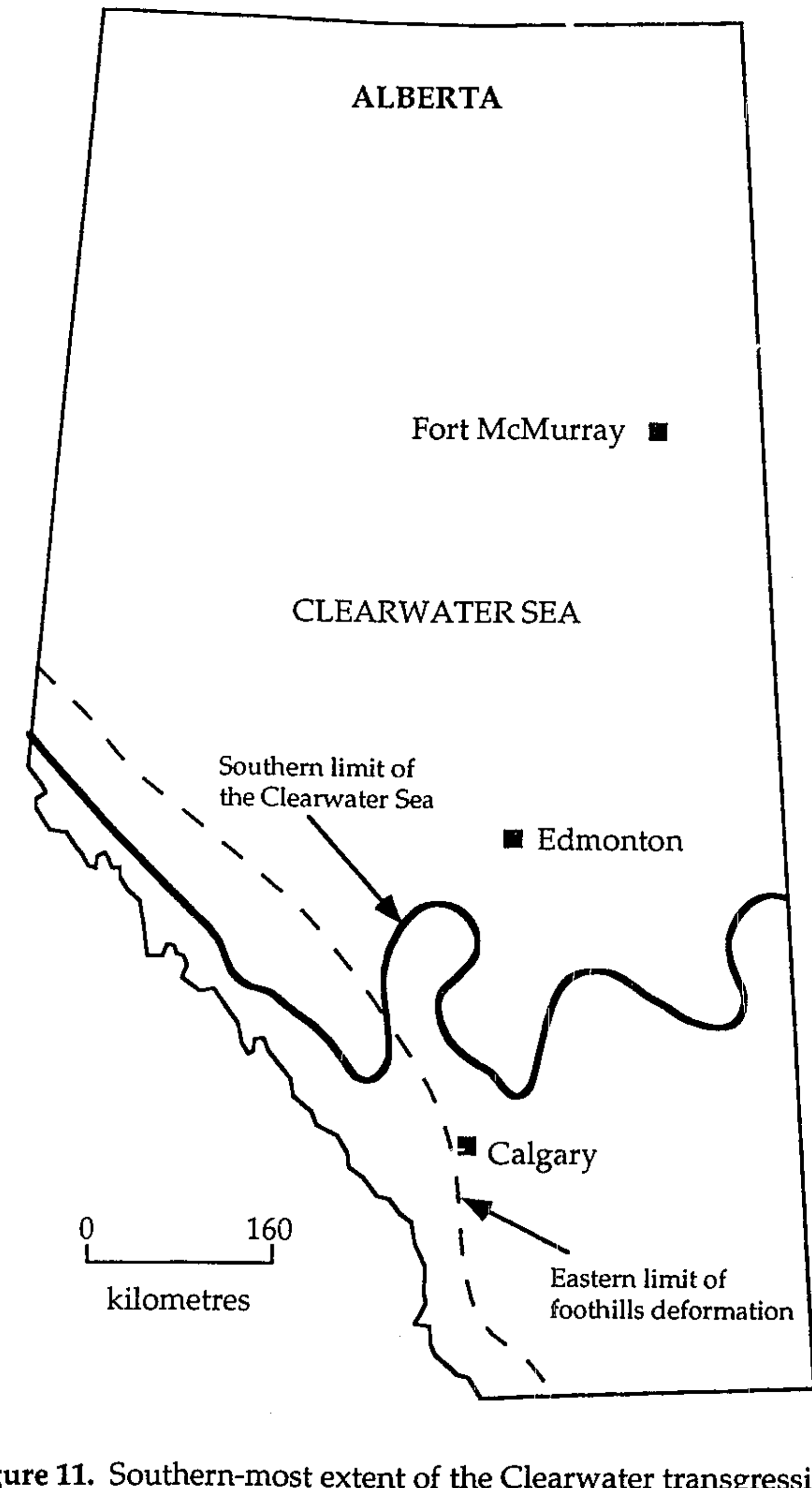

Figure 11. Southern-most extent of the Clearwater transgression in Alberta (modified from McLean and Wall, 1981).

CHAPTER 2 - SEDIMENTOLOGY

FACIES

One of the most extensively used, albeit the most frequently misused, concepts in sedimentary geology is the facies concept. The original definition of the term "facies" is clear and unambiguous, but in recent times, the term has been applied to numerous concepts that are unrelated to the original. Facies comes from the Latin meaning face, figure, appearance, aspect, look, or condition (Teichert, 1958). The term was first used by Nicolaus Steno in 1669 to represent the entire aspect of part of the earth's surface during an interval of geologic time. The modern usage of the term "facies" was introduced by Gressly in 1838 to represent the lithological and paleontological aspects of a sedimentary rock unit (Teichert, 1958; Walker, 1992).

Facies is a purely descriptive term. The characteristics of a facies that distinguish it from surrounding sedimentary units can be used to determine an environment of deposition for that particular sedimentary unit (Teichert, 1958). According to the original definition, facies is an abstract concept; it is not a particular rock type, but an expression of the properties of the rock (Teichert, 1958). Paleoenvironmental interpretation is the goal of facies descriptions. Genetic interpretations should not be included in a facies description, however, because the environment is not the facies, it produces the facies (Teichert, 1958).

For the present study, the facies are described and analyzed to determine the processes and depositional environments responsible for their formation. The ichnology of each facies is also described because trace fossils are effective tools for the interpretation and reconstruction of depositional environments. By using both the sedimentology and ichnology, as well as their relative position in the facies succession, the depositional environment of each facies was determined.

The facies are later grouped together into facies associations (see Chapter 3). The facies associations represent facies that are related genetically. The facies in a facies association were formed together within a certain depositional environment. When facies are grouped together into facies associations, it gives a clearer picture of the depositional environment by taking into account all the facies together, not just as single lithologic units, but as part of larger complex.

In this study, nine main facies were recognized:

Facies 1 - Mudstone

Subfacies 1a - Massive white to light gray mudstone

Subfacies 1b - Dark gray to black carbonaceous mudstone

Subfacies 1c - Flat to low angle laminated light gray to beige mudstone

Subfacies 1d - Medium to light gray interlaminated to silty mudstone

Subfacies 1e - Gray structureless mudstone

Subfacies 1f - Interlaminated dark gray mudstone

Facies 2 - Coal

Facies 3 - Structureless sand

Facies 4 - Flat to low angle planar stratified sand

Facies 5 - Small-scale cross-stratified sand

Facies 6 - Large-scale cross-stratified sand

Facies 7 - Heavily bioturbated sand

Facies 8 - Carbonaceous sand

Facies 9 - Interbedded sand and mud

Numbers will appear in parenthesis after the name of a facies within the following text (as well as in Chapter 3). These refer to the facies numbers of the above list.

Facies 1 - Mudstone

This facies is divided into six subfacies based on colour, preserved sedimentary structures, and bedding styles.

Subfacies 1a - Massive white to light gray mudstone

Description:

This subfacies is found mainly in the lower member of the McMurray Formation, but there are two examples in the study area where it is present in the upper member (wells 3-30-94-7 W4 and 16-33-94-7 W4).

The mudstone can range in colour from white to light gray and, rarely, to medium gray. The surface appears chalky, but it breaks in a blocky manner with the broken surfaces having a waxy texture. The blocks may display slickensides. Rooting is common and is the only form of bioturbation present in this subfacies. The root traces are generally filled with carbonaceous material (Fig. 12a), but may be filled with mud. Carbonaceous debris is scattered throughout the subfacies. It may take the form of coaly fragments a few centimetres in diameter or individual flakes a few millimetres in diameter. Coal laminae and wood fragments are also present.

Another characteristic of this subfacies (although not present in all cases) is the presence of small (0.5 cm, or less, in diameter) "mudballs" (concretions) (Fig. 12b). These "mudballs" disintegrate easily when scratched or crushed by a fingernail. They generally have an outer rim and are concentrically laminated, and may have a nucleus of carbonaceous debris. The "mudballs" are found only in the lower member of the McMurray Formation.

Swelling clays (such as smectite) are probably the main constituent of the mudstone. When sprayed with water, the clays in the mudstone swell and the mudstone becomes very slick. Siderite nodules with diameters of 2-5 cm are present in this subfacies. Pyrite is also found throughout as nodules, dendritic clusters, and disseminated grains (Fig. 12c). The mudstone tends to be siltier when present in the upper McMurray, and may show mudcracks.

Basal contacts with underlying facies are generally gradational, but may be sharp when in contact with Devonian carbonates. The subfacies commonly has a gradational upper contact with *dark gray to black carbonaceous mudstone* (1b).

Interpretation:

As a channel overflows its banks, fine-grained, suspended load material is carried out onto the flood plain. The clay then settles from suspension due to the decrease in velocity of the water flow, caused by the unconfined flow (Galloway and Hobday, 1983; Collinson, 1986). This subfacies is interpreted to represent those flood plain deposits.

Because the flood plain is rarely inundated, subaerial exposure is common and pedogenesis (soil formation) may occur (Collinson, 1986). The development of a soil is evidenced in this subfacies by the root traces and abundant carbonaceous debris (Leckie *et al.*, 1989). The blocky nature of the mudstone, the slickensides, and the concretions are also evidence of soil development (Leckie *et al.*, 1989; Retallack, 1990). Slickensides form in clayey soils when the blocks of soil (peds) continually move past one another during swell-shrink cycles caused by wetting and drying of the soil (Retallack, 1990). Another way slickensides form is by the crushing of peds against one another during compaction and burial.

Subaerial exposure is indicated by the mudcracks found in this subfacies in the upper McMurray. The white to light gray colour of the mudstone also indicates a subaerial, oxidizing environment (Visher, 1965).

The siderite and pyrite found in this subfacies are probably diagenetic in nature, not depositional. They were probably precipitated from slightly reducing ground waters (Collinson, 1986).

Subfacies 1b - Dark gray to black carbonaceous mudstone

Description:

This subfacies is found only in the lower member of the McMurray Formation. The mudstone is organic rich, which gives the mud its dark colour. Along broken surfaces, the mudstone has a waxy texture, and there may be rare faint slickensides. Carbonaceous debris, coaly fragments, and wood fragments are abundant throughout the subfacies (Fig. 13a). Root traces can be seen rarely. Pyrite is common, both in nodules and disseminated grains.

The basal contact is gradational with *massive white to gray mudstone* (1a).

Interpretation:

The high organic content of this subfacies indicates that there was abundant vegetative growth. Subfacies 1b is interpreted to be representative of a marsh environment, possibly associated with interchannel topographic lows (Kalkreuth and Leckie, 1989; Galloway and Hobday, 1983). The gradational contact with the underlying *massive white to gray mudstone* (1a) indicates that Subfacies 1b represents the continuation of plant growth on old overbank deposits.

The pyrite present is probably diagenetic in nature, forming after burial due to reducing groundwaters.

Subfacies 1c - Flat to low angle laminated light gray to beige mudstone

Description:

This subfacies is found only in the lower member of the McMurray Formation. It is generally found in direct contact with the underlying unconformity, although not always (*eg*. well 10-27-94-7 W4).

The mudstone is very faintly laminated. In the 16-26-94-7 W4 well, the bedding planes are emphasized by pyrite that formed along the plane. Pyrite is very common in this subfacies, both in nodules and disseminated grains. Swelling clays (such as smectite) are the main constituent of this mudstone.

The mudstone has a waxy texture and displays slickensides on broken surfaces. There are some faint root traces filled with mud. There is little to no carbonaceous debris in this subfacies. Fractures and possible mudcracks are common (Fig. 13b). The fractures are generally filled with fine sand. The fractures can be quite large (up to 29 cm long and 6 cm wide).

Basal contacts with the unconformity can be sharp or gradational. With underlying sand bodies, the contact is sharp and irregular. The upper contact with overlying sand is sharp.

Interpretation:

This subfacies is very similar to Subfacies 1a, but without the soil development.

During flood stages, a river channel will overflow its banks. When it tops the bank, flow is no longer confined and flow velocity decreases rapidly (Galloway and Hobday, 1983; Collinson, 1986). The very fine grained, suspended load material is carried out onto the flood plain, where it settles out of suspension (Galloway and Hobday, 1983; Collinson, 1986). This subfacies is interpreted as representing these flood plain deposits.

The mudcracks and fractures present are due to the drying out of the deposits between flooding events (Collinson, 1986). The faint, rare root traces also indicate subaerial exposure. The lack of soil development may be due to an arid climate where there was not much vegetative growth (Collinson, 1986). Another possibility is that the top portion of this subfacies was stripped off by subsequent channel deposition caused by channel migration.

The pyrite was precipitated due to the presence of reducing groundwaters.

Subfacies 1d - Medium to light gray interlaminated to silty mudstone

Description:

This subfacies is found throughout the McMurray Formation in all three members, however, it is most common in the middle member. It is characterized by medium to light gray mudstone with laminations of white silt and, rarely, very fine sand (Fig. 13c). The beds and laminations can be flat or inclined at a low angle. Bedding may be contorted and chaotic. The laminations are generally lenticular, but can also be planar.

Roots are rare and found in this subfacies only in the upper McMurray. Siderite is common as nodules or a cement. Pyrite nodules are also present, with alteration rings discolouring the mudstone around the nodules. Carbonaceous debris is rare, but is present in some wells.

This subfacies commonly has a gradational lower contact with *interbedded sand and mud* (9) and a gradational upper contact with *gray structureless mudstone* (1e). These three subfacies commonly occur in succession. Subfacies 1d may also have a sharp upper contact with *interbedded sand and mud* (9) depending on the sand content of that facies. Upper and lower contacts of Subfacies 1d with sand facies are generally sharp and planar.

Ichnology:

Burrowing is present in this subfacies in the silty and sandy laminations; the mudstone shows no bioturbation. The white silt usually fills and lines the burrows so they are visible in the gray mudstone. The intensity of burrowing ranges from rare to common within the silty and sandy laminations; in the subfacies as a whole, however, bioturbation is rare.

Planolites is the most abundant trace fossil in this subfacies. Other traces present are *Skolithos*, *Palaeophycus*, rare *Cylindrichnus*, and rare *Teichichnus*. The *Planolites* are small (1-2 mm in diameter), round to oval burrows found in the silt and sand laminations. The burrows are filled with either white silt or sand, making them stand out in the gray mudstone. The *Skolithos* are vertical burrows 1-2 mm in diameter and less than 1 cm long. These burrows tend to be filled with the gray mudstone and seem to cut through the white silt laminae (Fig. 13d).

The other burrows are also small, relatively simple forms. The *Cylindrichnus* can be distinguished from *Skolithos* by the slight flare at the top of the former. *Teichichnus* is a small horizontal burrow (5 mm long, 3-4 mm wide) with vertical spreiten, usually filled with sand.

Interpretation:

This subfacies is interpreted as representing channel abandonment deposits in a meandering estuarine channel system. Channel abandonment occurs due to the cut off of meander loops, either by: a) chute cut-off or b) neck cut-off (Fig. 14) (Blatt *et al.*, 1980; Harms *et al.*, 1982; Galloway and Hobday, 1983; Collinson, 1986).

A chute cut-off occurs when the river cuts across a meander loop, cutting chutes into the point bar (Collinson, 1986). As the chute takes up more of the river flow, the old meander bend is gradually abandoned (Collinson, 1986; Harms *et al.*, 1982).

A neck cut-off occurs when the neck of the meander loop is breached during a flood, cutting a channel across the neck (Collinson, 1986; Galloway and Hobday, 1983). In this case, the river abandons the meander loop abruptly; the ends of the loop are rapidly plugged and an oxbow lake is formed (Collinson, 1986; Harms *et al.*, 1982).

With a chute cut-off, the abandonment succession grades upward from trough cross-stratified channel sands to interbedded and cross-laminated sand and mud, to mudstone (Fig. 15a) (Harms *et al.*, 1982). With a neck cut-off, mudstone sits directly on sands or on a thin succession of sand and mud (Fig. 15b) (Harms *et al.*, 1982).

It is into this environment that the sediments of Subfacies 1d were deposited. The entire succession in each well must be examined to determine if the subfacies results from a neck cut-off or a chute cut-off in that particular case. In most cases in the study area, this subfacies represents channel abandonment due to a neck cut-off.

The rarity of roots in this subfacies indicates that the sediments probably remained subaqueous.

The estuarine nature of this environment is indicated by the small size of the burrows, low diversity of forms, simple morphology of the burrow forms, and sometimes high abundance of burrows. These characteristics all indicate a stressed environment such as a brackish water, estuarine environment (Pemberton *et al.*, 1982; Wightman *et al.*, 1987; Ranger and Pemberton, 1992).

Subfacies 1e - Gray structureless mudstone

Description:

This subfacies is generally found in the middle member of the McMurray Formation, but may be present near the top of the lower member.

This subfacies is characterized by mudstone that ranges in colour from light to dark gray and displays no sedimentary or biogenic structures. There can be rare silt laminations, but there are generally no observable structures. Rare carbonaceous debris or wood fragments may be present. Siderite is common and is present as a cement that discolours the mudstone to orange or yellow (Fig. 16a). Pyrite is also present and shows alteration rings that again discolour the mudstone, in this case to greenish-brown. There is no burrowing or rooting. Swelling clays (such as smectite) are the main constituent of this subfacies.

The basal and upper contacts are gradational with *medium to light gray interlaminated to silty mudstone* (1d). Upper contacts with other facies (sand facies) are sharp.

Interpretation:

This subfacies is interpreted as being representative of the continued abandonment of a channel meander loop evidenced by the deposits of Subfacies 1d. This subfacies was probably deposited in an oxbow lake (Fig. 17) that only received sediment from suspension during flood periods (Collinson, 1986). The lack of rooting indicates a subaqueous environment. The siderite and pyrite are interpreted to be diagenetic features that formed after burial.

Subfacies 1f - Interlaminated dark gray mudstone

Description:

There are only two examples of this subfacies in the study area and they are restricted to the upper member of the McMurray Formation.

The mudstone is very similar in appearance and composition to the *dark gray carbonaceous mudstone* (1b) of the lower member. Subfacies 1f, however, is characterized by laminae of sand and white silt intercalated with the mudstone (Fig. 16b).

The lower contact of this subfacies is gradational with the *massive white to gray mudstone* (1a) of the upper McMurray. The upper contact with *heavily bioturbated muddy sand* (7) in the 16-33-94-7 W4 well is sharp and burrowed. The upper contact of Subfacies 1f in well 3-30-94-7 W4 is gradational with *interbedded sand and mud* (9).

Ichnology:

Burrowing in this subfacies is present in the silty and sand laminae. *Planolites* and *Skolithos* are the two forms observed. Both forms are 1-2 mm in diameter or width, with the *Skolithos* less than 1 cm in length. *Planolites* may be filled with either sand or silt, whereas the *Skolithos* are filled with sand. Burrowing is common to rare in this subfacies. Directly below the lower contact of sand laminae within the mudstone, burrowing seems to be the most intense.

Interpretation:

This subfacies is interpreted to be representative of a marsh environment possibly associated with interchannel topographic lows (Galloway and Hobday, 1983; Kalkreuth and Leckie, 1989), similar to Subfacies 1b. In this case, however, there seems to have been a periodic influx of marine water into the area, evidenced by the sand laminations and bioturbation. The sand laminations indicate short-lived events when currents were high enough to transport sand, and bioturbation appears to be associated only with these events.

Facies 2 - Coal

Description:

This facies is found only in the lower member of the McMurray Formation, and reaches a maximum thickness of 3.2 m. The coal is dark gray to black in colour and smudges the fingers when handled. It is generally quite silty and may have disseminated sand grains scattered throughout (Fig. 16c). The coal is fissile and displays many surface cracks. Flakes of carbonaceous debris and distinct layers may be observed. Pyrite nodules are very common. The basal and upper contacts are sharp and generally flat (Fig. 16d).

Interpretation:

In areas with extensive plant growth, dead vegetation accumulates on the ground and forms a mat of vegetable matter. Peat will form from this mat if the area is free from detrital influx and the vegetative mat is water saturated due to high groundwater tables, such as occurs in a swamp or marsh environment (Galloway and Hobday, 1983; Selley, 1988). The peat will then be transformed into coal after burial (Galloway and Hobday, 1983).

This coal facies is interpreted to have formed in a levee to backswamp environment next to a meandering fluvial channel. The silty nature of some of the coal indicates some minor influence from the river channel, probably from flooding or crevasse splays. The sharp lower contact of the coal with sand may be due to compactional subsidence superposing the coal directly on channel-fill sands (Galloway and Hobday, 1983).

Facies 3 - Structureless Sand

Description:

This facies occurs only in the middle member of the McMurray Formation. It is characterized by massive sand with no biogenic or physical sedimentary structures (Fig. 18a,b). Grading and stratification are also absent. The sand is typically fine grained but may rarely be coarse to very coarse, with rare granules. Although the sands have variable grain size, they are not graded. Mud intraclasts are common in this facies; they are angular to subrounded and are composed of the same material as *interbedded sand and mud* (9) or *medium to light gray interlaminated to silty mudstone* (1a). The intraclasts have a random orientation (Fig. 18c), and are variable in size, ranging from 1-2 cm to around 10 cm in length. The intraclasts may be as wide as the core tube (6.5 cm), making it difficult to determine if they are beds or intraclasts. The intraclasts may make up more than 50% of this facies in some cases. The intraclasts are rarely sideritized. Wood fragments and carbonaceous debris are very rarely observed. The contacts are generally gradational but may be sharp.

Interpretation:

Massive or structureless sands are formed either by very rapid deposition from suspension or by deposition from very highly concentrated sediment dispersions during sediment gravity flows (Blatt, *et al.*, 1980; Boggs, 1987). The lack of stratification indicates an absence of traction (grain to bed contact) transport, because traction leads to the formation of lamination (Blatt, *et al.*, 1980; Boggs, 1987). The sand grains are held in suspension by fluid turbulence generated by the motion of the current. When there is a flattening of the slope or a dilution of the current, deposition occurs (Blatt *et al.*, 1980).

Massive or structureless sands may also be a product of extensive biogenic activity (Blatt, *et al.*, 1980; Boggs, 1987). Bioturbation by organisms may destroy any evidence of physical sedimentary structures, producing a massive-looking sand. However, there is usually evidence of bioturbation in the form of mottling or remnant burrows (Boggs, 1987).

Liquefaction is another way that structureless sands may be formed by destruction of primary structures (Blatt, *et al.*, 1980; Boggs, 1987). Liquefaction occurs when grains in a loose, cohesionless sediment temporarily lose contact with each other and become suspended in the pore fluid (Blatt, *et al.*, 1980; Boggs, 1987). This fluid-supported sand behaves like a high-viscosity fluid that is easily deformed and can flow rapidly down gentle slopes (Boggs, 1987). Sediments deposited rapidly or cohesionless sediments subjected to strong shocks, or a series of shocks, are subject to liquefaction (Blatt, *et al.*, 1980).

The mud intraclasts deposited along with the sand are also affected by liquefaction. Any preferred orientation that the intraclasts may have had would be destroyed by liquefaction, producing the observed random orientation of the intraclasts. The intraclasts are angular to subrounded, indicating that they were not transported far from their place of formation. The lack of abrasion of the mud intraclasts indicates that secondary processes, such as liquefaction, were responsible for the massive texture of this facies. Primary processes that could produce a massive texture would probably be too energetic for the mud intraclasts to remain intact and unabraded (Fox, 1988). Sometime after deposition of the sand and intraclasts, liquefaction occurred and imparted a massive texture on the sand.

The collapse of a channel bank may have been the cause of liquefaction in this case. If the sand was deposited rapidly on a gentle slope, such as the channel bank, a shock of some sort may have caused the sand to lose cohesion and flow down the bank. This would have produced the structureless sand of this facies. The intraclasts were formed as the bank collapsed and then transported by the sand flow.

Facies 4 - Flat to Low Angle Planar Stratified Sand

Description:

This facies is found throughout the McMurray Formation. It is characterized by flat to low angle planar stratified sands. Sets of low angle stratified sands may show truncation surfaces and opposing dips. Stratification varies from laminations (1-2 mm thick) to beds (greater than 1 cm thick). The sand is generally very fine to fine grained but may range up to medium to coarse grained. The sands may be well to poorly sorted. Because of a high bitumen content and the generally uniform grain size, stratification is generally difficult to discern, and these sands may appear massive. Grain size differences and rare mud laminae help to indicate stratification.

Mud intraclasts that have their long axes lined up in a preferred orientation are common in this facies (Fig. 18d). The intraclasts are made up of the same material as *interbedded sand and mud* (9) or *medium to light gray interlaminated to silty mudstone* (1a). The intraclasts can make up 30-40% of the unit, and rarely up to 50%. The intraclasts are generally subangular to subrounded, and are typically 1-2 cm in length, but may range up to 7 cm long and 1-2 cm wide. The mud intraclasts may rarely be sideritized.

Another feature of this facies is the presence of units of thinly interlaminated carbonaceous debris, sand, and mud (Fig. 18e). These units can be up to 15 cm thick, with the laminae being 1-2 mm thick. The units generally grade into underlying and overlying sand. Carbonaceous debris, wood fragments, and coaly laminae are found rarely, scattered throughout this facies.

Contacts are generally gradational, but may be sharp. The contacts may be indistinct if it is a contact between sand and sand, because of the heavy bitumen staining.

Ichnology:

Bioturbation in this facies is rare to absent. Burrowing is found mainly within the mud laminae, but may rarely be seen in the sand. The mud intraclasts also show burrowing, but since they are composed of material from other facies, they won't be considered here. Burrows within the sand are generally lined with mud, making them visible in the bitumen stained sand (Fig. 19a).

Planolites, Cylindrichnus, and *Palaeophycus* are the most abundant burrow forms present in this subfacies. There are also minor occurrences of *Skolithos* and *Arenicolites*. The mud laminae are generally thoroughly bioturbated (Fig. 19b). A vertical cross-section through *Cylindrichnus* shows a central sand shaft and a relatively thick (1-2 mm) mud lining that may be laminated. The burrow tapers down (Fig. 19a). An oblique cross-section through *Cylindrichnus* shows a round central core of sand (2-3 mm in diameter) surrounded by an irregular halo of mud (Fig. 19b). The other traces are also small and are sometimes difficult to distinguish because of the thorough mixing.

Interpretation:

Flat to low angle planar stratified sands were deposited under upper flow regime conditions, in plane beds (Harms and Fahnestock, 1965). Under upper flow regime conditions, flow resistance is small, sediment transport is large, and turbulence is low (Simon *et al.*, 1965; Harms and Fahnestock, 1965). Sediment is transported by grains continuously rolling and sliding downstream along the bed. Plane beds are characterized by a surface with no elevations or depressions larger than a sand grain (Simon *et al.*, 1965). Plane beds form in fine-grained sediments under lower stream power than required to form plane beds in coarser sediments (Simon *et al.*, 1965). Stratification is produced by a pulsating flow that alternates between the uplift of low speed fluid from the boundary ("bursting") and the inrush of high speed fluid toward the boundary ("sweeping") (Cheel and Middleton, 1986). Each pulse deposits a lamination.

Mud intraclasts in flat to low angle planar stratified sand are generally small and subrounded, indicating high energy flow conditions (Smith, 1972). The preferred orientation of the intraclasts indicates that they were subject to upper flow regime conditions that produced horizontally stratified deposits. The intraclasts were broken down and abraded as they were transported at high velocities. As the intraclasts became smaller, due to erosion and abrasion, the surface area exposed to shear forces and the effect of bottom impact were reduced (Smith, 1972). These small, rounded intraclasts were transported some distance from their place of formation. There are, however, some large angular mud intraclasts in this facies. They are not abraded and, therefore, were not transported far from their place of origin. They were probably deposited under less energetic conditions. The intraclasts were formed due to collapse of the channel bank. As water flows past the outside bank of a channel meander, it erodes the bank and causes slumping and collapse of the bank material. The mud clasts formed by this are then transported downstream by the current.

The thinly interlaminated carbonaceous debris, sand, and mud could not have been deposited under high flow regime conditions. The carbonaceous debris and mud would have very low settling velocities and, therefore, were likely deposited from suspension under very weak current conditions (Harms *et al.*, 1982).

The rare mud laminae indicate some fluctuation in current velocities. The laminae were probably deposited from suspension, under low flow energy conditions. The trace fossils within these mud laminae indicate some influx of marine or brackish water. The small size and high abundance of the burrows indicate a stressed environment. The environment may have been fluvially dominated, indicated by the lack of burrowing in the sand and plane bed deposition, but the presence of trace fossils within the mud laminae indicates some minor marine influence. This facies is interpreted to have been deposited in a brackish water environment, with the clasts indicating downstream transport of bank collapse material.

Facies 5 - Small-Scale Cross-Stratified Sand

Description:

This facies is found throughout the McMurray Formation. The cross-stratification is considered "small-scale" because the cross-sets are generally less than 5 cm thick and both the upper and lower set bounding surfaces are clearly visible. Also, whole cross-strata can generally be differentiated into foresets and toesets (Fig. 20a-d). The individual cross-laminae are visible due to differential bitumen saturation.

Two main types of cross-sets are found in this facies: tabular-shaped and trough-shaped, with the former being the most common. The upper and lower bounding surfaces of the tabular sets are generally flat and virtually parallel to one another. These surfaces may dip slightly (up to 10^o). The cross-strata are steeply dipping and, in superimposed sets, the cross-strata 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 sets have a concave-upward lower bounding surface with a scoured upper surface. The cross-strata are generally gently dipping and dip in opposite directions in superimposed sets. The cross-strata seem to be more or less parallel with the set's lower bounding surface.

The sand in this facies is very fine to fine grained. Bitumen saturation is high due to the well-sorted nature of the sand. It is only in areas with moderate bitumen saturation that the small-scale cross-stratification can be seen. As stated above, differential bitumen saturation helps to highlight the cross-strata. In some examples in the lower McMurray, the cross-strata appear unstained in heavily stained sand (Fig. 20e, f). This may be due to a higher argillaceous content. Within the middle McMurray, mud drapes are rarely seen (Fig. 20a). These are thin (2-3 mm) laminations of mud interlaminated with the small-scale cross-stratified sand. If staining is very heavy, portions of this facies may appear massive.

Basal contacts with underlying facies are generally sharp and scoured, but may also be gradational.

Ichnology:

Bioturbation is rare to absent in this facies. It is seen mainly in thin mud drapes that are rarely interlaminated with the small-scale cross-stratified sand, within the middle member of the McMurray (Fig. 21a). Within the sand, escape structures (fugichnia) are the only observable traces. The escape structures can be up to 1-2 cm in length. They are characterized by sand laminae that are bent and point down in a V shape (Fig. 21b). Rare *Skolithos* with a dark wall, are also present. The most common burrow in the mud drapes is *Planolites*, that are round to oval and 1-2 mm in diameter. *Cylindrichnus* is rare and is generally of the form with a central sand core surrounded by a halo of mud (Fig. 21b). *Palaeophycus* is also rare; these burrows are similar in size to *Planolites*, but have a mud wall and the same fill as the surrounding sediment (usually sand).

Interpretation:

Small-scale cross-stratification is produced by the migration of current, wave, and combined flow ripples. Ripples are triangular-shaped bedforms 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). In the lower flow regime resistance to flow is large and sediment transport is small (Simons *et al.*, 1965). 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 side) of the ripple (Simons *et al.*, 1965). Ripples are generally spaced less than 20-30 cm apart and are less than 2-3 cm high. The ratio of spacing to height is about 10:1 (Harms *et al.*, 1982). Ripples do not form in sediment with diameters greater than about 0.5-0.6 mm (Selley, 1988).

In profile, ripples may be either symmetric or asymmetric. The tabular-shaped cross-bed sets in Facies 5 were produced by asymmetrical ripples. These ripples are characterized by steep laminae that are parallel with the lee side of the ripple. They are formed by unidirectional currents, such as in a river channel (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). The tabular sets in the small-scale cross-stratified sands of the McMurray Formation do not have high angles of climb and were, therefore, probably formed by migrating current ripples with little deposition from suspension. A vertical section transverse to flow shows trough-shaped sets (Fig. 21c, d). The tabular-shaped sets are seen in vertical sections parallel to flow.

Symmetrical ripples, often called oscillation or wave ripples, 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. The asymmetrical laminations may be due to an uneven oscillatory flow in which the current in one direction is stronger than in the other (Harms *et al.*, 1982). The uneven flow produces a net translation or migration of the wave ripple (McKee, 1965). Net migration can also occur if a unidirectional current is superimposed on the oscillatory flow of waves (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 mud drapes were likely deposited from suspension during slack water conditions caused by a reduction in current velocity.

Another line of evidence, along with the combined-flow ripples, that indicates estuarine conditions is the characteristics of the trace fossils present in this facies. They are small, morphologically simple forms of low diversity, indicating a stressed environment. The small-scale cross-stratified sand is interpreted to have been deposited as ripples, migrating across the floor or point bar of an estuarine channel.

Facies 6 - Large-Scale Cross-Stratified Sand

Description:

This is the most common sand facies in the McMurray Formation in the study area. It is found in the middle and lower members of the McMurray and is characterized by large-scale cross-stratified sand (Fig. 22a-c). It is termed "large-scale" because the inclined strata extend across the width of the core tube. The cross-strata sets range in thickness from 5 cm to greater than 75 cm. It is difficult to determine the upper limit of the cross-bed set thickness because the core tubes are segmented into short lengths, making accurate measurement difficult. Individual cross-strata range in thickness from about 0.5 cm to 3 cm, with an average thickness of about 1 cm. The average dip of the strata is about 10°, with dips ranging from 5-30°. Adjacent sets commonly dip in opposite directions with truncation surfaces clearly visible (Fig. 22d, e). The individual cross-strata are differentiated by grain size or colour change due to variable bitumen saturations.

The cross-strata commonly alternate between fine and coarse material within a single set. Grain size can range from fine sand to pebbles. The coarser grained material (coarse sand to pebbles) is most abundant in the lower member and lower part of the middle member of the McMurray Formation, where the sand becomes gravelly. The sand in the rest of the middle member is well to moderately sorted and mainly fine grained. Rarely, layers of granules, one or two grain diameters thick, may be present within the large-scale cross-stratified sand.

In large-scale cross-stratified sand, the cross-strata within a set are generally parallel with the set's lower bounding surface, but commonly meet the lower bounding surface tangentially. Rarely, the cross-strata will meet the set's lower bounding surface at a sharp angle.

Mud laminae are commonly found within this facies. These laminae are generally conformable with the sand in which they are found. The boundaries of the mud laminae are sharp but may also be gradational or burrowed. The laminae may be continuous or discontinuous across the width of the core. The mud may be interlaminated with sand laminae in beds a few centimetres thick, within the cross-bed set. Mud intraclasts are also common in this facies. The intraclasts generally have a preferred orientation and the beds containing these intraclasts are conformable with the cross-stratified sand (Fig. 22f). The intraclasts may make up 30-40% of the facies in some beds. The clasts are generally small (about 5mm long) and subrounded. There are, rarely, large (up to 6 cm long) angular clasts found in portions of this facies. The large clasts may have a horizontal orientation within the large-scale cross-stratified sand. The intraclasts are made up of the same material as *interbedded sand and mud* (9) or *medium to light gray interlaminated to silty mud* (1d). Individual intraclasts are commonly found scattered throughout the facies.

Carbonaceous debris, coaly laminae, and wood fragments are common in this facies in the lower member and lower part of the middle member of the McMurray. The coal laminae are less than 1 cm thick and may be continuous or discontinuous across the width of the core. The carbonaceous debris and coaly laminae may be thinly interlaminated with mud in beds about 5-10 cm thick, that are conformable with the cross-stratified sand in which they are found. The carbonaceous debris may also be thinly intercalated with the cross-stratified sand. The woody fragments may be up to 2 cm thick and 5 cm long, but are generally smaller (around 1 cm square).

Basal contacts are gradational, but may also be sharp, scoured, or loaded. Upper contacts are gradational, but may be sharp. *Large-scale cross-stratified sand* (6) generally grades up into *flat to low angle planar stratified sand* (4) or *structureless sand* (3) or *interbedded sand and mud* (9) and, rarely, *small-scale cross-stratified sand* (5).

<u>Ichnology:</u>

Bioturbation is rare to absent in this facies. The mud laminae are commonly burrowed. Rarely, there are burrows in the sand. These burrows are usually lined or filled with mud, making them visible in the heavily bitumen stained sand. *Cylindrichnus* and *Planolites* are the most abundant traces present. There are some minor occurrences of *Palaeophycus* and rare escape structures (fugichnia). In general, burrowing is present only in the middle McMurray examples of this facies.

Cylindrichnus are mud-lined and, therefore, visible within the sand. *Planolites* are usually found within the mud laminae and are small, round burrows filled with sand. The mud laminae may be thoroughly or sparsely burrowed. If *Planolites* is the only trace present, the mud laminae are usually sparsely to moderately burrowed. If *Cylindrichnus* occurs within the mud laminae, burrowing is more intense. *Palaeophycus* are filled with sand and have a thin mud wall. The escape structures are found within the sand. All of the traces are small (less than 1 cm in length or diameter) and are morphologically simple forms.

Interpretation:

The large-scale cross-stratified sand is interpreted to be the product of the migration of two-dimensional (straight-crested) and three-dimensional (linguoid) dunes (Harms *et al.*, 1982). Dunes are formed in the upper part of the lower flow regime and are similar to ripples in both geometry and movement, but are about one order of magnitude larger (Middleton and Southard, 1984). They can be formed in sediment ranging in size from less than 0.1 mm up to gravel sizes (Harms *et al.*, 1982), the grain size range of Facies 6. Dunes form and are stable at moderate flow energy conditions, intermediate between ripples and plane beds.

Under weak flow conditions, dunes are straight-crested (two-dimensional) in plan view, while at higher velocities they become more irregular and linguoid (three-dimensional) (Harms *et al.*, 1982). The straight-crested dunes produce tabular cross-stratification (Harms and Fahnestock, 1965; Harms *et al.*, 1982). The cross-stratification is produced by deposition on the lee face (avalanche face) of the dune. The cross-strata meet the set's lower bounding surface at an angle, and, rarely, may meet the surface tangentially. Where the cross-strata are tangential with the bounding surface, there may be influence from hydraulic conditions other than unidirectional flow. The average dip of the foresets is about 30^o or more. Tabular cross-stratified sets range in thickness from a few decimetres to a metre or more (Harms *et al.*, 1982).

Trough cross-stratified sands are produced by linguoid dunes (Harms *et al.*, 1982). The cross-strata are generally curved and meet the set's lower bounding surface tangentially. In a vertical section transverse to flow, the set's lower bounding surfaces are concave upward and the strata are approximately parallel to the surfaces. The trough cross-stratification is developed within elongate scours that develop downstream of the linguoid dune, parallel to flow. Low angle, curved laminae fill the scours (Harms *et al.*, 1982). The strata are deposited either from suspension or by avalanche down the lee slope of the dune. The average dip of the foresets at their steepest part is about 25-30°. The maximum thickness of the trough cross-stratified sets is a few decimetres (Harms *et al.*, 1982).

The carbonaceous debris, woody fragments, and mud intraclasts may have accumulated within the scours. The coaly laminae and layers of carbonaceous debris are conformable with the sand strata. Flow velocities must have been periodically very low to allow the deposition of material with low specific gravity, over the deposition of sand. The flow was probably directed up the avalanche face of the dune as reverse eddies (Harms and Fahnestock, 1965). The mud intraclasts are quite small and rounded, indicating some transport from their point of origin. The preferred orientation of the intraclasts indicates that they were probably deposited on the avalanche face or within the scours, along with the sand.

The granule and pebble layers probably mark the bottom of the lowest dune troughs. The pebbles and granules were transported during upper flow regime conditions but then rolled upstream into the dune scours during lower regime flow. The pebbles would have come to rest at the bottom of the scours (Harms and Fahnestock, 1965).

It is difficult to differentiate between tabular and trough cross-stratification due to the small width of the drill core. There are some features that can be used to distinguish the two types (Fox, 1988). Tabular cross-stratification may be distinguished by the angular intersection of the cross-strata with the set's lower bounding surface, and cross-bed set thickness up to >75 cm. Trough cross-stratification can be distinguished by: cross-strata dip reversals in adjacent cosets; tangential contacts and cross-strata parallel with set lower bounding surfaces; and shallow dips of the cross-strata. In this facies, trough cross-stratification seems to be more abundant.

The mud laminae indicate that flow velocities decreased enough to allow mud to be deposited out of suspension. The composite sand and mud interlaminations indicate a fluctuating current, alternating between energies high enough to deposit sand and lower energies where mud was deposited from suspension. There are, rarely, small-scale cross-stratified sands found at the top of sets of large-scale cross-stratified sand. These also represent a lowering of flow energy conditions.

The lack of bioturbation in this facies may indicate an environment that was inhospitable for benthic organisms. The high-energy environment and migration of large-scale bedforms may have been too energetic for many organisms. Also, the high-energy environment is not conducive to the preservation of biogenic sedimentary structures.

The few trace fossil forms that are present indicate a brackish water environment. The forms are morphologically simple and are small. There is a low diversity of forms, also indicating a stressed environment. The large-scale cross-stratified sand is interpreted to have been deposited in dunes formed in an estuarine channel. The portions of this facies in the middle member that show no burrowing may have been deposited in the fluvially dominated portion of the estuary.

The total lack of bioturbation in the lower McMurray examples of this facies indicates no marine or brackish influence. Therefore, within the lower member, this facies is interpreted to have been deposited in a fluvial channel, as opposed to an estuarine channel.

Facies 7 - Heavily Bioturbated Sand

Description:

This facies is generally found in the upper member and the upper part of the middle member of the McMurray Formation. It may also rarely be present further down in the middle member. It is characterized by sand that is thoroughly bioturbated (Fig. 23a). No physical sedimentary structures, except rare, irregular, muddy interbeds, can be discerned, and only rarely can individual burrows be seen. The sand is generally thoroughly mixed with mud. The sand is very fine to fine grained, but may rarely be medium to coarse. In the 8-27-94-7 W4 well, there is no visible mud mixed with the sand, but the bitumen staining is irregular and it may be due to bioturbation (Fig. 23b).

The lower contact may be gradational with underlying sand facies or sharp and burrowed with underlying mud facies. The upper contact is generally gradational with either sand or *interbedded sand and mud* (9). The contact is sharp when overlain by the Wabiskaw Member of the Clearwater Formation.

Ichnology:

Individual burrow forms are difficult to discern because of the intensity of the burrowing. *Cylindrichnus* and *Planolites* are, again, by far, the most abundant trace fossils observed. *Palaeophycus* and *Skolithos* are also present.

All of the trace fossil forms are small (less than 1 cm in length or diameter) and they seem to be simple straight shafts or simple horizontal burrows.

Interpretation:

This facies lacks any distinct physical sedimentary structures due to the thorough bioturbation. Any physical sedimentary structures have been almost completely obliterated by burrowing organisms.

Sedimentation rates had to be low for the organisms to rework the sediment so thoroughly, otherwise sedimentary structures would have been buried and preserved. The ability of the organisms to rework the sediment exceeded the rate of reworking by physical processes (Frey and Howard, 1986), implying slow current or wave processes. The thorough bioturbation also implies favourable conditions for a large population of organisms that could quickly rework the sediment and destroy all physical sedimentary structures (Howard *et al.*, 1975).

The muddy nature of the facies indicates mud deposition was occurring. The mud was probably deposited from suspension when current velocities were low. There was alternation between sand and mud deposition, indicating fluctuations in current energy. These fluctuations may have been tidally influenced (Howard and Frey, 1973).

The ichnology lends support to the interpretation of a tidally-influenced environment. The high abundance of burrows indicates a marine or brackish influence. The low diversity of burrow forms, their simple morphology, and their small size all indicate brackish water conditions (Ranger and Pemberton, 1992). The last three characteristics are evidence of a stressed environment, such as in an estuarine channel, where salinity fluctuates. This facies may represent point bar deposition in an estuarine channel, although without physical sedimentary structures, this interpretation is not definite. However, the trace fossil evidence does indicate that this facies was deposited in a brackish water, estuarine environment.

Facies 8 - Carbonaceous Sand

Description:

This facies is found in the lower member and lowest part of the middle member of the McMurray Formation. It is characterized by sand with abundant carbonaceous debris, coal laminae, and wood fragments (Fig. 23c). The sand is generally poorly sorted with grain sizes ranging from very fine to very coarse. The carbonaceous debris ranges in size from very fine flakes to wood fragments 2-3 cm long (Fig. 23d). The carbonaceous material is scattered throughout the facies, although there are rare discrete coaly laminations. The laminations may be inclined. In general, however, there are no sedimentary structures observed. Bedding is commonly churned up and chaotic. Bitumen saturation ranges from excellent to poor, depending on the mud content of the sand. Mudballs similar to those found in the *massive white to light gray mudstone* (1a) may be present. Basal contacts may gradational or sharp. The upper contact is gradational.

Interpretation:

It is difficult to determine how these sands were deposited because of the lack of primary physical sedimentary structures. The chaotic bedding indicates that these deposits underwent secondary modification. The poor sorting indicates that current energy was low (Blatt, 1982). The amount of carbonaceous debris and coal laminae also indicate low current energy levels, otherwise the larger pieces would have been broken up and destroyed. Some transportation of the sand must have occurred because of the rare stratification. Bed load transport produces stratification in some form (Harms and Fahnestock, 1965).

The mudballs may indicate the onset of soil formation, which may have modified or destroyed the original sedimentary structures in the sand.

The abundance of carbonaceous material may also be explained by proximity to a highly vegetated area, such as a marsh, or swamp.

Facies 9 - Interbedded Sand and Mud

Description:

This facies is found mainly in the middle member of the McMurray Formation, but may, rarely, be found in the upper and lower members. Facies 9 includes thickly interbedded to thinly intercalated sand and mud. The sand-to-mud ratio varies considerably within this facies; it can range from sand-dominated, to equal sand and mud, to mud-dominated.

Interbedded sand and mud is flat to low angle stratified, with inclination of the beds ranging from 0-15^{o} (Fig. 24a). Dip reversals may, rarely, occur within single sets of interbedded sand and mud. Microfaults (throws of 1-2 cm) are rarely present within this facies. Synaeresis cracks are also rare and may be found within the mud interbeds, filled with sand from overlying beds. Flame structures are very scarce, but may be present within the sand interbeds.

The sand and mud are commonly coarsely interbedded. The sand beds range in thickness from 2-30 cm, and the mud beds range in thickness from 1-20 cm (Fig. 24b). Less commonly, the sand and mud are thinly interbedded, with the beds less than 1 cm thick (Fig. 25a, b). The thickly interbedded sand and mud appear to be in couplets. Each couplet consists of a sharp-based, or scoured, sand that may have a sharp or gradational contact with the overlying mud. Rip-up clasts of underlying mud beds may be present at the base of the sand interbeds. The contacts between the thinly interbedded sand and mud are generally sharp and may be wavy. The contacts between the interbeds may also be burrowed.

The sands are typically very fine to fine grained and may be small-scale cross-stratified. The sands may also appear to be massive or flat to low angle planar laminated. The sand beds may contain mud partings and flaser beds. These may drape the small-scale cross-stratification or may be intercalated with sand laminae. The mud beds are generally finely laminated and contain intercalations of sand.

Basal contacts of this facies with other facies are generally gradational, but may be sharp or scoured. Within the facies, the different types of *interbedded sand and mud* (sand-dominated, mud-dominated, etc.) are generally in gradational contact, but may, very rarely, be in sharp contact.

Ichnology:

Bioturbation is very common in this facies. Burrows generally extend down from the mud interbeds into the sand beds. The very top portions of the mud interbeds may be undisturbed, as are the lower portions of the sand interbeds. The most intense burrowing usually occurs at the interface between the sand and mud. Burrowing may be so intense that the sand and mud are thoroughly homogenized, with only faint or, possibly, no indications of lamination or bedding (Fig. 25c, d). Alternatively, some *interbedded sand and mud* may be totally unburrowed (Fig. 25e, f).

The trace fossils present within the *interbedded sand and mud*, in approximately decreasing order of abundance, include: *Planolites*, *Cylindrichnus*, *Gyrolithes*, *Skolithos*, *Palaeophycus*, *Arenicolites*, *Teichichnus*, and fugichnia (escape structures).

Planolites are generally found within the mud beds. They are sharp-walled and unlined. *Cylindrichnus* and *Gyrolithes* generally occur in monospecific assemblages (Fig. 26). Burrowing is intense in these horizons, but there is typically only one burrow form. The cross-sectional views of *Cylindrichnus* and *Gyrolithes* show a distinct fabric; all of the burrows are dipping in the same direction. The escape traces are found within the sands. They are visible due to laminae that bend downward in a V-shape.

Interpretation:

The *interbedded sand and mud* facies is interpreted to represent point bar lateral accretion deposits in an estuarine meandering river system. This facies is composed of the inclined heterolithic stratification (IHS) of Thomas *et al.* (1987). IHS basically consists of inclined, alternating coarser and finer units arranged as upward fining couplets (Thomas *et al.*, 1987). The rhythmic alternation of sand and mud is indicative of a tidally influenced environment (Thomas *et al.*, 1987; Allen, 1991). The alternations are due to regular periodic fluctuations in current velocity and water level associated with tidal cycles, with coarser material associated with periods of high velocity (Thomas *et al.*, 1987). The thinly intercalated sand and mud may be representative of the diurnal or semi-diurnal tidal cycle, but where the mud laminae are greater than 1 cm in thickness, they may represent several slack water periods or the fallout that occurs after storms (Thomas *et al.*, 1987). The sand beds were probably deposited during a single ebb or flood tidal-current flow. The more thickly interbedded sand and mud are probably representative of the neap-spring tidal cycle, or possible seasonal tidal fluctuations. Each sand-mud couplet represents rapid deposition, indicated by escape structures and coarser grain size, followed by lower energy conditions and mud sedimentation.

Inclined heterolithic stratification (IHS) has also been termed "epsilon cross-stratification" (ECS) (Allen, 1963). This terminology is slowly going out of use, however. The reasons for the discontinuation of the term "epsilon cross-stratification" are (Thomas *et al.*, 1987): 1) ECS is a non-descriptive term which has become imbued with strong genetic connotations; 2) the original definition (Allen, 1963) is too restrictive to include the many new types of IHS now known; and 3) it is inappropriate for IHS to be classified as a form of cross-stratification due to the fact that the mechanisms of formation (point-bar lateral accretion, for example) are different than those that form true cross-stratification (bedform migration and flow processes). This stratification is developed by lateral accretion of sediments on the inclined surface of point bars in meandering river channels (Allen, 1963; Howard *et al.*, 1975; Flach and Mossop, 1985; Collinson, 1986; Thomas *et al.*, 1987; Rahmani, 1988). The inclined layers are defined by alternations in grain size and there is generally an overall fining upward pattern (Collinson, 1986; Thomas *et al.*, 1987), whether in the couplets or the whole interbedded sand and mud unit. The interpretation of the IHS can be aided by study of the associated facies (Thomas *et al.*, 1987). The succession of large-scale cross-stratified channel sands to IHS to abandonment deposits to overbank or tidal flat deposits helps to identify the IHS deposits as lateral accretion point bar deposits (Ranger and Pemberton, 1992; Bechtel *et al.*, 1994).

There are two very important characteristics of estuaries that affect sedimentation patterns: the turbidity maximum and the salt wedge. The salt wedge is present in estuaries due to the density difference between saltwater and freshwater. The salt wedge is a body of salty water resting on the bottom of the estuary (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 (Bechtel *et* *al.*, 1994). The mixing of the saltwater and freshwater is important in an estuary because of 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 maximum mud deposition is affected by the location on the turbidity maximum. The turbidity maximum may be landward of the salt wedge or it may 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 the trapping of suspended sediment and, therefore, the formation of the turbidity maximum (Dyer, 1986; Allen, 1991). Density currents are due to the vertical circulation patterns caused when the landward flow of saltwater converges with the seaward flow of freshwater. Where these two converge, a suspended sediment trap is created and the turbidity maximum is formed (Allen, 1991). At periods of low river discharge, tidal current asymmetry plays a major part in the maintenance of the turbidity maximum (Dyer, 1986; Allen, 1991). During spring tides, current velocities are high, muddy sediment is eroded and resuspended, and the turbidity maximum expands up the estuary. During neap tides, current velocities are low and suspended material is deposited during the slacks, and the maximum decreases in volume (Dyer, 1986; Allen, 1991). This cyclicity results in the alternation of sand and mud found in tidal estuarine deposits, such as in Facies 9 in the McMurray Formation.

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, spring tides, and/or storm events (Bechtel *et al.*, 1994).

The inclined heterolithic stratification (interbedded sand and mud) of the McMurray Formation may be sand-dominated or mud-dominated (Fig. 27). The sand-dominated IHS generally grades up from large-scale cross-stratified sands. The sand beds were probably deposited during times of increased fluvial discharge or during high velocity tidal currents, with the muds being deposited during periods of slack water as well as when the turbidity maximum migrated through the area. The location of the sand-dominated point bar within the estuary (whether it is fluvial or marine dominated) can be determined by the extent of burrowing. The sand-dominated point bar is not formed within the turbidity maximum due to the relative lack of mud within the point bar. 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.

The mud-dominated IHS was deposited within the turbidity maximum, which is the zone of maximum mud accumulation. Again, the abundance or paucity of burrowing will place the point bar within or landward of the salt wedge, respectively. Irregularly interbedded sand beds within the mud-dominated IHS may have been deposited due to storm events or very high fluvial discharge events (eg. seasonal runoffs). The more rhythmic cycles were probably deposited during neap-spring tidal cycles.

Thomas *et al.* (1987) suggest that the recognition of the trace fossils is the single most significant criteria for distinguishing tidally influenced IHS from fluvial IHS. The estuarine nature of IHS in the McMurray Formation is reflected in the trace fossil assemblage. Brackish water environments produce a trace fossil assemblage with distinct characteristics (Pemberton *et al.*, 1982; Wightman *et al.*, 1987; Ranger and Pemberton, 1992; Pemberton and Wightman, 1992), all of which are observed in this subfacies: 1) the trace fossils are typically smaller than their fully marine counterparts (Fig. 28a), due to stressed conditions; 2) the trace fossils are typically restricted to morphologically simpler forms, *eg. Planolites* (Fig. 28b); 3) there is a low diversity of trace fossils, including local monospecific assemblages (Fig. 26); 4) the trace fossils may be present in high abundances (Fig. 28c); and 5) there is a combination of traces from both the *Skolithos* and *Cruziana* ichnofacies.

The mud beds in which *Planolites* and other traces are found must have been firm at the time of burrowing, otherwise the burrows would have collapsed. Consolidation of the substrate probably occurred due to emergence during low energy conditions. The traces were formed by opportunistic organisms that colonized the mud during submergence. The burrows were then filled with sand from overlying sediments deposited during flooding events.

The presence of traces produced by opportunistic colonizing organisms supports the idea of the cyclic nature of the IHS (Bechtel *et al.*, 1994). Trace fossils of opportunistic organisms (*Cylindrichnus* and *Gyrolithes*) represent the colonization of sand beds after high energy flow conditions wane and the substrate becomes stable. This produces monospecific assemblages (Fig. 26). The fabric in these assemblages is interpreted to be normal to the depositional dip of the point bar surface.

There are several criteria established to determine the presence of tidal influence on point bars (Thomas *et al.*, 1987). Within the McMurray Formation, some features that suggest a tidal influence are (Bechtel *et al.*, 1994): 1) lower point bar and channel deposits are large-scale cross-stratified sands; 2) presence of wavy parallel laminations, flaser bedding, and small-scale cross-stratification; 3) abundant bioturbation; 4) mud drapes in the underlying large-scale cross-stratified sands; 5) synaeresis cracks associated with fluctuating salinities.

The cyclic nature of tidally influenced deposits are their most characteristic feature (Nio and Yang, 1991). Within the McMurray, the cyclic nature of the IHS is indicated by (Bechtel *et al.*, 1994): 1) regular presence of sharp-based sands overlain by muds; 2) angular rip-up clasts and intraclasts of mud interbeds, suggesting initial consolidation and possible desiccation of IHS during ebb-tide conditions; and 3) syndepositional micro-faulting associated with rapid deposition on a sloping surface.

Figure 12. Subfacies 1a. **A)** Root traces (arrows) filled with carbonaceous debris; from 16-33-94-7 W4 (184.1 m) (upper McMurray). **B)** "Mudballs" (arrows) showing outer rims and concentric laminations; from 10-27-94-7 W4 (249.8 m) (lower McMurray). **C)** Disseminated pyrite (arrows) and siderite nodule (S); from 10-27-94-7 W4 (252.6 m) (lower McMurray).

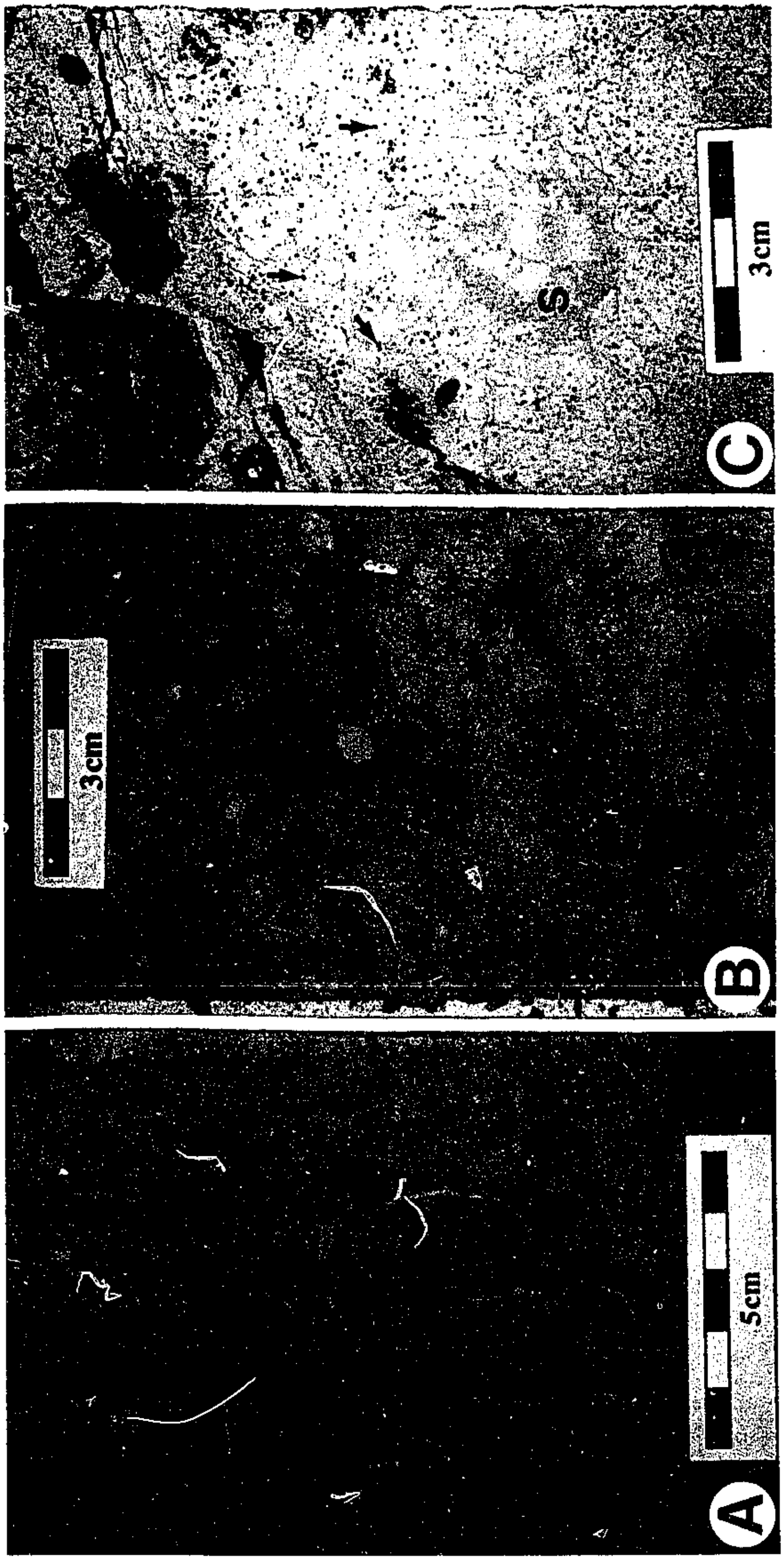
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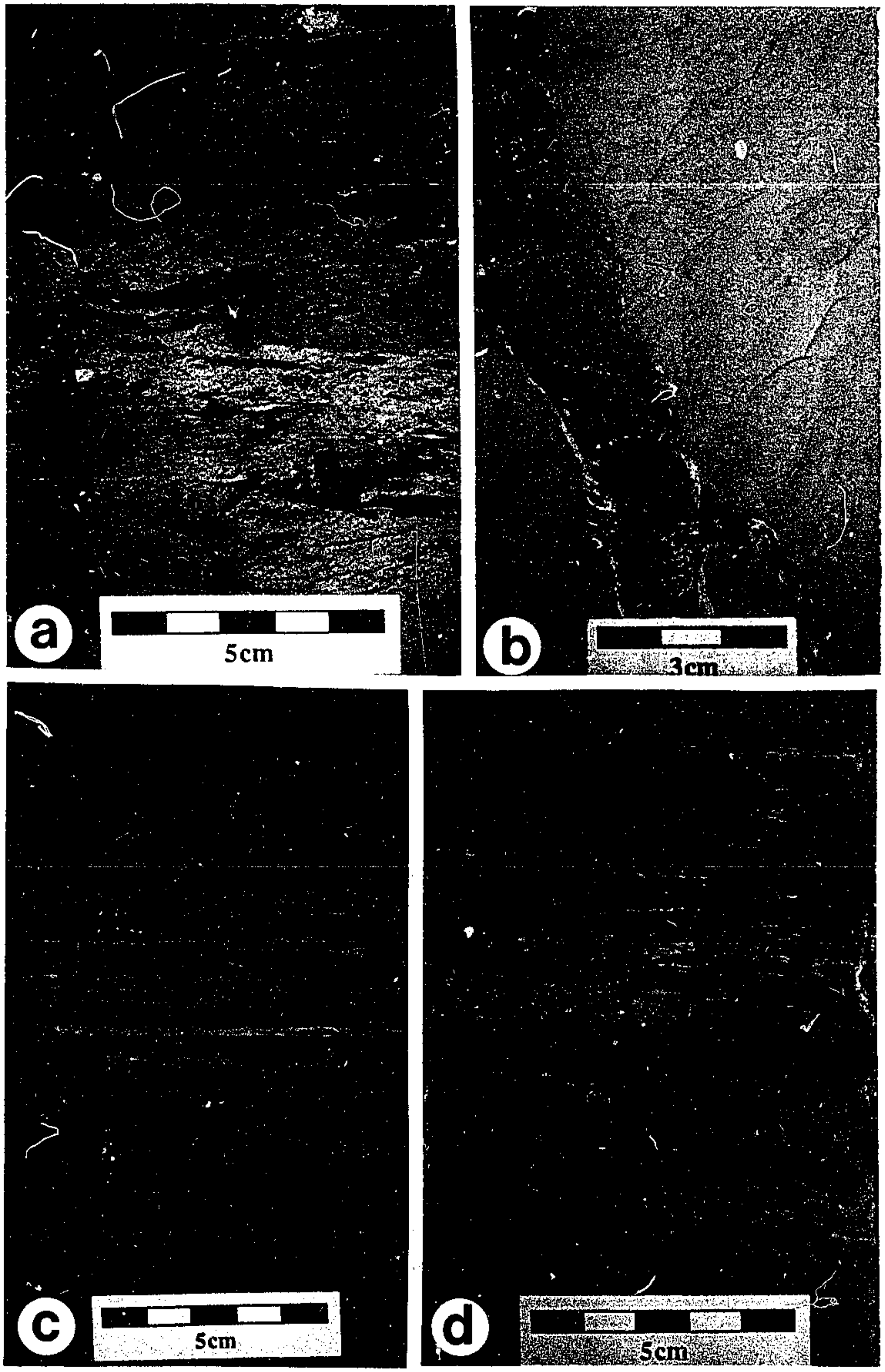
Figure 13. **a)** Subfacies 1b - carbonaceous debris and coaly fragments, in lower McMurray; from 3-29-94-7 W4 (240.0 m). **b)** Subfacies 1c - sand-filled fracture in lower McMurray; from 16-26-94-7 W4 (297.95 m). **c)** Subfacies 1d - laminations of white silt and sand (dark brown) within medium gray mudstone in middle McMurray; from 1-34-94-7 W4 (250.0 m). **d)** Subfacies 1d - burrows cutting through white silt laminae in medium gray mudstone in middle McMurray; from 16-33-94-7 W4 (187.3 m). Sk - *Skolithos*, Ar - *Arenicolites*.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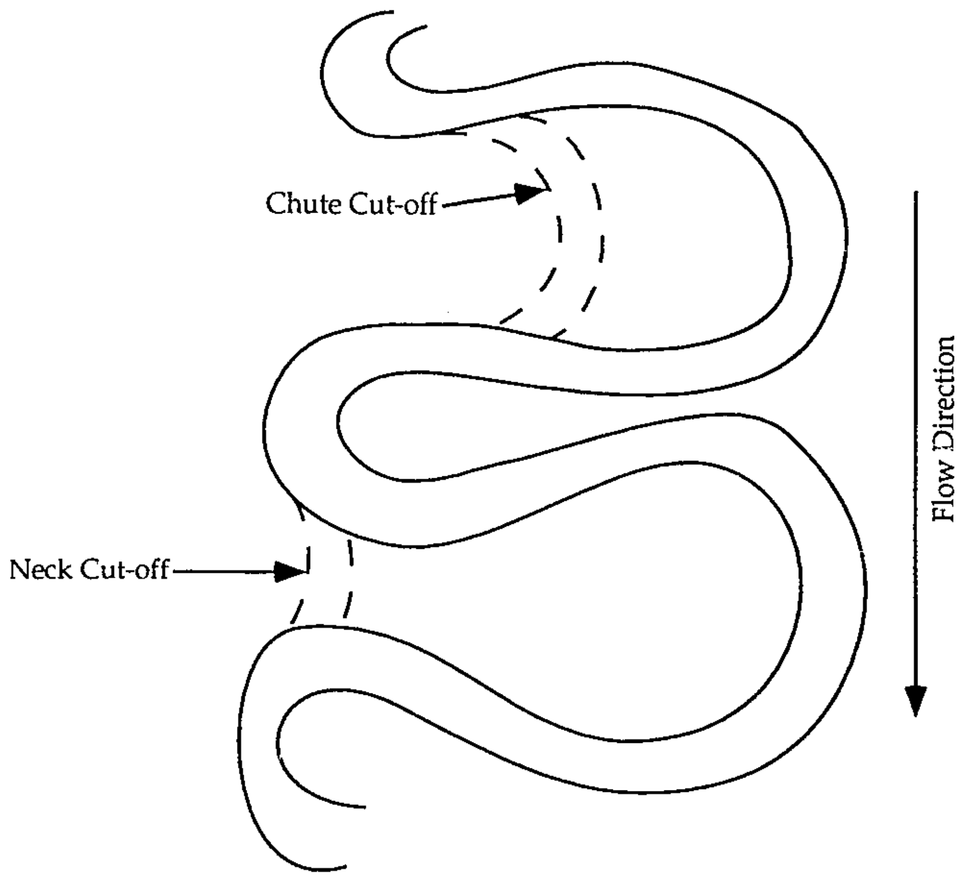


Figure 14. Meander loops abandoned by chute cut-off or neck cut-off. Dashed lines indicate new channels (modified from Harms *et al.*, 1982).

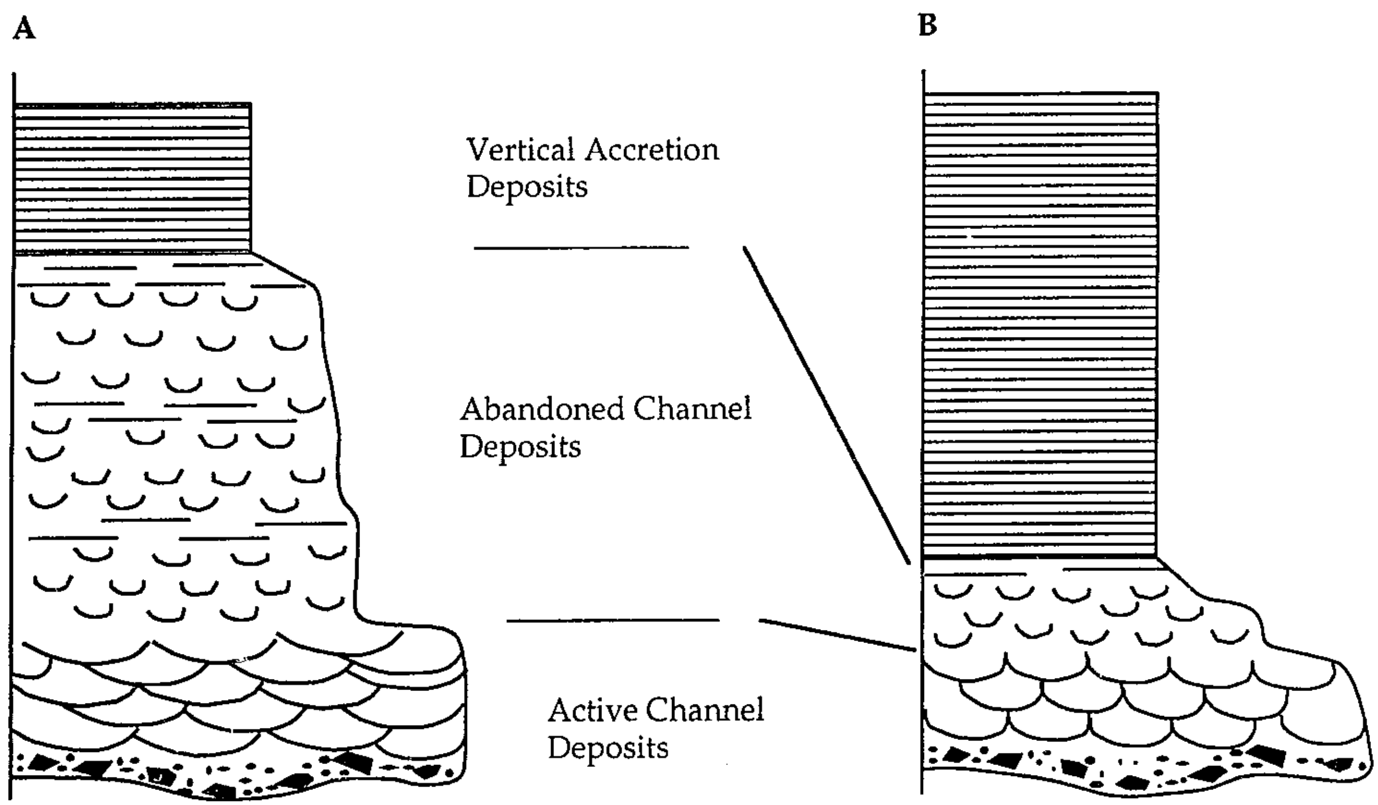
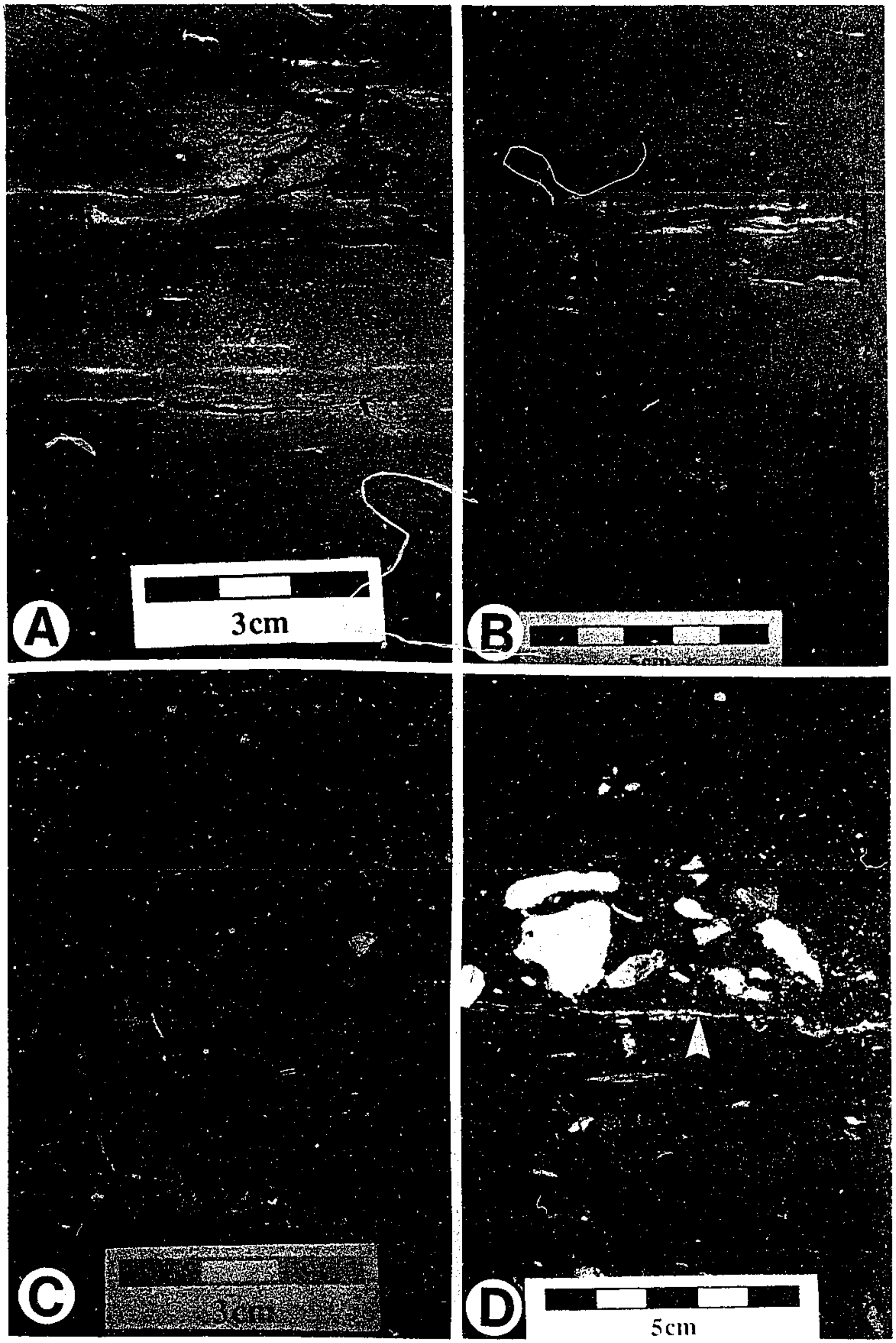


Figure 15. A) Idealized vertical succession in a chute-cutoff. B) Idealized vertical succession in a neck cut-off (modified from Harms *et al.*, 1982).

Figure 16. A) Discolouration of Subfacies 1e (gray structureless mudstone) caused by siderite cement; from 9-10-94-7 W4 (199.6 m) (middle McMurray). **B)** Subfacies 1f - dark gray mudstone with interlaminations of white silt and sand (dark brown due to bitumen stain) in upper McMurray; from 16-33-94-7 W4 (182.4 m). **C)** Coal (Facies 2) showing disseminated sand grains scattered throughout; from 16-33-94-7 W4 (245.7 m) (lower McMurray). **D)** Flat, planar upper contact (arrow) of coal (lower McMurray) with overlying sand (middle McMurray); from 10-18-94-7 W4 (201.8 m).


A
3cm
B
C
3cm
D
5cm

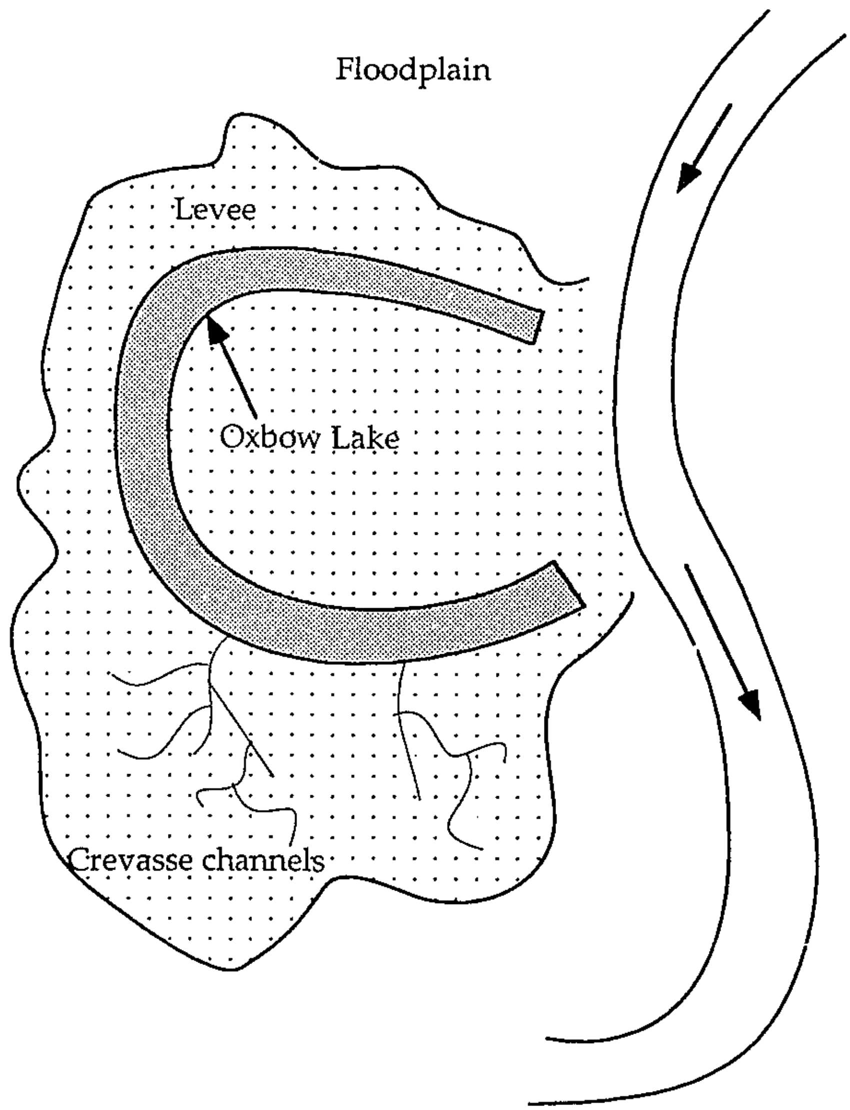


Figure 17. Oxbow lake formed by neck cut-off of a meander bend, with preserved levee, crevasse channel, and crevasse splay deposits (modified from Collinson, 1986).

Figure 18. A) Fine-grained, structureless sand (Facies 3); from 3-29-94-7 W4 (198.9 m) (middle McMurray). **B)** Structureless sand of variable grain size; from 8-27-94-7 W4 (225.0 m) (middle McMurray). **C)** Mud intraclasts displaying random orientation within structureless sand; from 4-14-93-7 W4 (207.7 m) (middle McMurray). **D)** Facies 4 (flat to low angle planar stratified sand) - box shot (B-bottom of core, T-top of core) showing preferred orientation of intraclasts; from 5-23-94-7 W4 (243.8 - 248.7 m) (middle McMurray). **E)** Thinly interlaminated carbonaceous debris, sand, and mud within facies 4; from 7-28-94-7 W4 (233.3 m) (middle McMurray)..

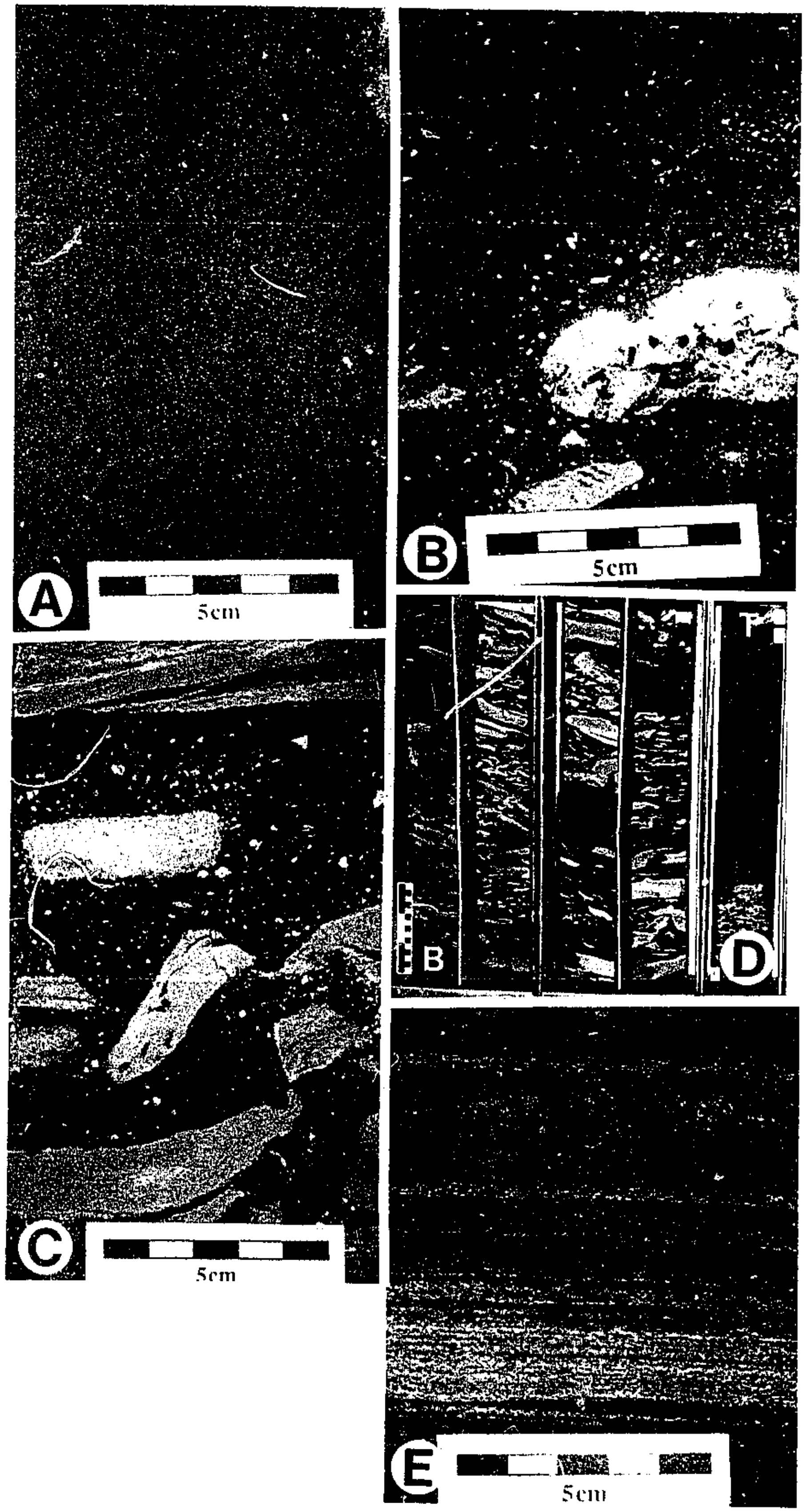

A
5cm
B
5cm
C
5cm
B
T
D
E
5cm

Figure 19. **a)** *Cylindrichnus* (Cy) within flat to low angle planar stratified sand (Facies 4). Note burrow on left side showing a central sand shaft and mud walls, with tapered bottom; from 4-14-93-7 W4 (191.9 m) (middle McMurray). Sk-*Skolithos*. **b)** Thoroughly bioturbated mud laminae within Facies 4, displaying oblique cross-section through *Cylindrichnus* (Cy); from 4-14-93-7 W4 (199.8 m) (middle McMurray). Sk-*Skolithos*, Pa-*Palaeophycus*.

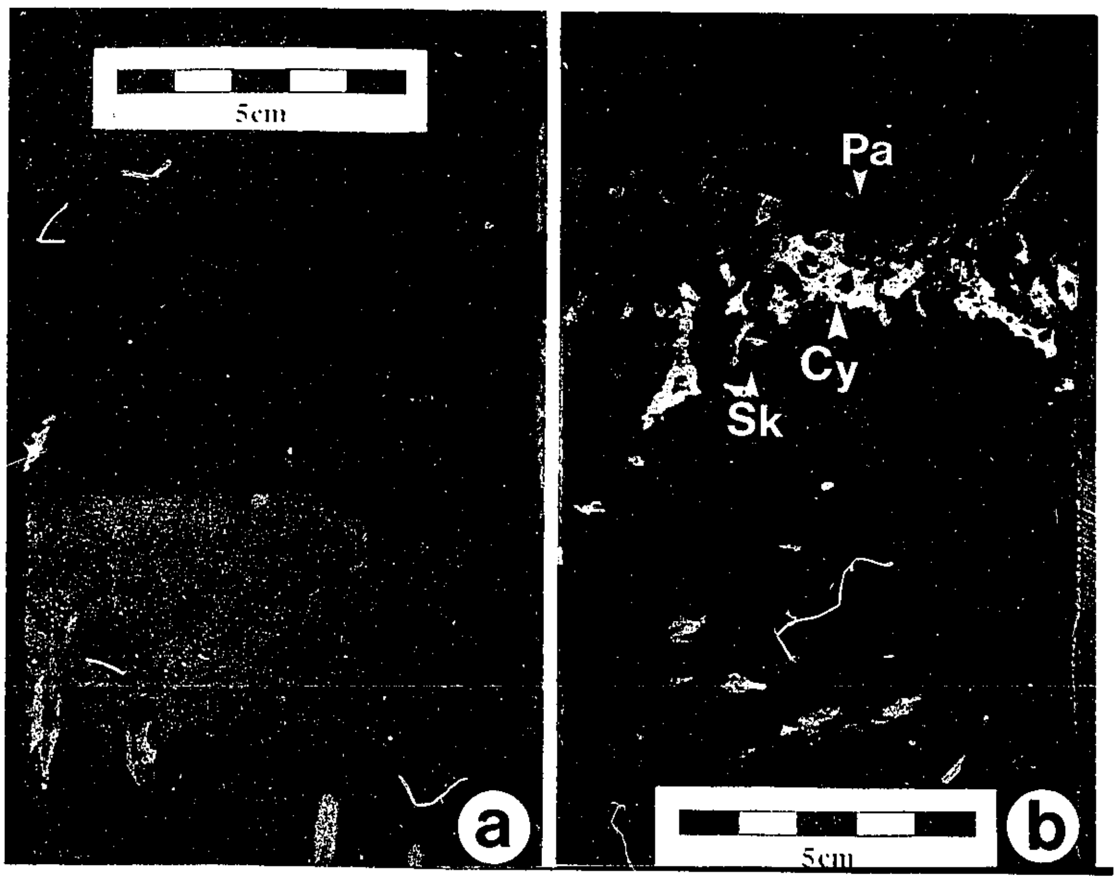

5cm
a
Pa
Cy
Sk
5cm
b

Figure 20. Facies 5. **A)** Asymmetrical small-scale cross-stratification displaying well defined foresets and toesets; from 8-27-94-7 W4 (215.9 m) (middle McMurray). **B)** Asymmetrical small-scale cross-stratification; from 15-32-94-7 W4 (181.6 m) (middle McMurray). **C)** Small-scale cross-stratified sand with some possible escape strucutres, or fugichnia (f); from 15-32-94-7 W4 (170.9 m) (middle McMurray). **D)** Small-scale cross-stratification; from 11-25-94-7 W4 (219.2 m) (middle McMurray). **E)** Unstained small-scale cross-strata, due to higher argillaceous content than surrounding sand; from 3-29-94-7 W4 (245.1 m) (lower McMurray). **F)** Unstained small-scale cross-strata; from 3-29-94-7 W4 (249.5 m) (lower McMurray).

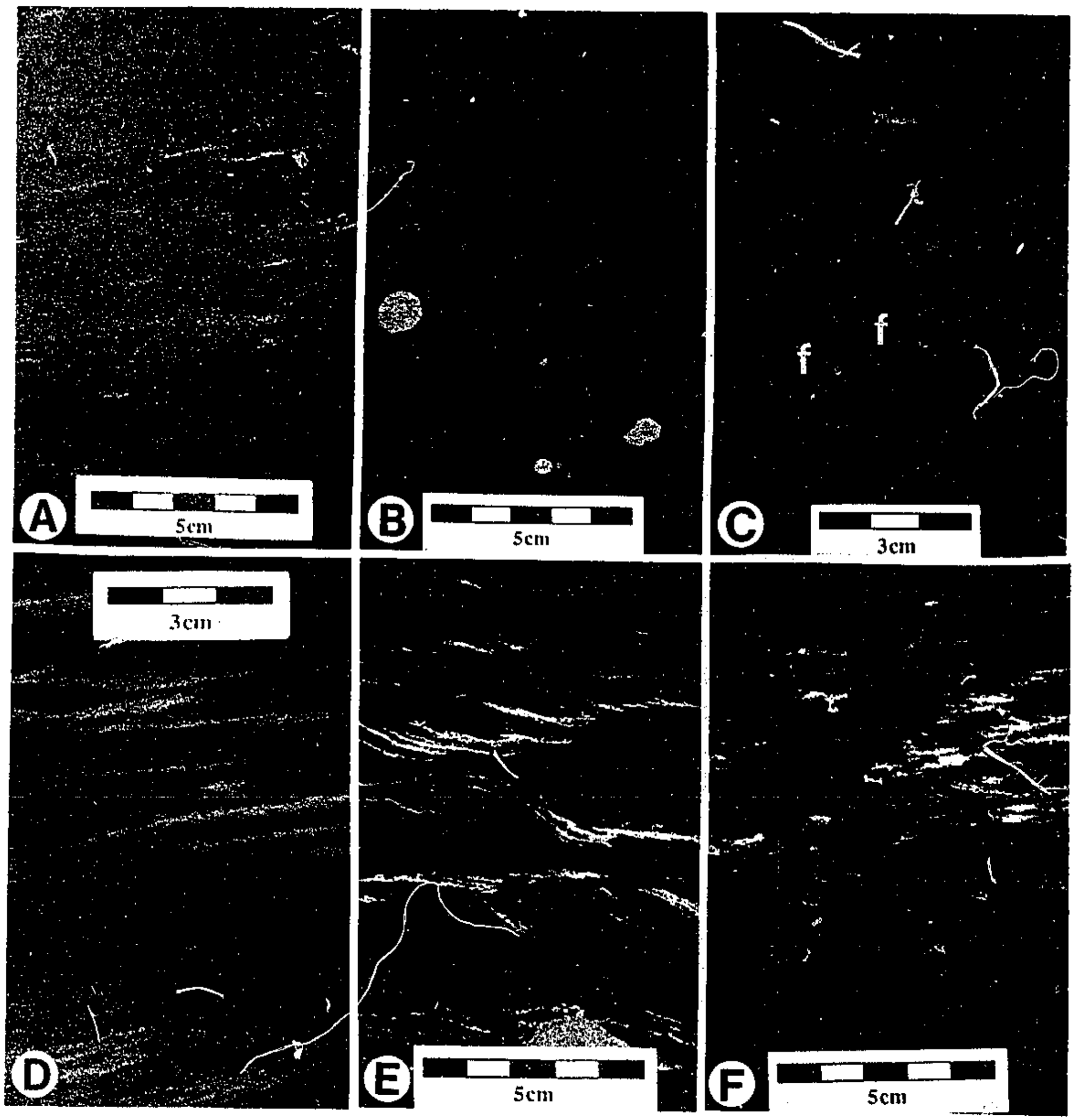

A
5cm
B
5cm
C
f
f
3cm
D
3cm
E
5cm
F
5cm

Figure 21. Facies 5. **a)** Thin mud drape within small-scale cross-stratified sand showing rare bioturbation (Pl-*Planolites*); from 7-28-94-7 W4 (208.6 m) (middle McMurray). **b)** Escape structure (f) within small-scale cross-stratified sand; *Planolites* (Pl) and *Cylindrichnus*(Cy) within bioturbated mud laminae; from 7-28-94-7 W4 (206.7 m) (middle McMurray). **c)** Unstained trough-shaped cross-strata sets, indicating a vertical section transverse to flow; flow was perpendicular to the plane of the photo; from 10-18-94-7 W4 (208.5 m) (lower McMurray). **d)** Trough-shaped cross-strata sets, indicating a vertical section transverse to flow; flow was perpendicular to the plane of the photo; from 15-32-94-7 W4 (173.8 m) (middle McMurray).

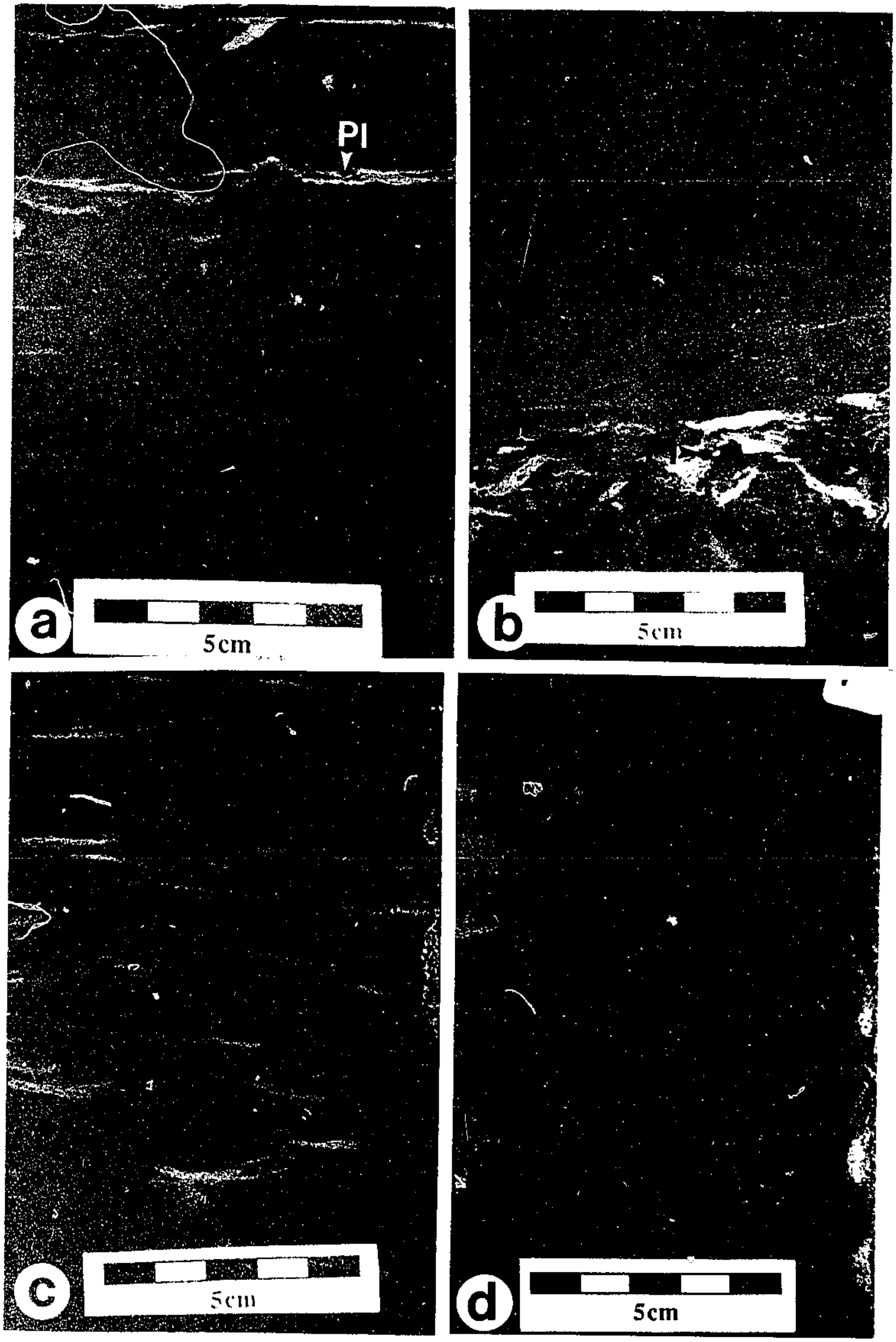

Pl
a
5cm
b
5cm
c
5cm
d
5cm

Figure 22. Facies 6. All examples are from middle McMurray except for F), which is from lower McMurray. **A)** Large-scale cross-stratified sand with cross-strata highlighted due to differential bitumen saturation; from 5-23-94-7 W4 (206.4 m). **B)** Large-scale cross-stratified sand with cross-strata highlighted due to grain size alternation; from 10-18-94-7 W4 (192.5 m). **C)** Large-scale cross-stratified sand displaying both grain size alternation and differential bitumen saturation. Cross-strata fine upward (centre of photo); from 10-34-94-7 W4 (202.4 m). **D)** Large-scale cross-stratified sand with adjacent cross-sets displaying opposing dips. Truncation surface is clearly visible across the centre of the photo; from 5-23-94-7 W4 (212.5 m). **E)** Large-scale cross-stratified sand with adjacent cross-sets displaying opposing dips. Truncation surface is clearly visible across the centre of the photo; from 9-10-94-7 W4 (220.3 m). **F)** Mud intraclasts showing preferred orientation within large-scale cross-stratified sand; from 3-29-94-7 W4 (242.7 m).

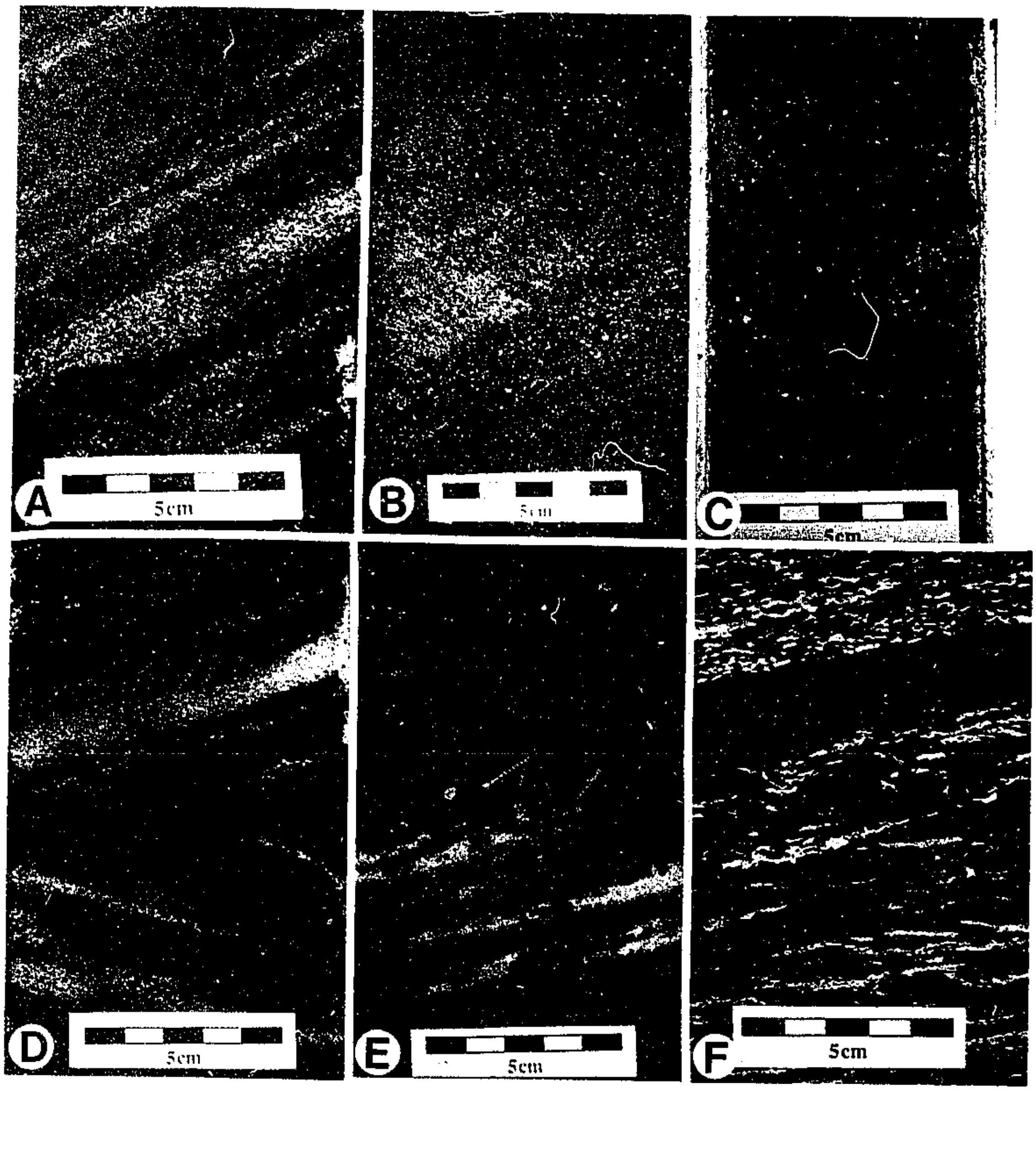

A
5cm
B
C
5cm
D
5cm
E
5cm
F
5cm

Figure 23. A) Heavily bioturbated sand (Facies 7); from 10-34-94-7 W4 (186.3 m) (middle McMurray). **B)** Heavily bioturbated sand (Facies 7) ? Mottled appearance may possibly be due to bioturbation; from 8-27-94-7 W4 (218.8 m) (middle McMurray). **C)** Carbonaceous sand (Facies 8) showing large coaly fragments and assorted carbonaceous debris; from 16-26-94-7 W4 (293.7 m) (lower McMurray). **D)** Carbonaceous sand (Facies 8) with large wood fragment; from 16-33-94-7 W4 (230.6 m) (middle McMurray).

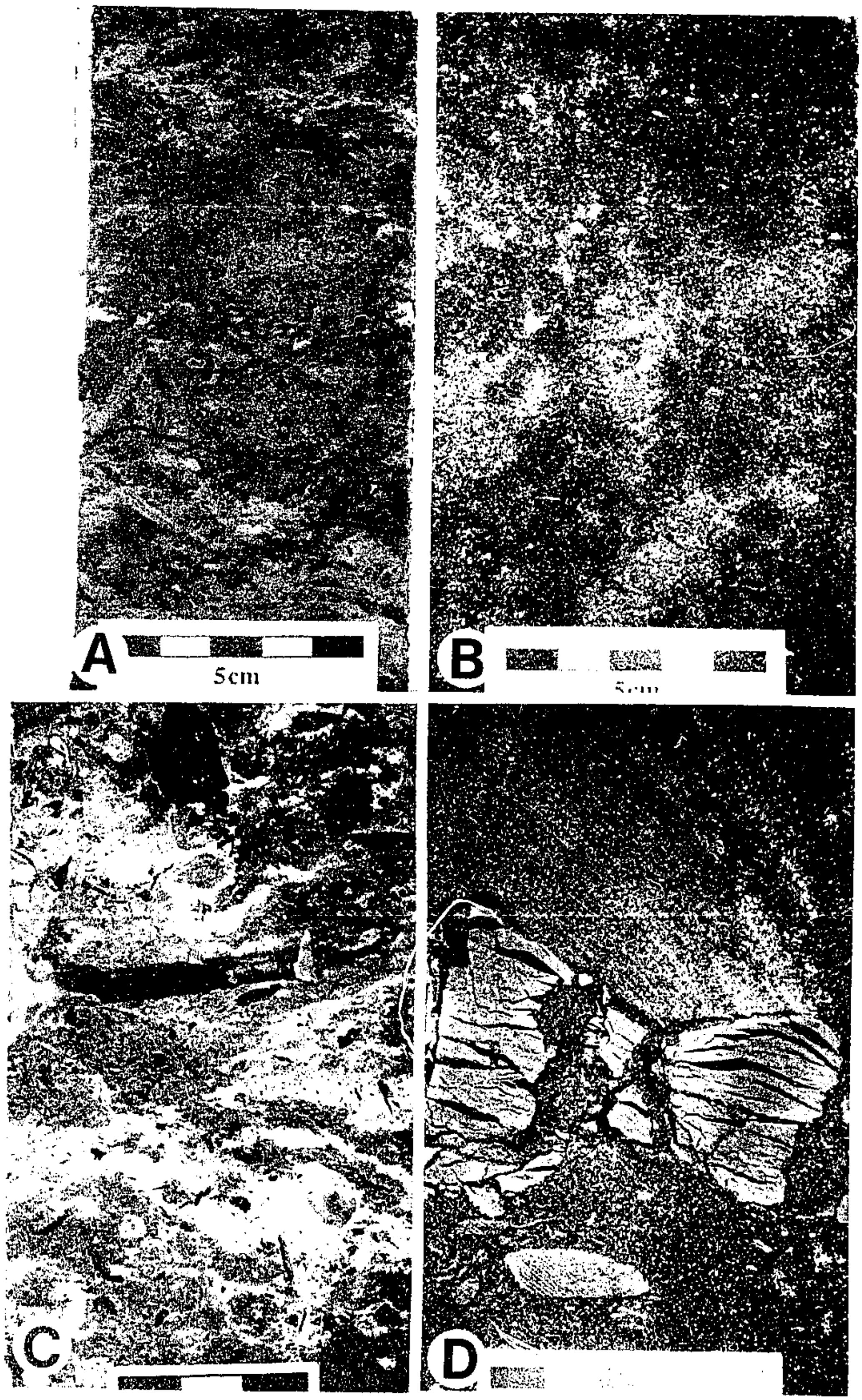

A
5cm
B
C
D

Figure 24. Facies 9. T - top of core; B - bottom of core. Note that in a) the top is to the left and in b) the top is to the right. **a)** Interbedded sand and mud, illustrating inclination of the beds and dip reversals; arrow indicates McMurray/Wabiskaw contact; from 16-26-94-7 W4 (203.9 - 213.45 m) (possibly upper McMurray). **b)** Thickly interbedded sand and mud; from 2-21-93-7 W4 (220.1 - 226.2 m).

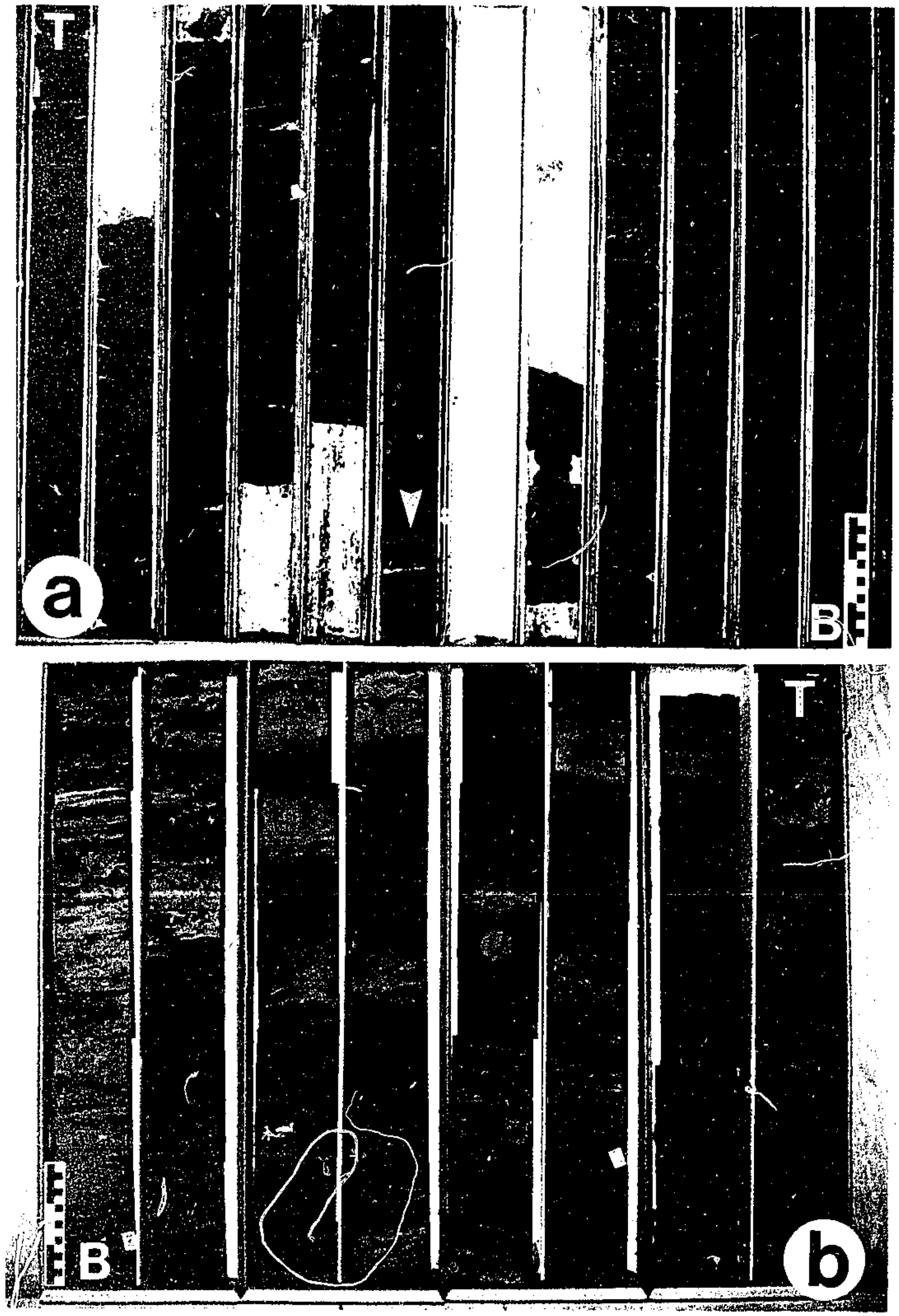

T
a
B
B
T
b

Figure 25. Facies 9. **a)** Thinly interbedded sand and mud; from 7-28-94-7 W4 (222.0 m). Cy-*Cylindrichnus*, Pa-*Palaeophycus*, Pl-*Planolites*. **b)** Thinly interbedded sand and mud with small-scale cross-stratification present in the sand bed near the top of the photo; from 11-18-93-7 W4 (179.5 m). **c)** Abundant bioturbation in interbedded sand and mud, effectively destroying bedding; from 15-32-94-7 W4 (181.3 m). Cy-*Cylindrichnus*, Pl-*Planolites*, Sk-*Skolithos*. **d)** Abundant bioturbation in mud-dominated interbedded sand and mud; from 3-29-94-7 W4 (221.4 m). Te-*Teichichnus*, Pl-*Planolites*. **e)** Unburrowed interbedded sand and mud; from 1-34-94-7 W4 (253.7 m). **f)** Unburrowed mud-dominated interbedded sand and mud; from 3-29-94-7 W4 (227.6 m).

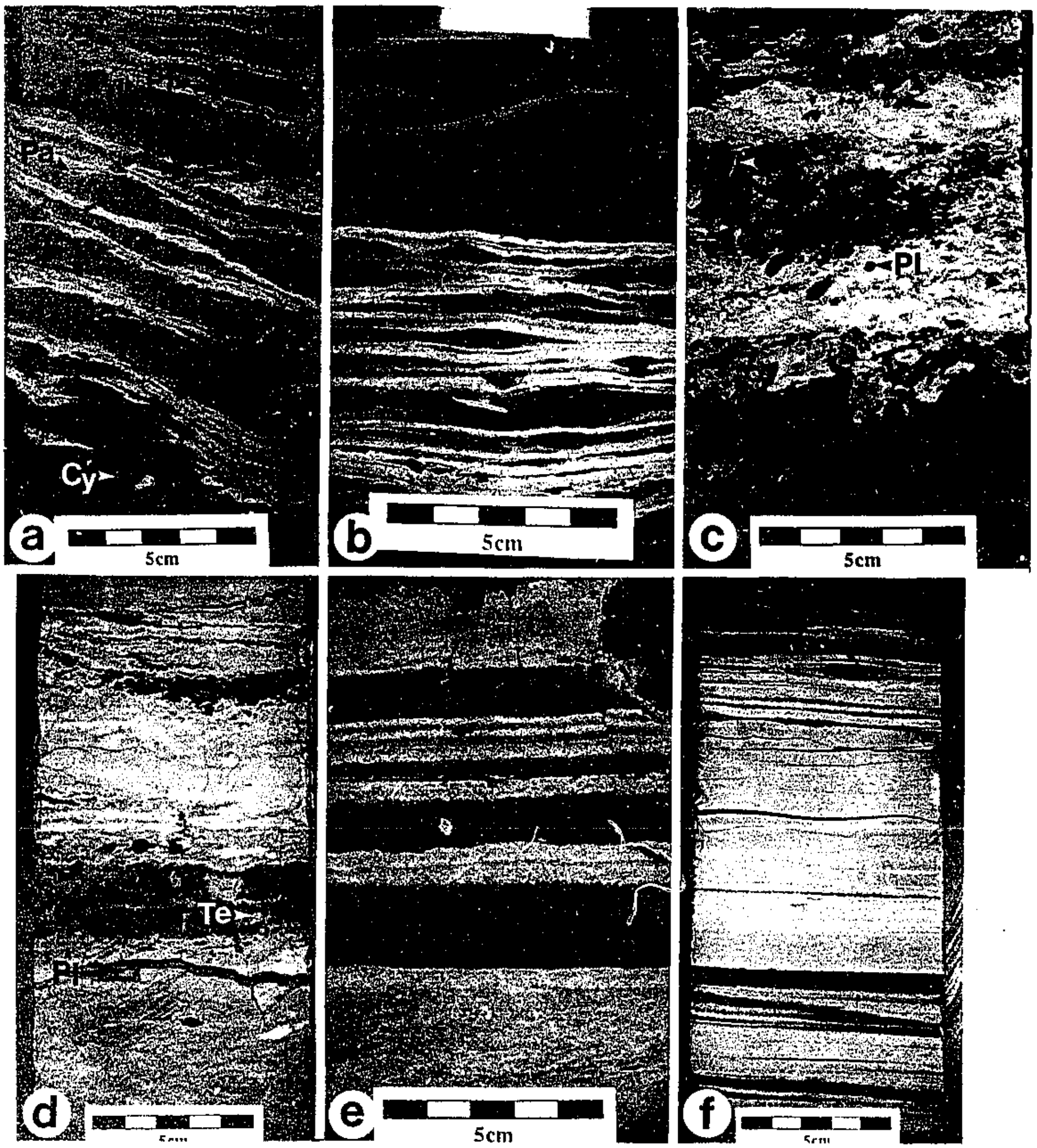

Pa
Cy
a
5cm
b
5cm
PI
c
5cm
Te
PI
d
e
5cm
f

Figure 26. Monospecific assemblages within Facies 9. **a)** *Cylindrichnus*; from 3-30-94-7 W4 (156.9 m). **b)** *Gyrolithes*; from 3-30-94-7 W4 (139.7 m).

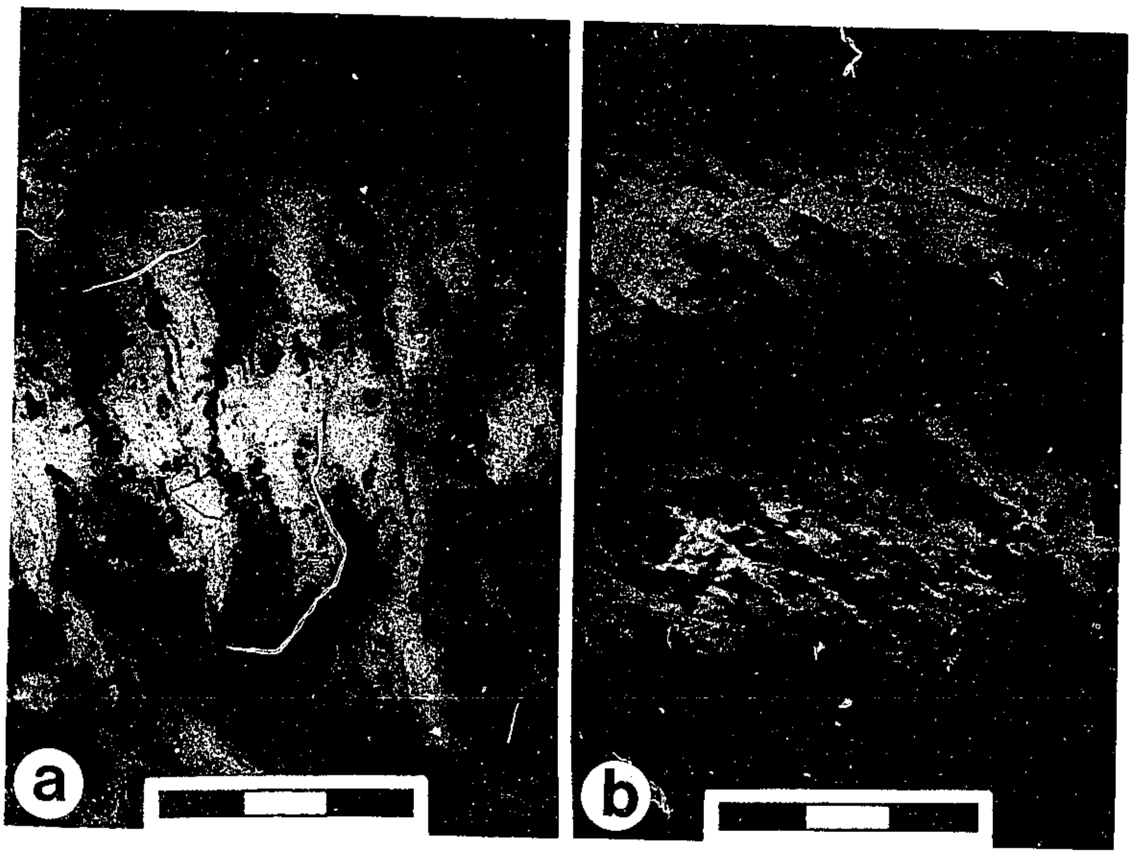


Figure 27. Facies 9. T - top of core; B - bottom of core. Note that in a) the top is to the right and in b) the top is to the left. **a)** Sand-dominated inclined heterolithic stratification (IHS); from 15-32-94-7 W4 (184.4 - 188.1 m). **b)** Mud-dominated IHS; from 3-30-94-7 W4 (142.3 - 148.9 m).

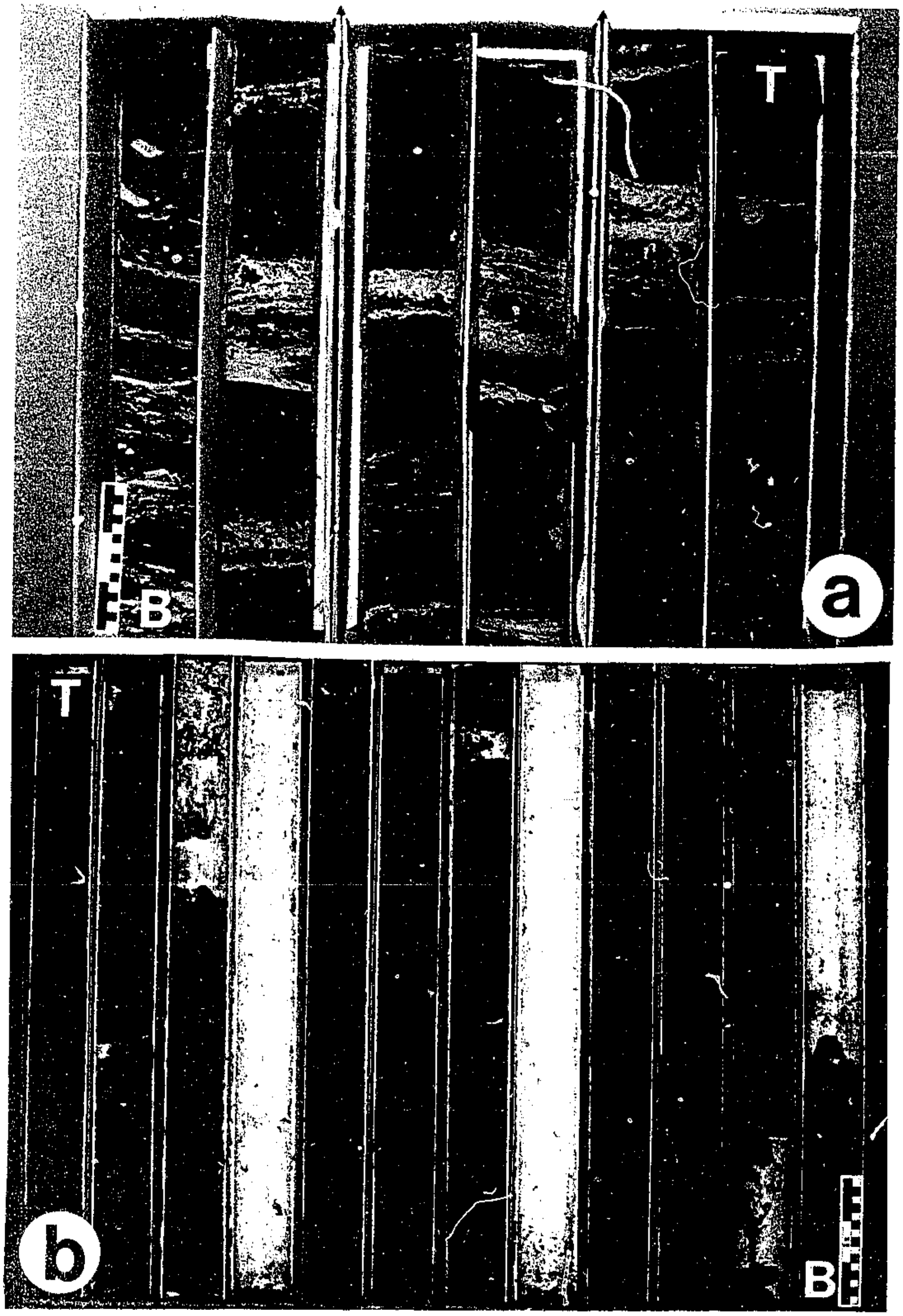
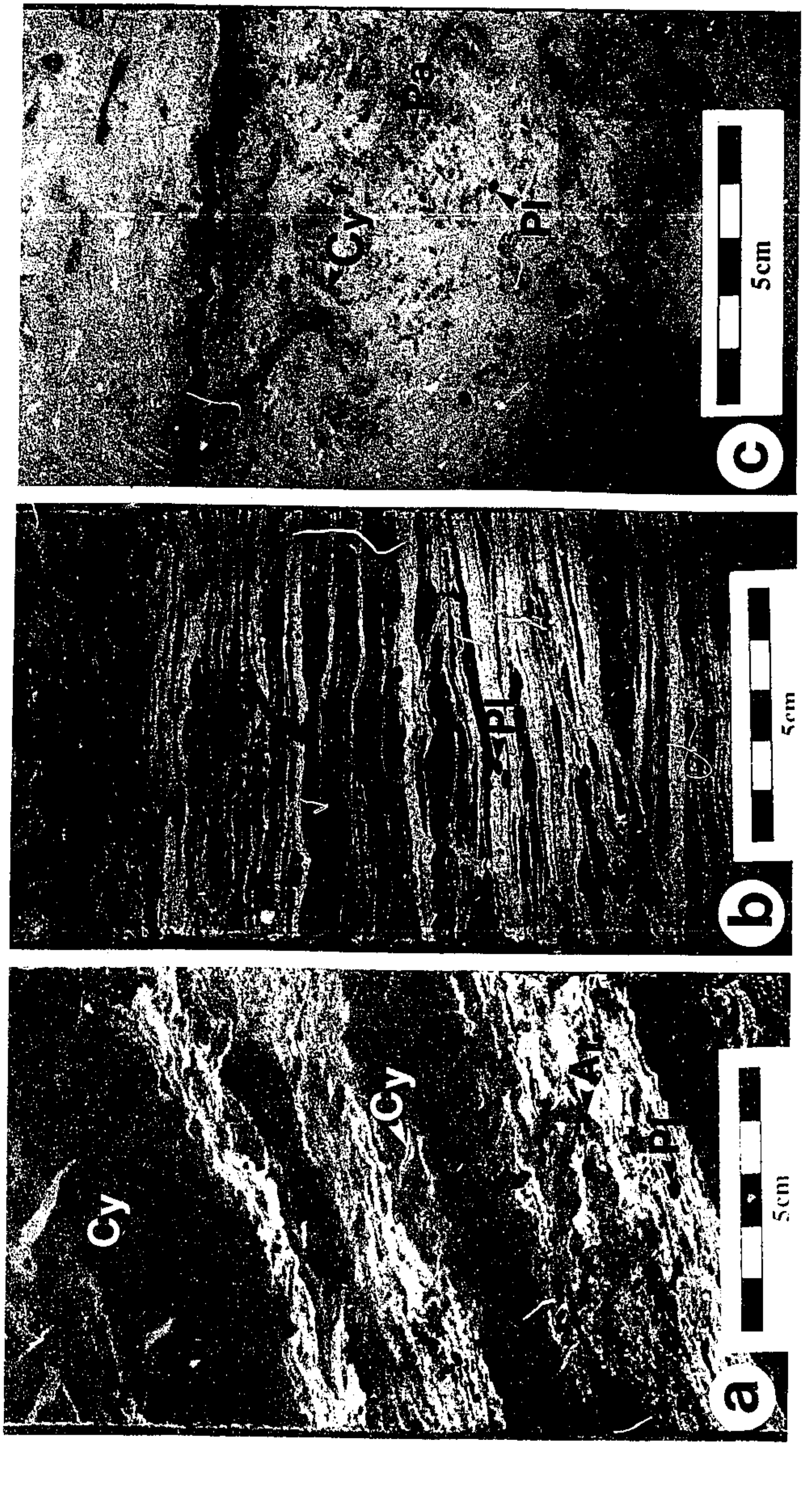

T
B
a
T
b
B

Figure 28. Facies 9. **a)** Inclined heterolithic stratification (IHS) showing the small size of the burrows; from 7-28-94-7 W4 (194.0 m). Cy-*Cylindrichnus*, Ar-*Arenicolites*, Sk-*Skolithos*. **b)** IHS showing morphologically simple forms; from 7-28-94-7 W4 (213.5 m). Sk-*Skolithos*, Pl-*Planolites*. **c)** IHS showing the high abundance of burrowing; from 15-32-94-7 W4 (159.6 m). Cy-*Cylindrichnus*, Pl-*Planolites*, Te-*Teichichnus*, Pa-*Palaeophycus*.


a
Cy
Cy
Ar
Pl
5cm
b
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c
Cy
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5cm

CHAPTER 3 - DEPOSITIONAL HISTORY AND ENVIRONMENTAL MODEL

LOWER MCMURRAY

The lowest informal stratigraphic division of the McMurray Formation, the "lower member" or "lower McMurray", is found in 12 of the 25 cores logged. The maximum thickness of 40.8 m is found in the east-central portion of the study area (well 10-12-94-7 W4) (Fig. 29). Thick successions of lower McMurray also occur in the northern and north-western portion of the study area. An isopach map of the lower McMurray (Fig. 29) and a cross-section across the northern portion of the study area (Fig. 30) show that deposition was controlled by the topography on the pre-Cretaceous unconformity (Fig. 8). The thickest successions of the lower member occur within NNW and NE-trending depressions on the unconformity surface. The areas lacking any lower member successions (across the central and southern portions of the study area) correspond to highs on the unconformity surface (Fig. 8).

Facies Association

A typical succession of the lower member of the McMurray Formation is found in well 10-27-94-7 W4 (Fig. 31). The entire lower member has a thickness of 36.6 m in this well. The succession is 22 m thick and consists of a single facies association. Sharp-based, large-scale cross-stratified, coarse to medium-grained sand at the base grades up into interbedded sand and mud. The interbedded sand and mud is overlain by silty mudstone, which grades up into massive white to gray mudstone. This mudstone is capped by dark gray carbonaceous mudstone, which marks the top of the lower McMurray.

The complete facies association is not observed in every example of the lower member in the study area. In general, however, the lower member displays a fining upward succession. In most cases, the lower member is capped by carbonaceous mudstone or coal. Large-scale cross-stratified sand is most commonly present at the base, but the sands may also be small-scale cross-stratified, flat to planar laminated, or structureless. Mudstones may, more rarely, be present at the base of the lower member. Very rarely, sand is totally absent from the lower member succession and mudstones are the dominant lithology.

The basal sands have a sharp or scoured contact with the underlying Devonian strata. Intraclasts of underlying calcareous mud may be present in the sand just above the contact. The sands are generally pebbly or coarse grained near the basal contact, with grain size decreasing upward. Grain size in the lower McMurray sands ranges from pebbles to fine sand. Wood fragments and coaly debris are common in the basal sands. The basal sands may rarely grade up into carbonaceous sand, where woody fragments, coaly laminae and fragments, and other carbonaceous debris are highly abundant. This sand also shows signs of soil formation, with rooting and concentrically laminated "mudballs" (concretions). The carbonaceous sand is overlain by coal.

Laminae and beds of mudstone are commonly intercalated within the basal sands, indicating periodically waning current strengths. Mud intraclasts are also common. The number and thickness of the intercalated mud beds tend to increase upward.

Interbedded sand and mud commonly overlies the basal sands with a sharp lower contact. The units of interbedded sand and mud are generally mud dominated, but may be sand dominated at the base, grading into mud dominated at the top. In the type well of the lower member (10-27-94-7 W4) (Fig. 31), the muddy interbeds are commonly composed of coal laminae interlaminated with sand. Microfaulting is common in the muddy interbeds. The bedding may also be distorted or chaotic in appearance and, rarely, may be broken up and brecciated, appearing slumped.

Generally, if interbedded sand and mud is present within the lower McMurray, it is either sharply or gradationally overlain by silty mudstone or, more rarely, coal. The silty mudstone may be at the top of the lower McMurray, or it may grade up into *massive white to gray mudstone* (1a), which then grades up into *dark gray to black carbonaceous mudstone* (1b). The massive and carbonaceous mudstones tend to show signs of soil formation, such as rooting, slickensides, and concentrically laminated "mudballs" (concretions). The carbonaceous mudstone, or coal, generally indicates the top of the lower McMurray.

Bioturbation, apart from rooting, is rare to absent in the lower McMurray. Within the sands of the lower member, small *Planolites* and *Cylindrichnus* are rarely observed within the intercalated mud laminae and beds. Burrows are also rarely observed within the muddy interbeds of the interbedded sand and mud. The burrows are mainly *Planolites* with rare *Cylindrichnus*. The silty mudstone also rarely shows burrowing. The paucity of burrowing in the lower member of the McMurray Formation indicates an environment of deposition that was inhospitable to burrowing organisms, such as one with high current energies and/or low water salinities.

Interpretation

The facies association of the lower member of the McMurray Formation was deposited in a high sinuosity, fluvial complex. The three main groups of deposits within this environmental complex are: channel deposits, bank deposits (which include levee and overbank deposits), and flood basin (or backswamp) deposits (Reineck and Singh, 1975). The fining upward succession, from scour-based sands to mud, reflecting a decrease in current velocity, is interpreted to be deposits formed due to lateral migration of a meandering channel. The channel system was confined to the deepest valleys on the sub-Cretaceous unconformity surface, and with aggradation, the fluvial deposits filled these valleys.

Meandering rivers form in areas with relatively low slopes, a regular discharge pattern, a high suspended load/bed load ratio, and cohesive banks that are resistant to erosion (Collinson, 1986; Leckie and Rosenthal, 1987).

Meandering in rivers is a consequence of flow instabilities caused by the asymmetrical distribution of flow velocity and turbulence within a channel bend (Galloway and Hobday, 1983; Leckie and Rosenthal, 1987). Maximum flow velocities are found along the outer, concave bank of a meander bend, within the thalweg or deepest part of the channel (Reineck and Singh, 1975; Galloway and Hobday, 1983; Collinson, 1986; Leckie and Rosenthal, 1987). There is a secondary, sideways flow component superimposed on the downstream flow; toward the outer bank at the surface and toward the inner (convex) bank near the stream bottom (Reineck and Singh, 1975) (Fig. 32). This is due to the deflection of the water by centrifugal force to the outer bank of the meander. The deflection force is greater at the surface than at the bottom of the channel, establishing a gradient. Water is forced down and then across the channel bottom toward the inner bank (Leckie and Rosenthal, 1987). Erosion is concentrated against the outer, concave bank, where shear stress is greatest. Blocks of the bank fall into the channel and are transported downstream by the current as clasts, where they are deposited on the channel floor. Intraclasts present within the basal sands are these transported blocks of the channel bank. Finer sediment is transported downstream and deposited on the less turbulent, gently sloping inner bank, or point bar, of the next channel bend. The erosion and subsequent deposition by lateral accretion cause the lateral migration of the channel, producing a fining upward succession (Reineck and Singh, 1975; Galloway and Hobday, 1983; Leckie and Rosenthal, 1987).

The basal zone of the succession is composed of gravel, pebbles, coarse sand with mud intraclasts, and wood fragments. It represents the lag deposits left behind in the deepest parts of the channel as the fine sand, silt, and clay are carried downstream by the current (Visher, 1965; Reineck and Singh, 1975; Leckie and Rosenthal, 1987). These coarse deposits are generally thin and discontinuous, having been deposited in the deepest scours on the channel floor. They are covered by finer grained sediments transported in bedforms such as dunes. The dunes migrate downstream and cover the channel floor and lower point bar, producing large-scale cross-stratification (trough cross-bedding) (Cant, 1982; Galloway and Hobday, 1983; Collinson, 1986). Further up on the point bar, planar-stratified and small-scale cross-stratified sands may be present (Visher, 1965; Cant, 1982; Collinson, 1986). Interbedded sand and mud, and silty mudstone may overlie the basal sands. These deposits represent further lateral accretion of the point bar, and possibly channel abandonment deposits due to neck or chute cut-offs. The mud and silt were deposited due to a decrease in current strength.

Bank deposits, such as levee and other overbank deposits, are formed when floodwaters overflow the channel banks. As the water tops the bank, flow velocity rapidly decreases, causing the deposition of the suspended sediment (Galloway and Hobday, 1983; Collinson, 1986). The coarser material (fine sand and silt) is deposited close to the channel, while the finer silt and mud are deposited farther from the channel. The result of this deposition is the formation of a stable ridge of sediment, or a natural levee, along the margin of the the river channel. The levees are highest at or near the edge of the channel, and they slope away from the river bank into the flood basin (Reineck and Singh, 1975; Galloway and Hobday, 1983). The sedimentary structures of the levee deposits indicate rapid deposition, multiple waning flow cycles, shallow flow depths, and subaerial exposure. The main sedimentary structures present are ripple laminations, planar laminations, laminated mud layers, and rooted zones. Mudcracks may also be present, indicating subaerial exposure and subsequent drying of the levee mud (Galloway and Hobday, 1983). Soil forming processes, as evidenced by slickensides, rooting, and concentrically laminated "mudballs", may destroy original sedimentary structures, leaving the levee muds and sands appearing massive. The *carbonaceous sand* (8) found in the lower McMurray may represent a levee deposit. The rooting, carbonaceous debris, and concentrically laminated "mudballs" indicate soil forming processes that may have destroyed the ripple and planar laminations within the fine sand.

Flood basin deposits are very fine grained, composed of silt and mud that settle out of suspension from floodwaters. The flood basin is rarely inundated and only major flooding events will deposit more fine sediment. Flood basin deposits may dry out between floods, producing mudcracks or other features of subaerial exposure, such as soils (Collinson, 1986). If the climate is wet, backswamps may form in the flood basin due to shallow water tables and heavy vegetation (Galloway and Hobday, 1983). The thick vegetation of the backswamp will cause the incorporation of organic material within the flood basin deposits (Reineck and Singh, 1975). The *dark gray to black carbonaceous mudstone* (1b) of the lower McMurray may have been formed in this way. If the organic material accumulates in a peat layer several feet thick, and is then buried, coal may form (Reineck and Singh, 1975; Galloway and Hobday, 1983). This is interpreted to be how the coal of the lower McMurray was formed.

Environmental Summary

The lower member of the McMurray Formation was deposited in the lowest valleys on the pre-Cretaceous unconformity surface. It was deposited in a high sinuosity, fluvial system confined by hills of Devonian carbonates. The main deposits are channel deposits, bank deposits, and flood basin deposits. The channel deposits were formed due to the lateral migration of a meandering channel. Deposition occurred mainly on the channel floor and point bars, with erosion occurring on the outer, concave bank of the channel. Channel meanders were abandoned and were filled with silty mudstone as the river migrated laterally across the flood plain. Levee and flood basin deposits were formed when the channel waters breached the banks and flooded the interchannel areas. Because the flow was unconfined, current velocity decreased rapidly, and the suspended load sediments (silts and clays) settled out. After deposition, the flood basin and levee deposits were disturbed by soil forming processes. In flood basin areas, coals were formed because of heavy vegetation present in backswamp areas.

MIDDLE MCMURRAY

The "middle member" (or "middle McMurray") is the thickest and has the best bitumen saturation of the three members of the McMurray Formation. It is found throughout the study area and often makes up the entire McMurray Formation. The middle McMurray may be in sharp contact with the lower McMurray or it may rest directly on underlying Devonian carbonates. The exact thickness of the middle McMurray is commonly difficult to determine because of the gradational upper contact with the upper McMurray and the fact that some cores start within the middle McMurray. However, by studying both cores and logs, an isopach of the middle McMurray was created (Fig. 33). The map shows that there is no influence of the underlying sub-Cretaceous unconformity on middle McMurray deposition. The thickest section of middle McMurray trends northwest across the northern portion of the study area. The maximum thickness is 78.1 m and it occurs in the 4-33-94-7 W4 well.

The division of the middle and upper members of the McMurray Formation is made very difficult by the gradational nature of the contact between the two. For this study, the top of the middle McMurray is put at the top of an overall fining upward succession. The upper McMurray generally displays an overall coarsening upward profile, so the contact is placed where the upward fining succession meets this upward coarsening succession. Some authors (*e.g.* Ranger, 1994) do not separate the McMurray into three separate members, but for the present study the traditional tripartite division was employed. In the present study area the separation of the three members is easier than in areas further south (*e.g.* Ranger, 1994).

Facies Associations

The middle McMurray is very complex in its lateral and vertical variability. Lateral correlation is very difficult due to adjacent wells commonly displaying differing vertical successions. There are two facies associations within the middle McMurray: a sandy facies association and a muddy facies association (Fox, 1988). Successions of the sandy facies association are generally overlain by successions of the muddy facies association, with a gradational contact between the two, and a sharp basal contact.

Sandy facies association

The sandy facies association consists mainly of *large-scale cross-stratified* (6) and *flat to low angle planar stratified sands* (4), with subordinate *structureless* (3) and *small-scale cross-stratified sands* (5). Mud and interbedded sand and mud may also occur in minor amounts. The sandy association may comprise the entire middle McMurray succession or there may be successions of the sandy association interbedded with successions of the muddy association.

Vertical successions of the sandy association are very complex and variable from well to well. Lateral correlation of successions is very difficult and, at times, impossible. The successions generally have *large-scale cross-stratified* (6) or *structureless sand* (3), and, rarely, *flat to low angle planar stratified sand* (4), at the base. The basal sands of a succession of the sandy association are generally coarser grained than units further up in the succession. Close to the base of the middle McMurray, the sands are coarse and pebbly. Grain size ranges from pebbly to very fine, with an overall upward fining trend. Sorting also tends to increase upwards.

The highly variable nature of the vertical successions does not allow for any patterns to be recognized. As stated above, a single succession may have *large-scale cross-stratifed* (6), *structureless* (3), or *flat to low angle planar stratified* (4) sand at the base. Each of these basal sand may grade up into any one of the other sand facies found in the sandy association, with no discernable pattern. However, *small-scale cross-stratified sand* (5) is most commonly found at or near the top of a vertical succession, since it is a predominantly fine to very fine grained sand facies. *Small-scale cross-stratified sand* (5) can be found just above a succession of the muddy association, or interbedded between units of the muddy association, or found directly below a succession of the muddy association (at the top of the sandy association). The top of a succession of the sandy association is generally gradational with overlying *interbedded sand and mud* (9) of the muddy association, but the contact may also be sharp in some cases.

Beds dominated by mud intraclasts (shale-clast breccias) are common within the sandy association. They occur in most facies of the sandy association, with no overall pattern or specific horizon of occurrence, so they cannot be used to correlate from well to well. These "shale-clast breccia" beds are interbedded with sand beds containing little or no intraclasts. Scattered mud intraclasts can be found throughout the facies of the sandy association. They may be found close to other argillaceous components of the sandy association indicating a possible relationship.

Mud beds and laminae, as well as beds of interbedded or interlaminated sand and mud, are found within the sandy association in minor amounts. The number and thickness of these argillaceous beds increase upwards until ultimately, a succession of the sandy association may grade up into a succession of the muddy association. The mud laminae and beds generally occur higher up within a sandy association succession, as well as higher up in the middle McMurray, while the lower basal sands are devoid of both intraclasts and mud beds. The mud beds are generally composed of thinly interlaminated sand and mud, but may also be composed of solid mud, a few centimetres thick. The mud beds generally have sharp upper contacts with sand, but they may also be burrowed. Lower contacts of mud beds with sand are generally gradational or burrowed.

The units of interbedded sand and mud within the sandy association may be 10-20 cm in thickness, with individual beds ranging from a few millimetres to a few centimetres thick. The upper and lower boundaries of these units may be in sharp contact with sand, but within the units the boundaries between the individual sand and mud beds may be gradational or totally obscured by burrowing.

Bioturbation is rare to absent within the sandy association. The sands are devoid of any bioturbation except for rare escape traces (fugichnia). Bioturbation is present mainly in the more argillaceous portions of the sandy association, such as the mud beds/laminae and interbedded sand and mud. The mud beds and laminae may be thoroughly bioturbated, so that no bedding contacts are visible. Alternatively, the mud beds and laminae may also be completely undisturbed by biogenic activity. It is the interbedded sand and mud units within the sandy association that generally show abundant to common bioturbation. As stated above, bedding in these units may be totally obscured due to biogenic activity. There is a very limited diversity to the burrow forms present. They also tend to be small in size, as well as morphologically simple. The traces that are present, in approximate order of abundance are: *Cylindrichnus, Planolites, Skolithos, Palaeophycus,* and escape traces (fugichnia). Within the sand, the traces are visible only if lined with mud, creating a contrast with the dark, bitumen stained sands.

Successions of the sandy association may be interbedded with successions of the muddy association. Where a succession of the sandy association overlies a succession of the muddy association, the contact is generally sharp and may be scoured.

Muddy facies association

The muddy facies association consists of *interbedded sand and mud* (9), *medium to light gray interlaminated to silty mudstone* (1d), and *gray structureless mudstone* (1e), with the first being the most dominant facies. *Interbedded sand and mud* (9) commonly comprises an entire succession of the muddy association. The other two facies are most commonly found in gradational contact with each other.

A typical succession of the muddy association starts with *interbedded sand and mud* (9) at the base, either in gradational or sharp contact with the underlying succession of the sandy association. The sand beds within the interbedded units are generally fine to very fine-grained and may display the small-scale cross-stratification associated with asymmetrical ripples. The interbedded unit becomes muddier upward with a decrease in the number and thickness of sand beds, until it ultimately grades up into *gray interlaminated to silty mudstone* (1d). The silty mudstone becomes less silty upwards until it grades up into the *gray structureless mudstone* (1e). This is a typical succession, but any combination of the three facies may occur. Rarely, *interbedded sand and mud* (9) may gradationally overlie the silty mudstone, for example. *Gray interlaminated to silty mudstone* (1d) may, rarely, be at the base of a succession, or it may comprise an entire succession of the muddy association. In this case, contacts with underlying and overlying sand are sharp; the top contact of the mudstone with sand may also be scoured. Contacts between the facies of the muddy association are generally gradational, but may, rarely, be sharp. Different units of *interbedded sand and mud* (9) may be in sharp contact with each other or one of the mudstone facies, for example.

Bioturbation is common in the muddy facies association, ranging from abundant to absent. Most of the bioturbation is found in the interbedded sand and mud units, mainly in the muddy beds or at the interface between muddy and sandy beds. Burrowing in the silty mudstone ranges from moderate to rare, whereas the structureless mudstone displays no burrowing at all. Different units of *interbedded sand and mud* (9), in direct contact, may alternate between intensely burrowed and non-burrowed. As with the sandy association, trace fossil forms are small and simple and display a low diversity. Monospecific assemblages may found within units of interbedded sand and mud. The traces present within the muddy association, in approximate order of abundance, are: *Cylindrichnus, Planolites, Palaeophycus, Gyrolithes, Skolithos, Arenicolites, Teichichnus,* and *Chondrites*(?). In general, bioturbation decreases upward in successions of the muddy association. However, it may also increase upward in some cases.

A succession of the muddy association almost always tops the middle McMurray member. The contact of the middle McMurray with the upper McMurray is generally placed where *structureless gray mudstone* (1e) begins to become siltier and grades upward into silty mudstone, another mudstone facies, or interbedded sand and mud.

Interpretation

The sediments of the middle McMurray are interpreted to have been deposited within an estuarine complex. The sediments of the sandy facies association are interpreted as estuarine channel bottom and lower point bar deposits. The sediments of the muddy facies association are interpreted as estuarine channel lateral accretion deposits (*ie.* point bar deposits), and channel abandonment deposits. The complex nature and variability of the middle McMurray deposits are a reflection of the complex nature of the depositional environment.

An estuary is defined by Dalrymple *et al.* (1992) as " 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 limits of tidal facies at its head to the seaward limits of coastal facies at its mouth." (Fig. 34). This definition implies that estuaries form as a result of a relative rise in sea level (*ie.* transgression) that causes marine water to move up fluvial valleys, mixing with the fresh water. In the case of the middle McMurray, a relative rise in the level of the Boreal Sea caused the flooding and drowning of the fluvial valleys of the lower McMurray, forming the middle McMurray estuaries.

The mixing of salt water and fresh water within the estuary produces two significant phenomena that affect sedimentation: the salt wedge (or salinity intrusion) and the turbidity maximum. The salt wedge is a body of salty water resting on the bottom of the estuary (Dyer, 1986), and the turbidity maximum is a zone fomed where the landward flow of seawater converges with the seaward flow of fresh water, producing a sediment trap (Allen, 1991). It is a zone of high concentrations of suspended sediment (Kranck, 1981; Dyer, 1986). These two features are discussed in greater detail in Chapter 2, in the interpretation of Facies 9 (*interbedded sand and mud*), the main component of the muddy facies association.

Tides have a great impact on sedimentation within an estuary (Clifton, 1982). In most estuaries, tides are the dominant energy source and are responsible for the mixing of fresh and salt water, resuspension of settled sediment, and transportation of suspended sediments landward or seaward. There are three main tidal processes that affect sedimentary processes: 1) landward deformation of the tide wave; 2) tidal discharge and channel stability; and 3) cyclic tidal current fluctuations (Nichols and Biggs, 1985). The cyclic nature of the tides is what produces the cyclic alternation of fine and coarse sediments in middle McMurray deposits.

River processes also affect sedimentation patterns within an estuary. A significant amount of sediment can be supplied to an estuary by river inflow. Most of the mud and suspended sediment present in an estuary is introduced by river discharge (Clifton, 1982; Nichols and Biggs, 1985). At the transition where fresh water meets salt water, the suspended sediment carried by the river flocculates and settles out. This is the zone of the turbidity maximum (Kranck, 1981; Nichols and Biggs, 1985; Dyer, 1986). River flooding will cause the turbidity maximum and the salt wedge to be displaced seaward (Nichols and Biggs, 1985; Allen, 1991; Allen and Posamentier, 1993; Ranger, 1994), changing the sedimentation patterns within the estuary. Tides will cause the reverse to occur; the salt wedge and turbidity maximum will be displaced landward.

In general, estuaries display a tripartite zonation (Fig. 34): the upper estuary consists mainly of fluvially derived sands; the middle estuary is dominated by muds and interbedded sand and mud; the lower estuary consists of seaward sourced sands (Dorjes and Howard, 1975; Rahmani, 1988; Ranger, 1994). The lower estuary is sandy due to the winnowing action of the tide and wave processes removing muddy material from the sediments (Clifton, 1982; Nichols and Biggs, 1985). The sands are deposited where current strengths are high. Interbedded sand and mud is deposited where currents are weaker, but still strong enough to transport sand, and suspended sediment is abundant, with mud being deposited at slack water times. Muds are deposited where current strengths are weak, possibly due to abandonment (Fox, 1988).

Sandy facies association

Tidal influence in the sandy facies association is reflected in the mud interbeds and laminae present in large-scale and small-scale cross-stratified sands. These muddy intervals indicate a reduction in the current velocity necessary to transport sand in bedforms such as current ripples and dunes. When the current velocity was reduced, mud was deposited (Clifton, 1982). The current velocity reduction was only temporary, as indicated by cross-stratified sand overlying the muddy interbeds. This is a persistant pattern in the middle McMurray sands, and reflects a cyclic pattern of sedimentation, such as occurs under a tidal influence.

Where the muddy interbeds are composed of interlaminated sand and mud, a smaller-scale tidal influence is indicated (Fox, 1988). Although flow was weakened enough to permit the deposition of a mud interbed, there was still some alternation between currents strong enough to transport sand and those weak enough to allow deposition of mud.

The muddy interbeds in cross-stratified sand of the middle McMurray probably reflect current velocity unsteadiness associated with the spring-neap tidal cycle (every 2 weeks) (Nichols and Biggs, 1985; Fox, 1988). The sands would have been deposited during the spring tidal phase, when current velocities are strong, and the mud would have been deposited during the neap tide phase, when current velocities are weaker. The alternation of sand and mud within these muddy interbeds indicates the smaller-scale, daily, ebb/flood tidal cycle. Both ebb and flood currents could transport sand, if the velocity is high enough. During slack water periods, mud would have been deposited on and between the bedforms (Clifton, 1982; Fox, 1988).

The sands of the middle McMurray sandy association were deposited in bedforms such as dunes and current ripples, on the channel bottom and lower point bar of an estuarine channel. They are similar to the fluvial sands of the lower McMurray, however the muddy interbeds and units of interbedded sand and mud reflect tidal influence on the middle McMurray deposits.

Bioturbation within the sandy association provides further evidence of a tidal influence on the deposits. The lower McMurray fluvial sands display no bioturbation at all. The weakening of current velocity allowing mud deposition during slack water or neap tides, also allows organisms to colonise the substrate, producing bioturbation. When current velocity strengthens, the organisms try to escape upward through the sand being deposited, producing the rare escape traces (fugichnia) observed in middle McMurray sands. The traces produced by these organisms indicate that the water was brackish, not fully marine. The small size of the burrows, the simple morphology of the forms, the low diversity, and the combination of traces from the *Cruziana* and *Skolithos* ichnofacies all indicate a stressed, brackish water environment (Pemberton *et al.*, 1982; Wightman *et al.*, 1987; Ranger and Pemberton, 1992).

Muddy facies association

The thick successions of interbedded sand and mud within the middle McMurray are lateral accretion deposits, most likely formed as point bars within a sinuous, migrating, estuarine channel. Tidal influence is indicated by the rhythmic alternation of the sand and mud (Thomas *et al.*, 1987). As stated previously (see Facies 9 interpretation in Chapter 2), the interbedded successions are interpreted as the inclined heterolithic stratification (IHS) of Thomas *et al.* (1987), and are most often described as point bar deposits in tidally influenced channels (deMowbray, 1983; Smith, 1988; Nio and Yang, 1991; Ranger and Pemberton, 1992; Shanley *et al.*, 1992).

The successions of IHS fine upward due to the lateral migration of the sinuous channel. As the estuarine channel migrates across the tidal flat, channel meanders are cut off and become abandoned. Current strength is no longer sufficient to transport sand, therefore only mud and silt are deposited and transported into this environment. The abandoned meander fills up with fine material after avulsion. The only influx of sediment is due to overbank, fresh water flow that occurs during fluvial flooding of the estuarine channel (Ranger, 1994). The abandoned channel meander becomes flooded with fresh water and suspended sediment, which accumulates, eventually plugging the meander. The rare bioturbation in the silty mudstone may be due to organisms being washed in with silt during strong tidal surges caused by storm events (Ranger, 1994).

Many of the features of the middle McMurray muddy facies association also occur in fluvial environments. However, the trace fossils present in the middle McMurray provide evidence of tidal influence and stressed conditions. For instance, the alternation between intensely burrowed and non-burrowed units within the IHS indicates a shifting to the salt wedge within the estuary, caused by tidal cycles, as well as fluvial discharge. The most compelling evidence, however, of a tidal influence is the traces themselves. Estuaries are affected by many different factors (*eg.* tidal and fluvial currents, salinity variations, etc.), creating a very stressful environment for any organisms. The traces observed within the middle McMurray are a typical brackish water assemblage (see Dorjes and Howard, 1975; Beynon *et al.*, 1988; Ranger and Pemberton, 1992), with small, morphologically simple forms. Diversity of forms is low, but there may be high abundances of single forms. Also, the traces tend to be from the *Cruziana* and *Skolithos* ichnofacies.

Environmental Summary

The middle member of the McMurray Formation was deposited in an estuarine complex formed due to the transgression of the Boreal Sea and the subsequent flooding of the lower McMurray fluvial valleys. The type of facies deposited depended on the current strength and position within the estuary. Cross-stratified sands were deposited where current strengths were high, such as the channel bottom and lower point bar. Interbedded sand and mud was deposited as lateral accretion deposits on point bars within the channel, where current strengths were weaker and there was a high concentration of suspended sediment. The muds were deposited under weak current conditions in abandoned estuarine channel meanders. The muds were deposited on top of the lateral accretion deposits. These muds are often absent due to erosion caused by the lateral migration of the estuarine channel. This lateral migration also caused the formation of stacked successions of estuarine channel deposits. The study area is small and localized, but it is interpreted that, because of the generally high mud content of the sediments, the middle McMurray was deposited in the upper to middle reaches of the estuary, under mesotidal (tidal range of 2 to 4 m) conditions.

The estuarine channels were part of large, regional valley complexes. Ranger (1994) has mapped the extent of some of these valley complexes in the Athabasca area. The valleys are on the order of tens of kilometres wide, with the channels themselves being 0.5 - 1 kilometre wide (Flach and Mossop, 1985).

UPPER MCMURRAY

The uppermost division, the "upper member" or "upper McMurray", is the most difficult of the three members of the McMurray Formation to define and interpret in the present study area. It is found in only 8 of the 25 cores logged and even then, a whole succession from the top of the middle McMurray to the base of the Wabiskaw is rarely present. The top of the core may also be within the middle McMurray and the gamma ray and resistivity logs must then be used to determine if the upper McMurray is present in that particular well. The gradational nature of the contact between the upper and middle McMurray also makes it difficult to determine where one begins and the other ends. Generally, the upper McMurray is a coarsening upward succession and the contact between upper and middle is placed at the base of this succession. The gamma ray log signature of the upper McMurray may be very distinct because of the coarsening upward nature of the succession (Fig. 35), since both lower and middle members are fining upward successions. The electric logs were used to determine thickness where no core was available.

An isopach map (Fig. 36) shows that the upper McMurray is missing in the northeast and west-central portion of Township 94. The thickness values that are present are probably values associated with erosion, and are, therefore, not indicative of the original thickness of the upper McMurray when deposited. As the Boreal Sea transgressed from the north, it eroded and washed away the sediments of the upper McMurray prior to deposition of the Clearwater Formation and, specifically the Wabiskaw Member of that formation. The fact that the transgression came from the north helps to explain why there are thicker and more continuous successions of upper McMurray in the southern portion of the study area, while in the north, there are areas where the upper McMurray is absent. The maximum thickness of the upper McMurray does happen to occur in the northern portion of the study area, however. In well 12-27-94-7 W4, the thickness of the upper McMurray is 9.7 m. In the 2-21-93-7 W4 well in the south, it has a thickness of 9.1 m. There is a zone of thick upper McMurray deposits in the north-central portion of the study area.

Facies Associations

There are two facies associations recognized in the upper McMurray in the study area. Both are overall coarsening upward successions. One is dominated by mudstone that becomes siltier and sandier upward, and by beds of *interlaminated dark gray mudstone* (1f). The second facies association is dominated by mainly horizontally bedded interbedded sand and mud. One or two coarsening upward packages may be present in a succession of this facies association.

The first facies association occurs in 4 of the 8 wells containing upper McMurray, with only 2 displaying *interlaminated dark gray mudstone* (1f). The basal contact of the facies association is generally gradational with underlying structureless mudstone of the middle McMurray. The basal facies of the association may be interlaminated to silty mudstone, interbedded sand and mud, or white to light gray mudstone. The amount of silt and sand increases upward within these facies. In two of the examples, the silty mudstone then grades upward into interbedded sand and mud. The coarsening upward succession in the 10-24-93-7 W4 well is capped by a silty sand, which is in sharp contact with the overlying Wabiskaw Member. Where the *interlaminated dark gray mudstone* (1f) is present, the succession of facies is slightly different. *Massive white to light gray mudstone* (1a) grades up into the *interlaminated dark gray mudstone* (1f), which is then sharply overlain by *heavily bioturbated muddy sand* (7) with a burrowed contact, or interbedded sand and mud.

The mudstone facies within this facies association can be distinguished from those of the middle McMurray by the presence of rooting, synaeresis cracks, and rare mudcracks. The middle McMurray mudstones do not display any of this evidence of subaerial exposure. This is one of the characteristics that separate the middle and upper members. Carbonaceous debris is also common within the upper McMurray. The sands are generally very fine to fine grained, and there is rare small-scale cross-stratification in the form of asymmetrical ripples.

Bioturbation is common in this facies association of the upper McMurray and tends to increase upwards. *Planolites, Palaeophycus,* and *Skolithos* are the main trace fossils present, with minor *Cylindrichnus, Arenicolites,* and *Teichichnus.* Bioturbation commonly obscures bedding contacts so that muddy laminae and beds are thoroughly mixed with sand. Rarely, there may be alternation between zones of heavy bioturbation and no bioturbation. The *interlaminated dark gray mudstone* (1f) is only moderately burrowed and the laminae of mudstone, silt, and sand are distinct, although contacts may be burrowed.

The second facies association of the upper McMurray is dominated by interbedded sand and mud. Unlike in the middle McMurray, the beds are not inclined at a high angle in the upper McMurray; they are generally flat but may be inclined at a low angle. The units are composed of thinly interbedded to interlaminated sand and mud, with mud beds generally 1 cm or less, but ranging up to 5 cm thick. The sand beds are composed of fine to very fine grained sand and may be up to 10 to 15 cm thick. Rarely, the sand beds may be somewhat muddy. The sand beds commonly display symmetrical and asymmetrical ripple cross-stratification. Synaeresis cracks may be present in the mud interbeds.

Most commonly, this facies association is composed of only interbedded sand and mud. In one well in the south (10-12-93-7 W4), the interbedded sand and mud is in sharp contact with overlying heavily bioturbated muddy sand. This is gradationally overlain by *flat to low angle planar laminated sand* (4) with minor mud laminae. The mud laminae are generally thoroughly bioturbated and do not have sharp contacts with the surrounding sand. Towards the top of this sand facies, the mud laminae become less burrowed, and the contacts with the sand are sharp.

This facies association sharply overlies structureless mudstone or, rarely, interbedded sand and mud of the middle McMurray. It has a sharp, scoured upper contact with the overlying Wabiskaw. As mentioned previously, one or two coarsening upward packages may comprise this facies association. Generally, the interbedded unit is muddier at the base. The thickness of the sand beds tends to increase upward while the number of mud beds decreases. A second, similar coarsening upward package may overlie this succession with a sharp contact. Contacts between the sandy and muddy beds are generally sharp and distinct. The sand beds may appear lensoid in shape in some instances where mud is dominant.

Bioturbation is moderate to common within the interbedded units of this second facies association. *Planolites, Palaeophycus,* and *Cylindrichnus* are the most common trace fossils present. *Skolithos* and *Arenicolites* are also present. Bedding may be mottled and obscured due to burrowing. Most commonly, the burrows are present within the muddy beds, but there may also be rare bioturbation in the sand beds. Overall, bioturbation tends to decrease upwards in this facies association.

Interpretation

The sediments of the two facies associations of the upper McMurray were deposited in two very different environments. The first facies association described above is interpreted to have been deposited in off-channel areas related to the latest estuarine channels present in the area. The second facies association is interpreted to be offshore marine sand bar or shoal deposits. The lack of available data makes interpretation of the upper McMurray depositional environments very difficult. The majority of the vertical successions are probably incomplete due to erosion caused by transgression of the Boreal Sea, so it is only with partial vertical successions in some cases that the following interpretations are made.

The first facies association represents the filling of shallow lakes and bays associated with interchannel topographic lows adjacent to the latest estuarine channels (Flach, 1984; Flach and Mossop, 1985). Water, probably from marine incursions as well as estuarine channel flooding events, accumulated within topographic lows adjacent to the estuarine channel, producing shallow lakes and brackish bays. They were filled as sediment from crevasse splays, associated with the channel, prograded out into the lakes. These progradational splay deposits may have coalesced with sand bars to form extensive sheet-like sand bodies that filled these bodies of water (Flach, 1984; Flach and Mossop, 1985; Beynon, 1994). Crevasse splays occur when there is a breach of the natural levee of a channel (Fig. 17). Water is diverted from the main channel and sediment is deposited in off-channel areas (Miall, 1992).

The coarsening upward successions, in some cases, are capped by organic mudstone. After the shallow bodies of water were filled, the deposits were subjected to vegetative growth, indicated by the extensive rooting in this facies association, as well as the dark gray (organic) mudstone. The topographic lows were probably marshy and heavily vegetated, which explains the presence of the organic mudstone (*interlaminated dark gray mudstone* (1f)); organic material from the abundant vegetation was mixed with mudstone. As the organic muds were deposited, however, there were periodic influxes of marine water, as evidenced by the silt and sand laminations, as well as the bioturbation, present in the mud. The bioturbation is associated only with the high energy events that deposited sand, indicating that the high energy events and sands were derived from marine sources.

Synaeresis cracks are common in this facies association. The cracks were formed at the sediment-water interface due to salinity fluctuations (Wightman *et al.*, 1987; Ranger, 1994). The synaeresis cracks are evidence of marine influence on these upper McMurray deposits.

Overlying the organic mudstone in this facies association is either *heavily bioturbated muddy sand* (7) or interbedded sand and mud that is well bioturbated. In the 10-24-93-7 W4 well, a similar, interbedded silty sand and mud unit is present at the top of the succession. These units probably all indicate an influx of sediment-laden marine water that flooded the area and deposited sand on top of the vegetated land surface. After the initial surge, it appears the environment was relatively quiet, indicated by the common bioturbation. It had to be a quiet environment with low current or tide energy to allow the organisms to rework the sediment (Howard *et al.*, 1975; Frey and Howard, 1986).

The low diversity of trace fossil forms, the high abundances in some cases, and the small, simple forms all indicate that the sediments of this facies association were deposited in a brackish water environment. It was not fully marine, but there was a marine influence.

The second facies association of the upper McMurray is interpreted to have been deposited as marine sand bars or inlet shoals (Greer, 1975; Flach, 1984; Flach and Mossop, 1985; Fox, 1988). The coarsening upward succession is very similar to those of tidal bars and shoals described by many authors (Johnson, 1978; Walker, 1984; Penland, *et al.*, 1986). The sand bars are interpreted to have been deposited in a nearshore environment, maybe just seaward of the estuary mouth, and possibly affected by longshore drift (Fox, 1988). The amount of mud present in this facies association indicates a high suspended sediment concentration which would indicate a nearshore environment influenced by estuarine processes (Howard and Reineck, 1972; Oertel and Dunstan, 1981; Fox, 1988).

Tidal bars and shoals generally have the same coarsening upward profile, caused by bar migration. The lower energy interbar trough deposits are overlain by higher energy deposits of the bar itself (Greer, 1975; Johnson, 1978; Penland, *et al.*, 1986). The lowest deposits, at the base of the sand body or within interbar troughs, are muddy with wavy or lenticular sand interbeds. Moving upwards, the amount of sand increases and the bedding becomes planar laminated, with possibly some ripple laminations. At the top of the succession, the bar crest, mud is very rare and the sand is planar laminated to medium-scale cross-stratified. This succession represents an overall increase in current energy and ability to transport sand. The bar deposits of the upper McMurray in the present study area do not appear to have the highest energy bar crest deposits. These deposits were probably truncated by an erosional event and subsequent deposition of the Wabiskaw Member.

The interbedded nature of some of the upper McMurray deposits indicates a continuing tidal influence, with currents ranging from strong enough for sand transport to weak enough for mud deposition. As mentioned above, the muddiness indicates estuarine influence. The amount of suspended sediment deposited on the shelf from the estuary depends on both river flow and neap/spring tidal cycles (Fox, 1988). Large amounts of suspended sediment are transported out of the Gironde Estuary during spring tides (Caistang and Allen, 1981). River floods can also carry large volumes of suspended sediment onto the shelf.

The bioturbation decreases upward in this facies association, which supports an increase in energy upwards. Again, however, the size and diversity of the trace fossil forms indicate a mainly brackish water assemblage.

It is interpreted that the second facies association of the upper McMurray represents sand bars present seaward of the estuary mouth, in a nearshore marine environment. The influence of the estuary is still quite evident in the amount of mud present and the brackish assemblage of trace fossils. The exact configuration of these bars is unknown due to a lack of lateral continuity. It is interpreted, however, that the bars are inlet shoals and are oriented perpendicular to the estuary mouth (Fig. 37).

Environmental Summary

The upper McMurray was deposited in two very different environments. The first facies association represents the off-channel facies associated with large estuarine channels. Shallow lakes, formed in topographic lows were filled with progradational crevasse splay deposits and later vegetated. There were periodic influxes of marine water during the time when organic mudstones were deposited, as evidenced by sand and silt interlaminations. A large incursion of sediment-laden marine water deposited muddy sand on top of the organic muds. The second facies association represents deposition on nearshore marine sand bars or shoals. The coarsening upward succession and decrease in bioturbation upwards indicate an increase in current energy. The migration of higher energy bar deposits over lower energy interbar trough deposits produced the upward coarsening profile. Tidal influence is indicated by the interbedded sand and mud. High concentrations of suspended sediment, probably from a nearby estuary, caused abundant mud deposition even though current energies were high. The brackish assemblage of trace fossils also indicates an estuarine influence on the deposits. The highest energy bar crest deposits were probably truncated due to the transgression of the Boreal Sea and subsequent deposition of the Wabiskaw Member.

The upper McMurray was deposited in both onshore and nearshore environments. The transgression of the Boreal Sea did not cover the entire area during upper McMurray time, so there was still some high ground for onshore, off-channel deposition. At the end of upper McMurray time, the entire study area was inundated by the Boreal Sea, and the fully marine Wabiskaw Member of the Clearwater Formation was deposited.

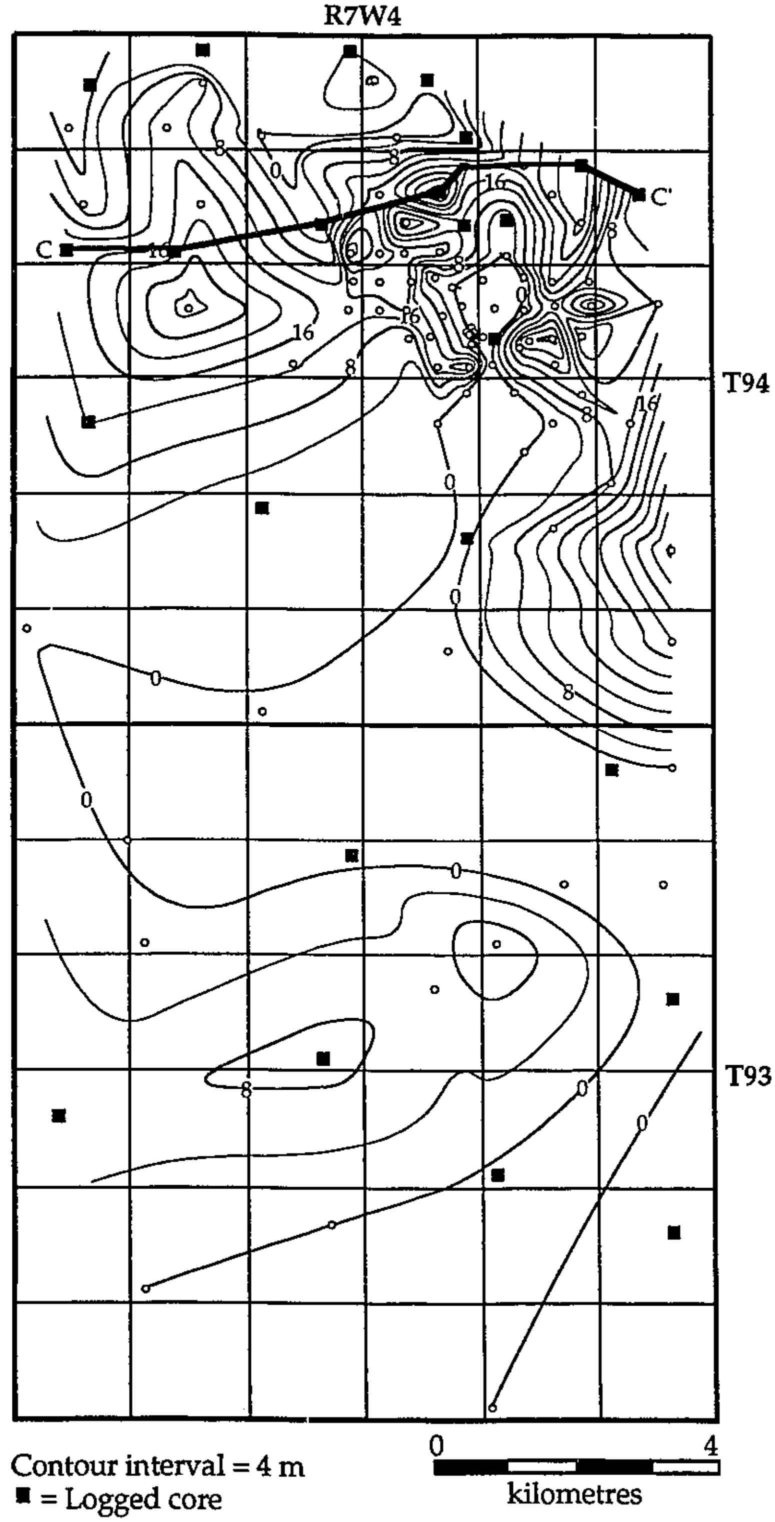


Figure 29. Isopach map of the lower member of the McMurray Formation.

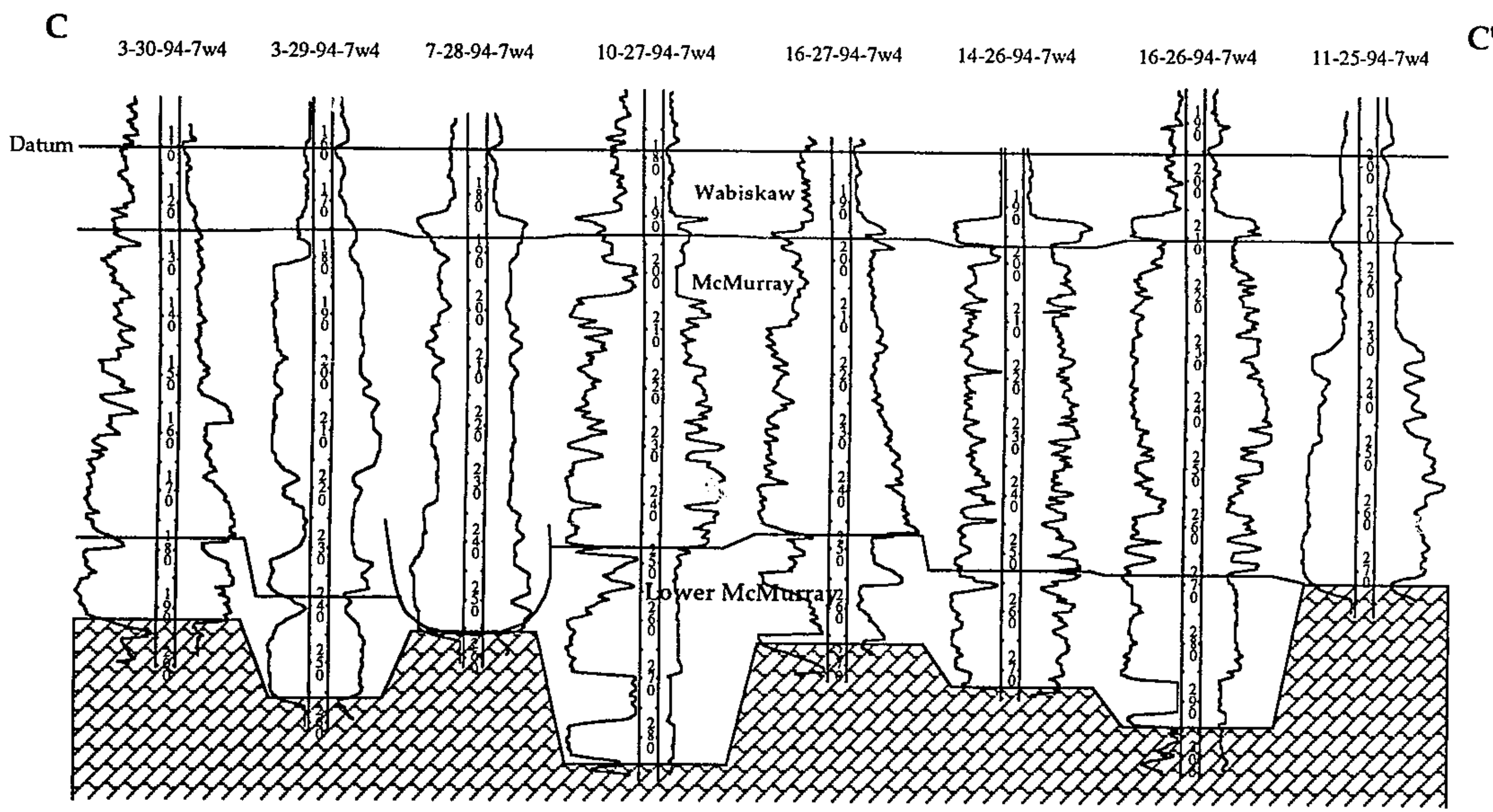


Figure 30. Cross-section across northern portion of study area (see Figure 29 for location) showing topographic control on lower McMurray deposition.

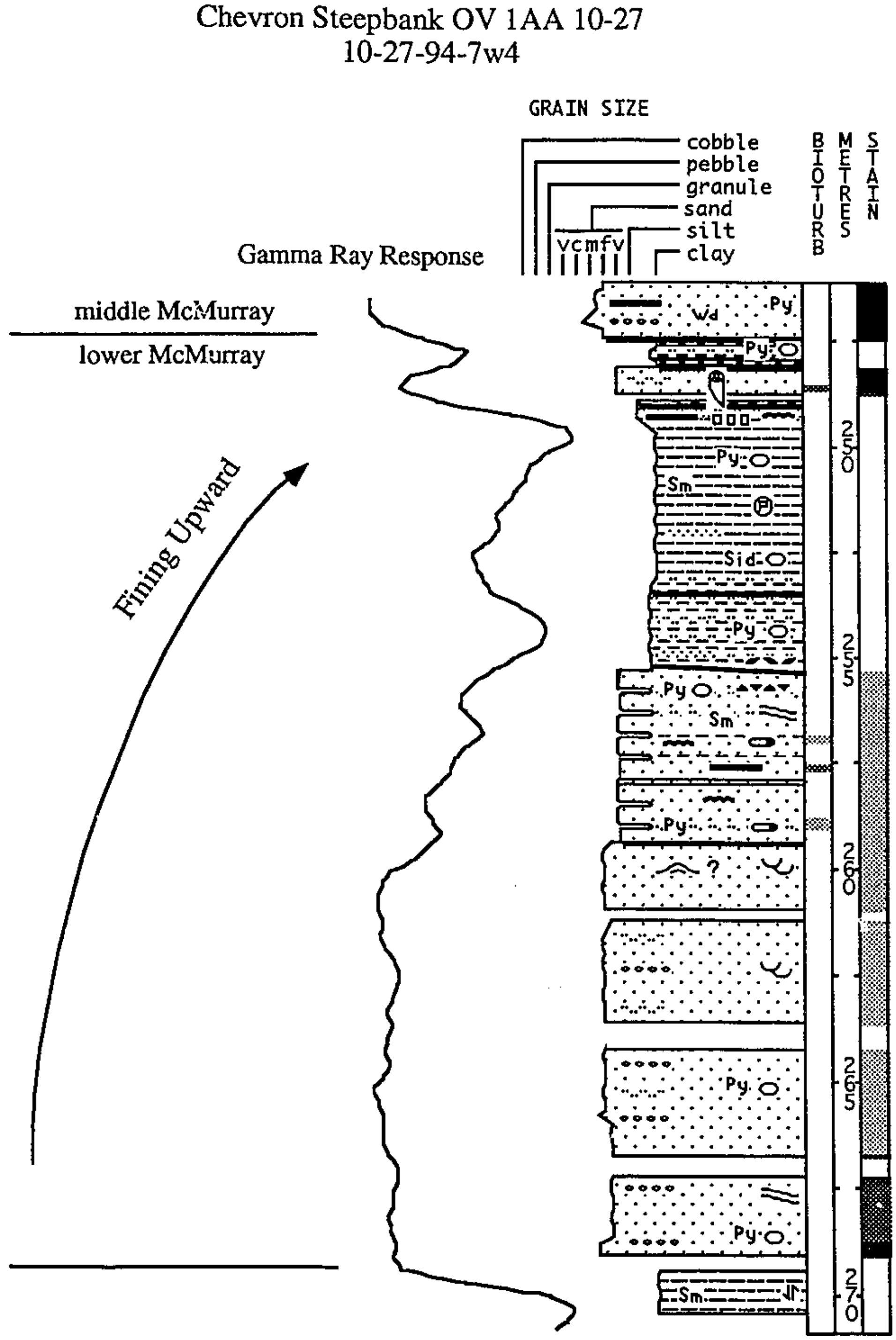


Figure 31. Strip log and gamma ray log of type section of the lower McMurray fining upward succession in well 10-27-94-7W4.

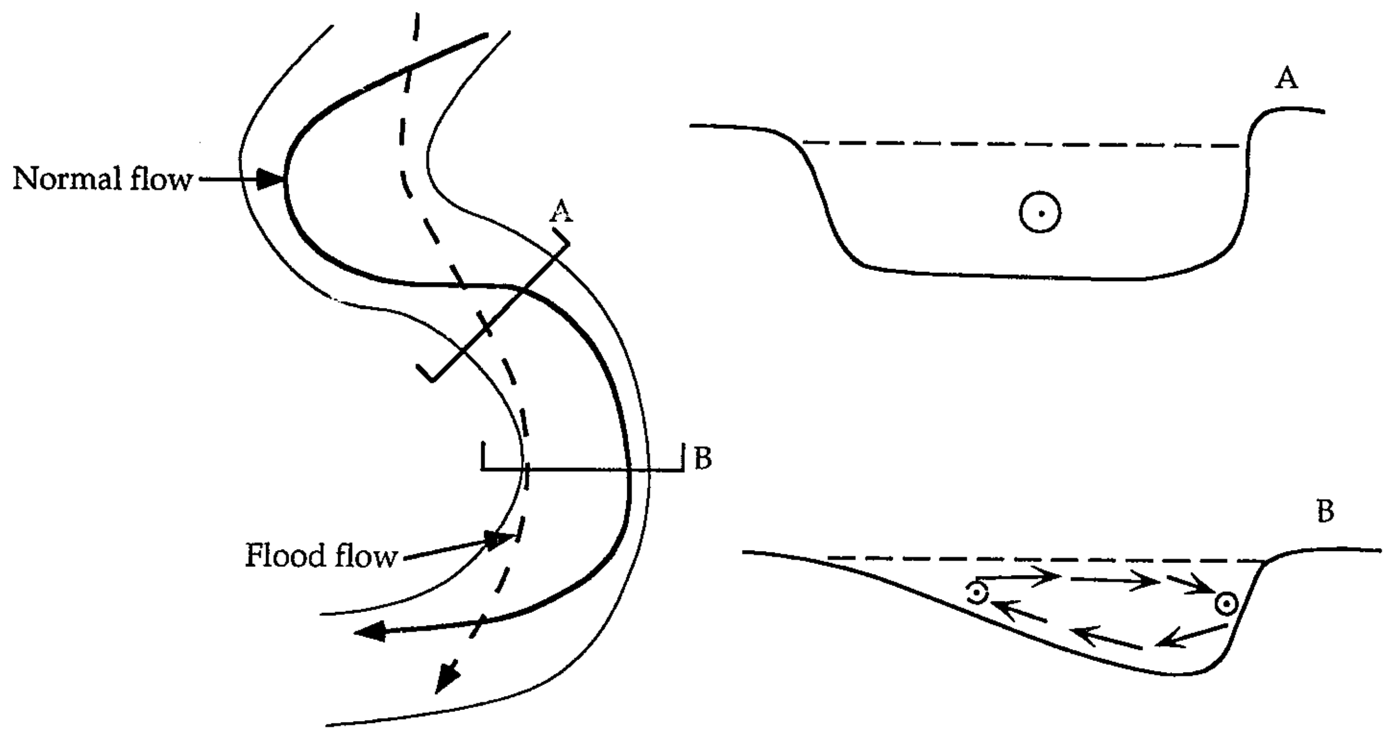


Figure 32. Velocity distribution in a sinuous meandering channel (modified from Galloway and Hobday, 1983).

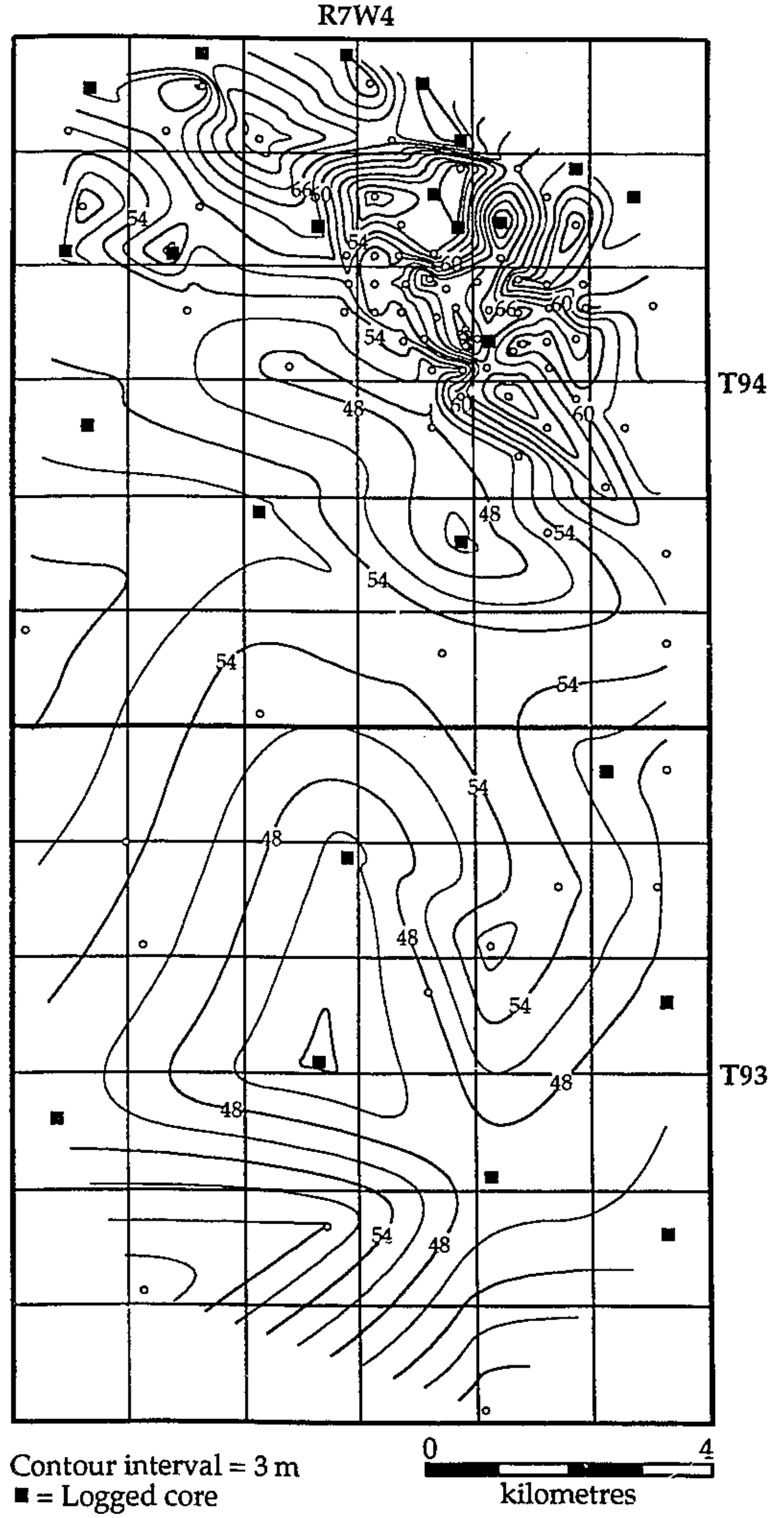


Figure 33. Isopach map of the middle member of the McMurray Formation.

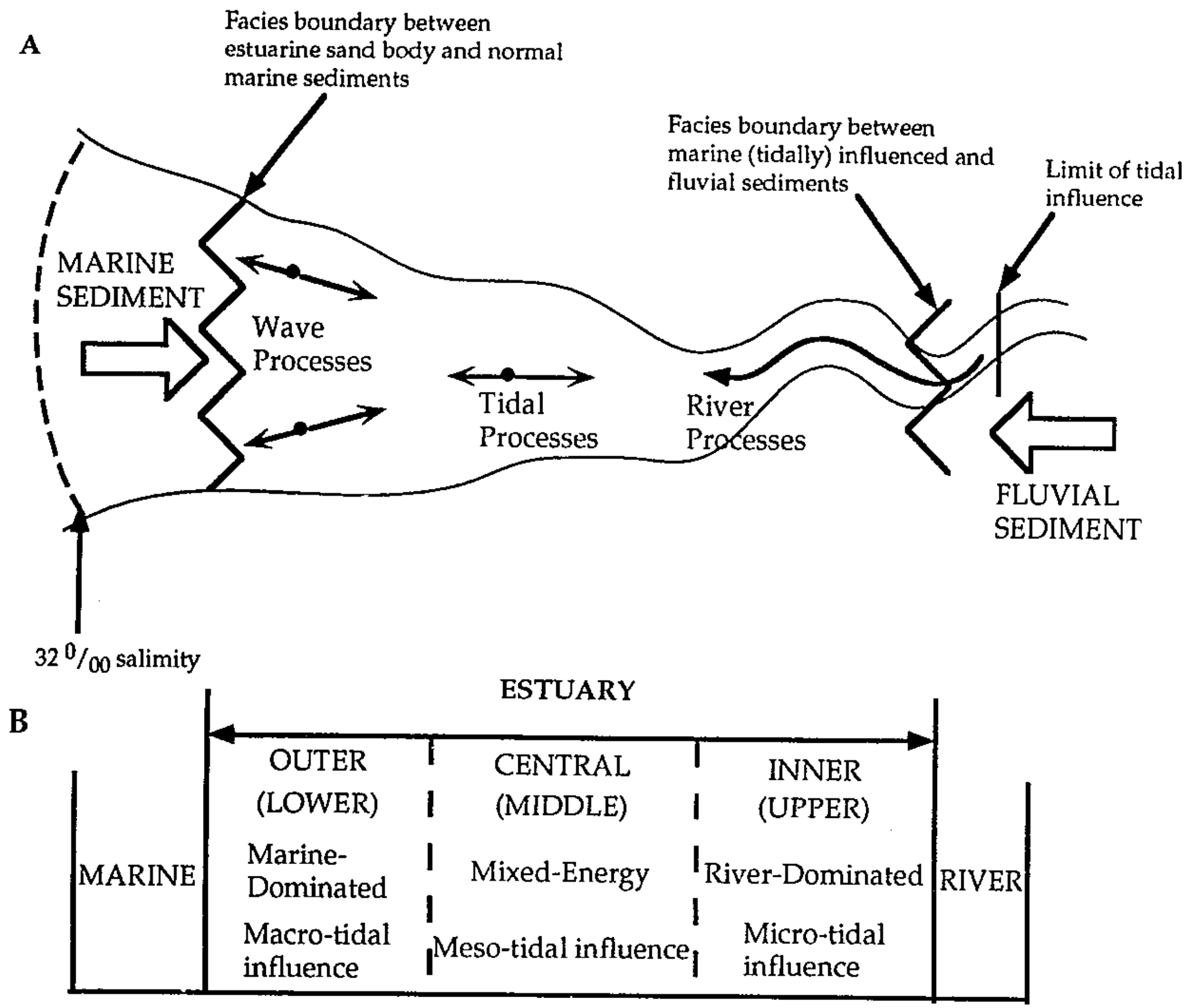


Figure 34. A) Schematic representation of an estuary. B) Tripartite zonation of the estuary according to dominant processes and tidal influence. (modified from Smith, 1988; Dalrymple *et al.*, 1992).

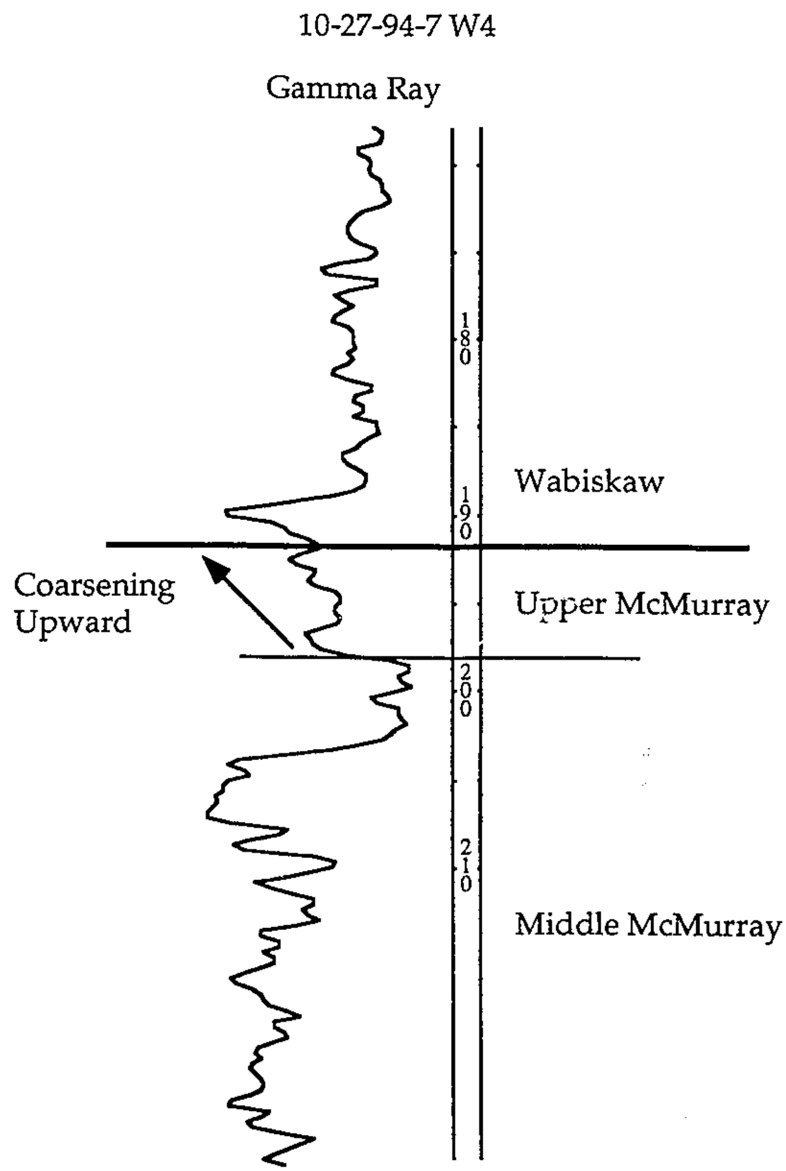


Figure 35. Coarsening upward gamma ray log signature in the upper member of the McMurray Formation.

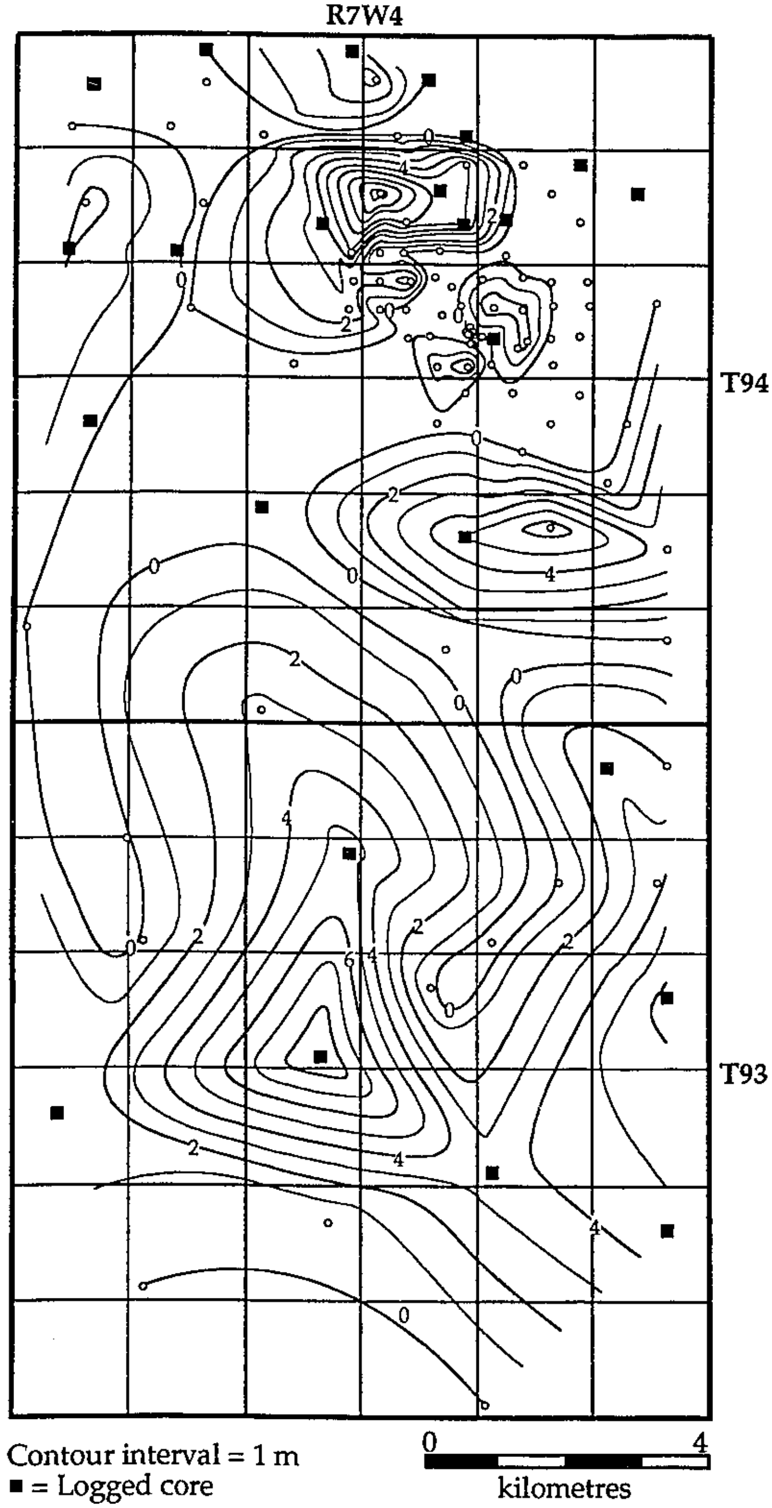


Figure 36. Isopach map of the upper member of the McMurray Formation.

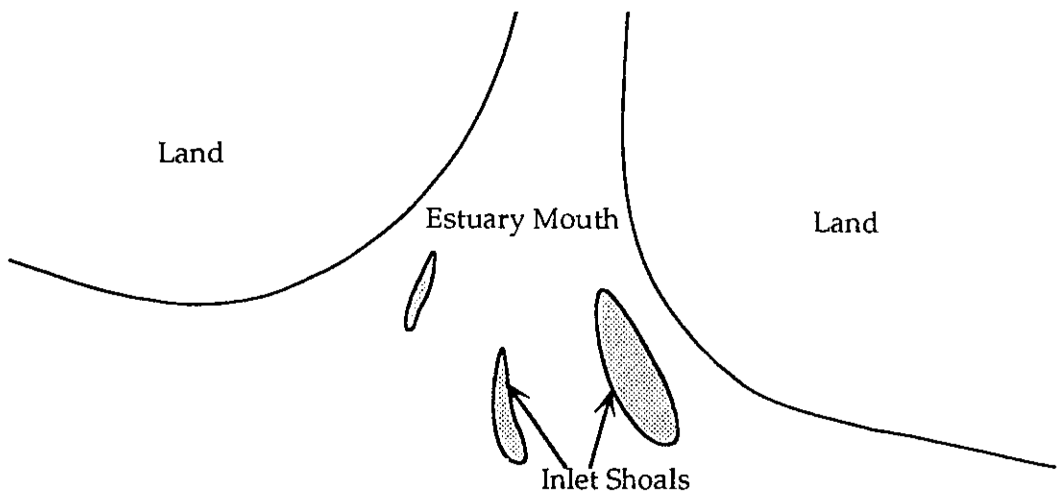


Figure 37. Possible configuration of sand bars (inlet shoals) of the upper member of the McMurray Formation, related to a retreating estuary.

CHAPTER 4 - HYDROCARBON DISTRIBUTION

Within the Athabasca Oil Sands Deposit, the McMurray Formation, combined with the Wabiskaw Member of the Clearwater Formation, contains 142 billion cubic metres (893 billion barrels) of bitumen in place, (ERCB, 1990). In the study area, knowledge of the distribution of the hydrocarbon and water zones within the McMurray Formation is important for the possible placement of injection and production wells. Bitumen distribution was determined so that the extent of the potential reservoir could be delineated. Knowledge of the gas distribution is important for several reasons: 1) the gas may adversely affect production processes; 2) it may provide a fuel source; and 3) it may provide a feedstock for upgrading processes.

METHODS AND RESULTS

For this study, both net pay (bitumen) and the amount of gas present within the McMurray Formation were determined. Two maps were constructed to show the distribution of gas and bitumen (Figs. 38, 39) within the entire McMurray Formation. Both geophysical logs and core observations were used in the calculation of gas thickness and net pay.

Gas Thickness

Gas thickness was calculated using the density porosity and neutron porosity logs. On older logs, bulk density and porosity logs were compared. Gas is indicated when the neutron porosity curve crosses over the density porosity curve, reading unusually low porosities (Schlumberger, 1989). These areas of cross-over were marked on the logs and then the net thickness of all of the gas zones was measured using calipers. The gas zones all occurred at the top of the McMurray Formation, or very close to the top, with only two small zones occurring near the top of the middle member in a two of wells.

A map of net gas thickness (Fig. 38) shows the thickest accumulations of gas occur in the east-central portion of the map area, with two wells each containing over 13m of gas. There are other, smaller accumulations in the northwest portion of the study area. There appears to be gas across the entire central portion of the study area. However, as the map indicates, there are a few wells to the west and in the centre where there is no data (ND); the contours have been extrapolated into these areas. The lack of data means that the contours across the centre and in the western portion of the map area may be suspect.

Net Pay

When determining net pay, the amount of gas present was not taken into account. Net pay refers only to the economical amount of bitumen present in the formation. That is, the amount of bitumen that can be recovered economically at present day oil prices and costs of production. The amount of bitumen present was measured from the resistivity logs for each well. An arbitrary resistivity cutoff for economic amounts of bitumen was determined by comparing the resistivity log to the core (if available). Within a porous sand, low values on the resistivity log indicate saline formation water, whereas the higher resistivity readings indicate hydrocarbons, in this case bitumen (Schlumberger, 1989). For the present study, the cutoff was determined to be 60 ohm-m, but in three wells 50 ohm-m was taken as the cutoff. This difference was due to the individual comparison of logs and core for individual wells. The factor affecting the cutoff appeared to be the fact that older resistivity logs had been measured using different tools than more recent logs (dual induction logs compared to dual focussed electrical logs, respectively).

A map of net pay (Fig. 39) shows that the thickest bitumen accumulations occur in a band starting in the east-central portion of the map area, and extending to the northwest. The highest net pay values are 64.5m in well 13-22-94-7 W4 and 60.5m in well 10-1-94-7 W4. There is an area of thick bitumen accumulation in the northwest portion of the map area. Another area of thick net pay is in the southern end of the study area. The central and southwest portions of the map area show the lowest net pay values, with bitumen accumulations of approximately 1m in the southwest, and 10-15m in the central portion.

The highest saturations (or best pay) is generally found in the *large-scale cross-stratified sand facies* (Facies 6). The sand in this facies is generally clean and porous, having been deposited within the channel where finer material has been winnowed out by the current. Other facies that contain very good pay accumulations (in order of importance) are: *flat to low angle planar stratified sand* (Facies 4), *structureless sand* (Facies 3), *small-scale cross-stratified sand* (Facies 5), and *interbedded sand and mud* (Facies 9). The amount of pay present in *interbedded sand and mud* is dependant on the number and size of the mud interbeds; the more mud, the less pay.

Net pay is not a measure of the continuous thickness of bitumen accumulation, but rather a sum of all the thicknesses of bitumen that occur within the formation. The beds containing bitumen generally consist of clean sand and may be separated by beds of shale or silty sand, or other lithologies that are not permeable or porous enough to contain bitumen. However, there may also be beds where a porous, clean-looking sand (according to gamma ray logs) has a low resistivity reading, indicating saline formation water instead of bitumen. These "water sands" are most common in the lower member of the McMurray Formation, but may also occur further up in the formation.

In most cases, the "water sands" overlie bitumen saturated sands and are generally overlain by a shaly bed, which is, in turn, overlain by more bitumen saturated sand. In some cases, the "water sands" occurring at the top of the McMurray Formation may be overlain by gas-filled sand. Because the water-filled sands generally appear to be found overlying bitumen and underlying shales, it is suggested that the water sands may represent a gas leg where the gas has leaked off and been replaced by meteoric and formation waters (Ranger, 1994). This also explains the occurrence of water between the bitumen and gas at the top of the formation. In this case, not all of the gas may have leaked out, and water may have percolated into the space vacated by the gas that did leak off. The remaining gas would remain at the top of the reservoir due to its lower density. The bitumen, however, has about the same density as water, but an extremely high viscosity, therefore it cannot readily migrate, and remains below the water.

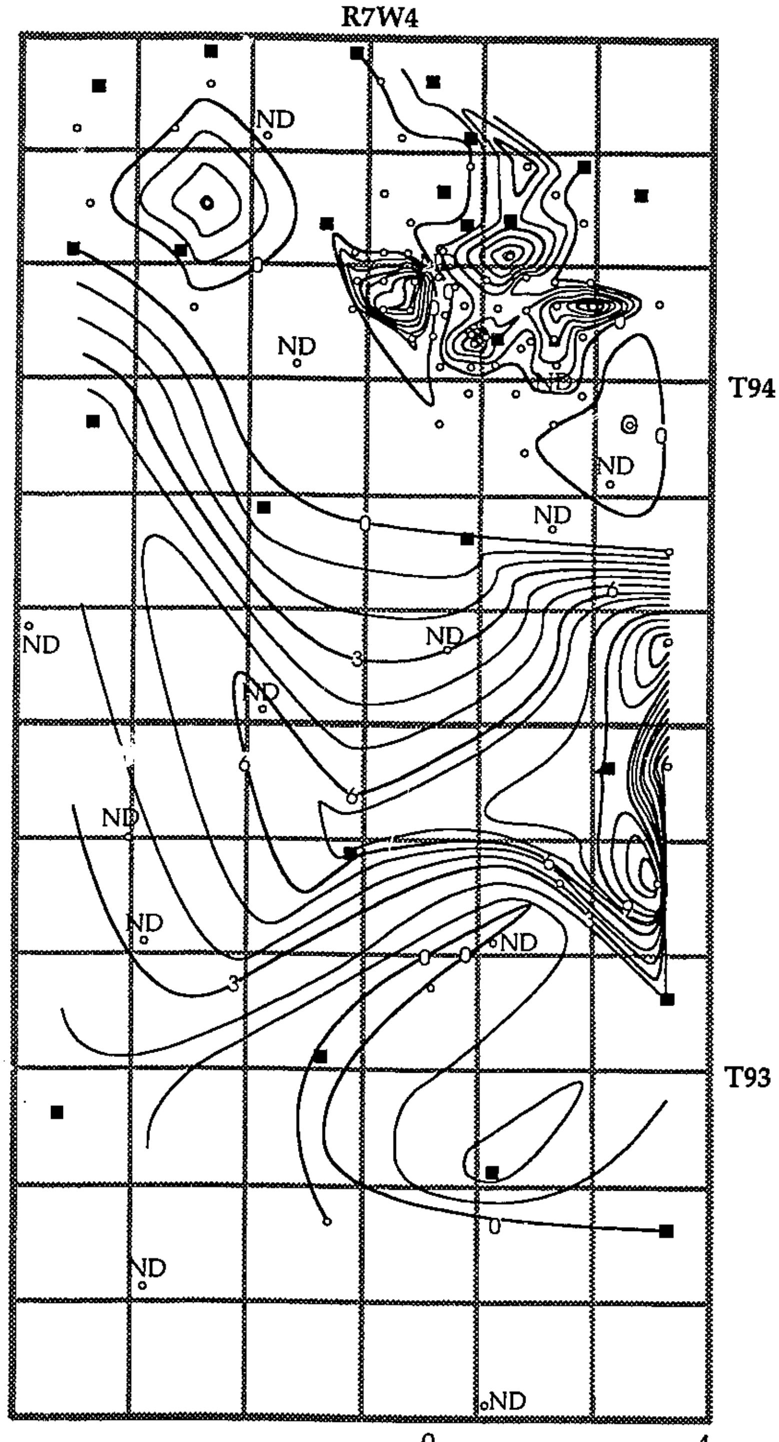
The shaly beds above some of the "water sands" probably acted as leaky seals, allowing the gas to build up and then slowly escape. The presence of water-saturated sand occurring between units of bitumen saturated sand has serious implications for the recovery and production of the bitumen from the McMurray Formation. The water zones (especially those above or within the bitumen) act as heat sinks, or "heat thief" zones, during steam production processes (Ranger pers. comm., 1995). The fact that the bitumen reservoir may not be continuous is very important for designing production strategies, such as where injection and production wells should be placed, and how deep they should penetrate. By using geologic interpretation and mapping, the location and extent of these reservoir sands can be determined.

Oil-Water Contact

The oil-water contact structure map (Fig. 40) shows a very similar pattern to that of the unconformity structure map (Fig. 8). The oil-water contact represented in Figure 40 is the basal oil-water contact present within the McMurray Formation; below all McMurray bitumen occurrences, which, in many cases, is coincident with the unconformity. The values obtained were calculated by subtracting the depth to the oil-water contact from the KB (Kelly Bushing) elevation above sea level, giving values in metres above sea level for the structure of the oil-water contact.

The oil-water contact slopes to the northwest and southeast, as well as the northeast, from a high in the southwestern portion of the map area (Fig. 40). There is a prominent low in the eastern portion of the map area, which corresponds to a prominent low on the unconformity surface. In the north, the pattern of lows in the oil-water contact structure map (Fig. 40) is very similar to that in the unconformity surface structure map (Fig. 8). The contours in Figure 40 do not extend into the extreme south of the map area, due to poor logs and the difficulty in determining where the oil-water contact is positioned.

The fact that the oil-water contact mimics the unconformity surface indicates that most of the oil was probably in place and immobile before collapse of the underlying Devonian evaporites, the major structural element in the study area.



Contour interval = 1 m
ND = No Data
■ = Logged core

Figure 38. Net gas thickness in McMurray Formation.

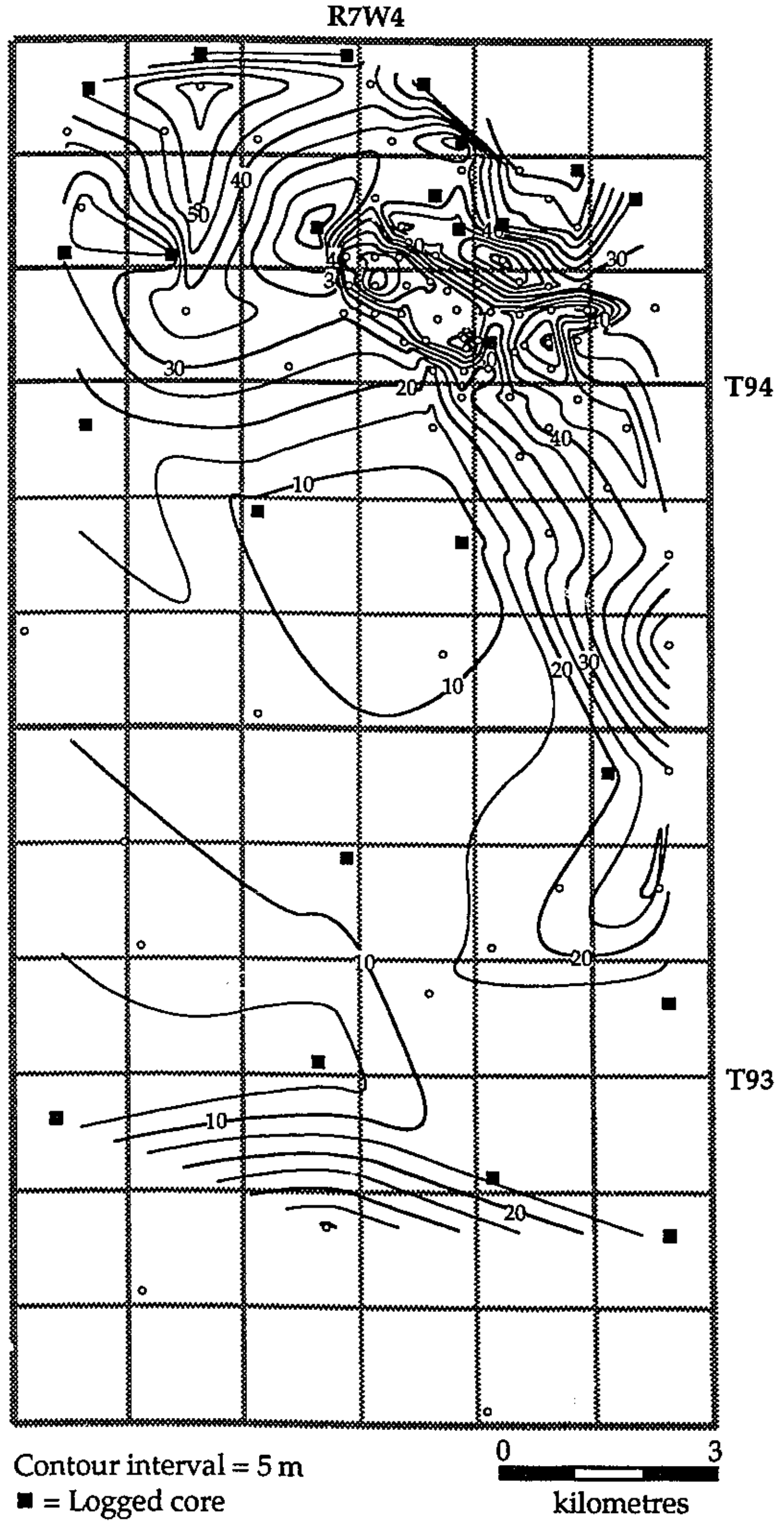


Figure 39. Net pay in the McMurray Formation.

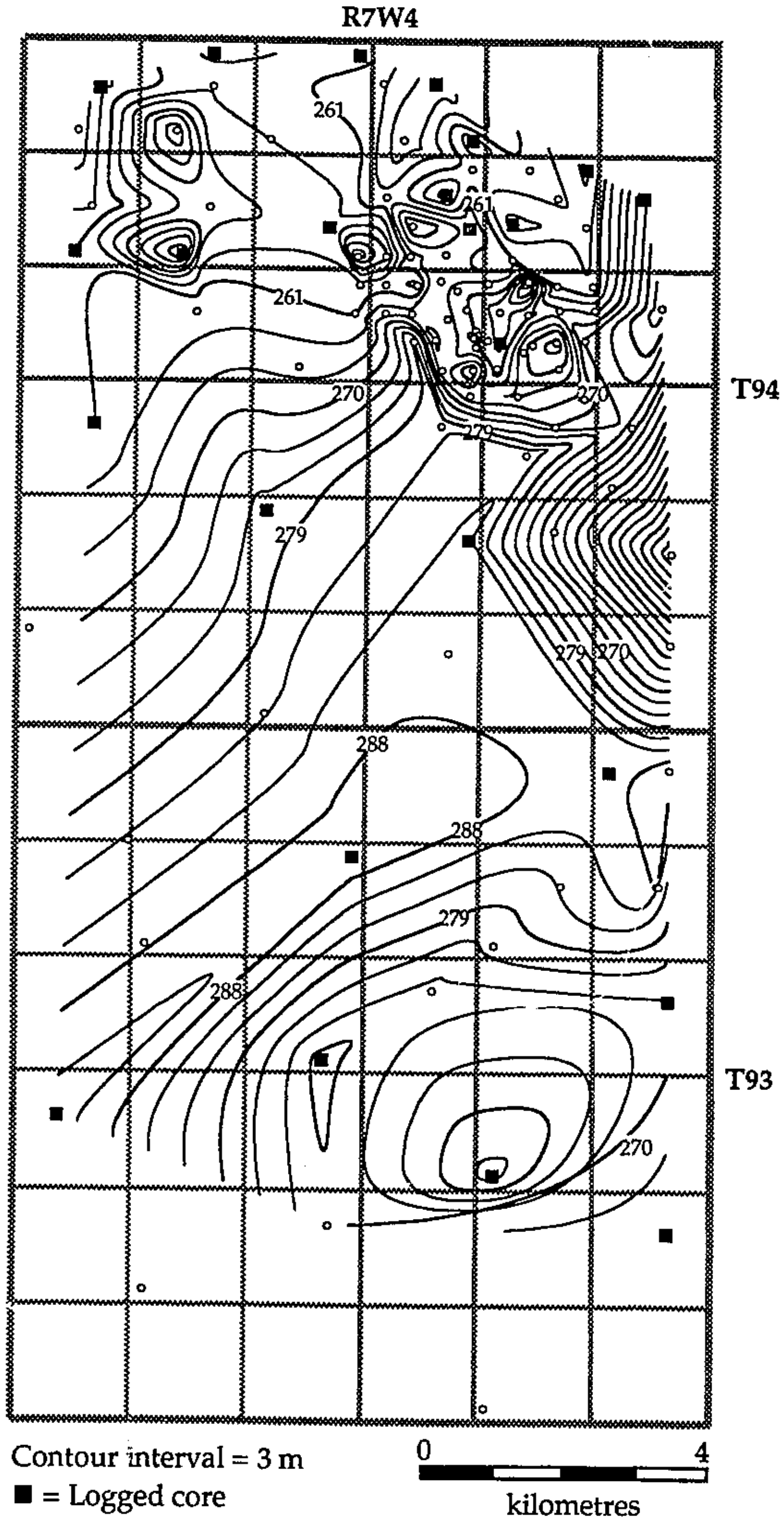


Figure 40. Structure map of the oil-water contact, McMurray Formation.

CHAPTER 5 - SUMMARY AND CONCLUSIONS

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 McMurray Formation was deposited in a north-northwest trending trough, as well as tributaries and valleys off this trough, bounded by the Canadian Shield to the east and a ridge of carbonates to the west, the "Wainwright Ridge". The main control on deposition was the structure of the sub-Cretaceous unconformity. The McMurray Formation tends to fill the valleys on the unconformity surface and thin over the hills and ridges. The lower member of the McMurray Formation was deposited in the lowest valleys on the unconformity surface. It was deposited in a fluvial channel complex bounded by hills of Devonian carbonates. The successions of the lower McMurray consist of fining upward successions representing the lateral migration and accretion of the channel. The sediments consist of channel, bank, and flood basin deposits. The channel deposits indicate channel floor, point bar, and channel abandonment deposition. The bank (or levee) deposits were formed when channel waters breached the banks and flooded the interchannel areas. The flood basin sediments were subaerially exposed and subjected to soil forming processes and vegetation. Coals and organic mudstones cap the lower member of the McMurray Formation due to the establishment of plant growth.

During the Lower Cretaceous, the Boreal Sea transgressed southward due to a global sea level rise, as well as the subsidence of the Alberta Basin caused by crustal loading as a result of the Columbian Orogeny, and collapse of the McMurray basin due to salt solution. The incursions of the Boreal Sea flooded the valley systems of the lower McMurray, developing the estuaries of the middle McMurray. Evidence for estuarine deposition includes the cyclic alternation between sand and mud, indicating a cyclic fluctuation in current strengths and energies, associated with tidal influence. The abundance of mud in the middle McMurray indicates the mixing of marine and fresh water, which enhances mud deposition due to flocculation caused by the salt wedge and turbidity maximum. The sandy sediments of the middle McMurray were deposited within estuarine channels, mainly on the channel floor and lower point bars. The inclined heterolithic stratification (IHS) present within the middle McMurray is due to tidally influenced point bar deposition. The muddy sediments of the middle McMurray represent channel abandonment. Estuarine channel meanders were cut off and gradually filled with fine sediment. The middle McMurray is basically a fining upward succession representing the lateral migration of sinuous estuarine channels.

With continued sea level rise, the estuaries retreated and the area was flooded. The middle McMurray sediments are overlain by nearshore marine, inlet shoal deposits, as well as some onshore deposits representing off-channel deposition related to the last estuarine channels. Shallow lakes formed in topographic lows adjacent to estuarine channels. Into these, progradational crevasse splay deposits were laid down. These were eventually vegetated and organic mud was deposited. Marine incursions are evidenced by silt and sand laminae within the organic mud. The nearshore marine bars are coarsening upward successions and represent the migration of higher energy bar deposits over lower energy interbar trough deposits. The abundance of mud indicates a high suspended sediment concentration and deposition close to shore, probably in proximity to an estuary mouth. The highest energy bar crest deposits were truncated by the full transgression of the Boreal Sea. At the end of McMurray time, the entire area was inundated and the shales and marine sands of the Wabiskaw Member of the Clearwater Formation were deposited.

The similarity of sediments from the lower and middle members of the McMurray Formation would make it difficult to determine which is fluvial and which is estuarine. However, by using the trace fossils present, it could be determined that the middle McMurray sediments were deposited in a brackish water environment, whereas the lower McMurray was deposited in a freshwater environment. Brackish water environments produce a trace fossil assemblage with distinct characteristics: 1) trace fossils are typically smaller than the fully marine counterparts, because of stressed conditions; 2) trace fossils are restricted to morphologically simple forms; 3) low diversity, including local monospecific assemblages; 4) high abundances; and 5) a combination of traces from both the *Skolithos* and *Cruziana* ichnofacies. The study of the traces within the McMurray Formation in the present study area was very important in the determination of the depositional environments.

The facies that contain the most bitumen are generally clean and porous sands, and are those deposited within channels where finer material was winnowed out by the currents. The beds containing bitumen may be separated by beds of shale and silty sand, creating problems for recovery. Water sands overlie bitumen saturated sands and may represent a gas leg where gas has leaked through the imperfect seal and been replaced by meteoric and formation waters. Gas may still be present overlying the water, indicating that not all of the gas has leaked off. Bitumen tends to be found below the water because it is very viscous and cannot readily migrate. Knowledge of the location of water zones is important for recovery and production of bitumen as the water zones can act as heat sinks, or "heat thief" zones, during steam production processes. The oil-water contact mimics the sub-Cretaceous unconformity surface, indicating that most of the oil was in place and immobile before collapse of the underlying Devonian carbonates.

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