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THE UNIVERSITY OF ALBERTA

A LITHOFACIES ANALYSIS OF THE MCMURRAY FORMATION, LOWER STEEPBANK RIVER, ALBERTA

by

© PETER FLACH

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "A Lithofacies Analysis of the McMurray Formation, Lower Steepbank River, Alberta" submitted by Peter Flach, B. Sc., in partial fulfillment of the requirements for the degree of Master of Science.

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Abstract

The lower Steepbank River is located in the surface-mineable area of the Athabasca oil sands. The whole of the McMurray Formation, which averages 50 metres in thickness, is well exposed in cutbanks of the 60 metre deep river valley. The study area covers twelve outcrops within a distance of 5.5 km.

A facies analysis of this small outcrop area in the Athabasca oil sands reveals five units in the McMurray Formation. The Lower Member, of coarse sandstone or conglomerate, is confined to local erosional lows and solution collapse depressions on the Devonian limestone surface. This is overlain by fine grained, trough cross-bedded fluvial sands of the Middle A Member with only isolated wedges of laminated overbank deposits preserved.

The Middle B Member makes up the bulk of the total thickness of the formation and consists of decimetre to metre bedded sands separated by thin partings of silt and clay. Tubular clay-walled burrows up to 5 mm in diameter and asymmetrical ripple marks are the most common structures. Bedding in this member has depositional slopes of 10 to 15 degrees, resembling very large scale cross-bedding. These beds, called delta foresets by Carrigy (1971) are interpreted to be epsilon cross-bedding, formed by lateral accretion on point bars of large (20 metre deep) migrating channels.

The Upper A Member is composed of horizontally bedded fine sand and silt, generally laminated to bioturbated. Locally present are lenses of coal and a smaller scale version of epsilon cross-bedding

(2 metres thick). A tidal flat environment is indicated. The Upper B Member is composed of dark grey bioturbated silty sand. The base is erosional and palynological evidence indicates a marine environment. This member is believed to represent the first truly marine sediments of the Clearwater transgression. Above the McMurray Formation lie the glauconitic, silty sands of the Wabiscaw Member, Clearwater Formation.

Acknowledgements

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CHAPTER 1

INTRODUCTION

Purpose

The McMurray Formation of the Athabasca area displays a wide range of lithologies and a complex arrangement of lithofacies. Clark and Blair (1927, p.72) found that "there is no system to the succession of rich and lean bituminous sand beds in sections through the sand formation. The formation is composed of a haphazard assortment of lenses of variable material." Ansley and Bierlmeier (1963, p.55), in a study of bedding continuity within the formation, found "that there is an extreme variation laterally, and difficulty is experienced in tracing thin beds even at 200 foot centers." This emphasizes the difficulties in correlation and facies analysis by subsurface data where only one-dimensional (vertical) control is available. The present study is based on closely spaced large outcrops, permitting both vertical and lateral control of facies changes.

The purpose of this study is to gain an understanding of the facies patterns in the McMurray Formation by making a detailed facies analysis of a small outcrop area in the Athabasca oil sands. With an understanding of the facies patterns in the outcrop area, an interpretation of depositional environments can be made. Models for the geometry and depositional environments of the facies within the McMurray Formation may aid in oil sand mining and <u>in situ</u> recovery by allowing prediction away from outcrops and drill holes of facies-dependant variables such as oil saturation and permeability.

Location and Access

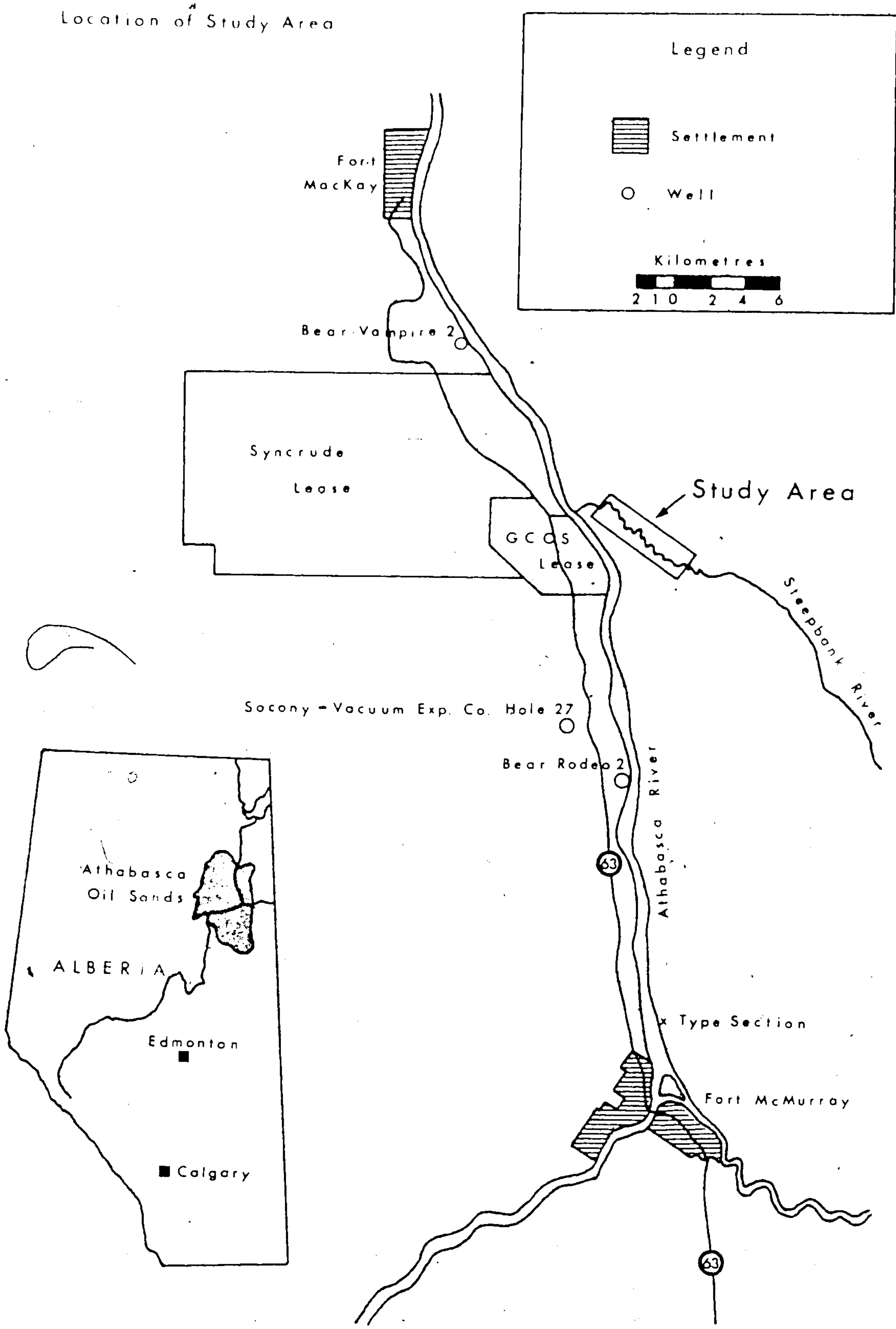
The study area is the valley of the lower Steepbank River, Twp. 92 Rge. 9 W4M, in the plains of northeast Alberta (Fig. 1). The Steepbank River enters the east side of the Athabasca River 35 km north of Fort McMurray, directly across from the Great Canadian Oil Sands plant.

The Steepbank River has eroded a valley 60 metres deep into the plains, producing many good exposures at its cutbanks. The portion of the river valley studied is 5.5 km long (straight line distance) and consists of outcrops 1 through 12 as shown on Figure 2. Some of the outcrops are very large - up to 300 metres in length along the river. Most outcrops expose complete or nearly complete sections of the McMurray Formation. Because of its excellent exposure, the Steepbank River valley was chosen for this study.

Access to the study area is possible by helicopter, as many landing sites are available in the Steepbank River valley. Access is also possible by boat across the Athabasca River from the Great Canadian Oil Sands plant, followed by a walk o[illegible].5 [illegible] to the Steepbank River by way of the cleared trail to the abandoned Petrofina airstrip (Fig. 2). When river level is high, the lower reaches of the Steepbank are navigable by small boats.

Because of the relatively small study area, a permanent camp was set up near the middle of the study area and access to the outcrops each day was by foot.

Figure 1.
Location of Study Area



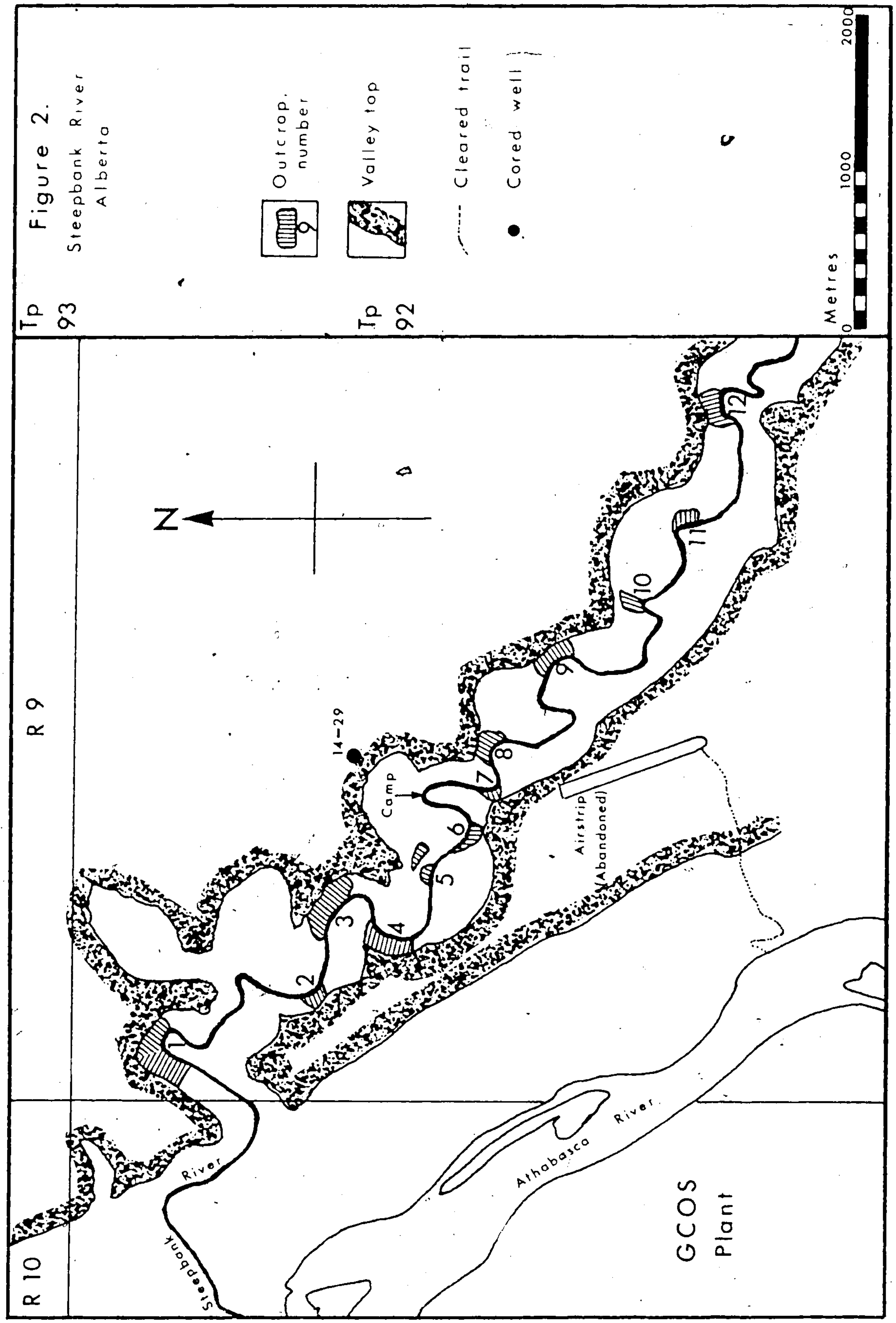


Figure 2. Steepbank River Alberta

Stratigraphic Setting

The formations outcropping in the study area are the McMurray and Clearwater Formations of the Lower Cretaceous Mannville Group lying unconformably on the Moberly Member of the Upper Devonian Waterways Formation (Fig. 3).

The Devonian limestone crops out in the downstream portion of the area but farther upstream it is below river level. The Clearwater Formation, represented by the glauconitic sand of the Wabiscaw Member, is very recessive and only the basal one or two metres is commonly well exposed. Lying between the limestone and the glauconitic sand, the McMurray Formation oil sands form the bulk of the sections.

The Prairie Evaporite Formation in the Steepbank River area lies at about 180 metres below river level. This estimate is based on extrapolation from the Bear Rodeo No. 2 and Bear Vampire No. 2 Wells (Fig. 1).

PERIOD		FORMATIONS ATHABASCA AREA		LITHOLOGY
Quaternary				Gravel and Sand
Lower Cretaceous	Mannville Group – Upper	Clearwater Formation		Shale and Sandstone
			Wabiscaw Member	Glauconitic Sandstone
	Mannville Group – Lower	McMurray Formation		Oil-impregnated quartzose sands
Devonian	Upper	Waterways Formation (Beaverhill Lake Fm)	Moberly Member	Shale and shaly limestone alternating with limestone
			Christina Member	
			Calmut Member	
			Firebag Member	
		Slave Point Formation		Limestone and dolomite
	Middle – Upper Elk Point Subgp.	Prairie Evaporite Formation		Halite, anhydrite, gypsum and dolomite
		Methy Formation		Reefal dolomite

FIGURE 3. Stratigraphic setting in the Athabasca oil sands area (from Carrigy, 1959a, 1973a and Norris, 1973)

Previous Work

Early descriptions of the Athabasca oil sands were given by Bell (1884) and McConnel (1893) who undertook reconnaissance mapping expeditions for the Geological Survey of Canada. McLearn (1917) named and defined the McMurray Formation. S.C. Ells of the Mines Branch studied the extent of the oil sands and the possibilities for commercial development (Ells, 1926).

Extensive drilling was carried out by the Federal Government from 1942 to 1947 for evaluation of oil sand deposits. Much of this drilling was in the Steepbank area, which was considered a potential site for a mining operation (Government of Canada, 1949). Hume (1947) made geological interpretations from the results of this drilling.

The most comprehensive report on the geology of the McMurray area is by Carrigy (1959a) who designated two type sections for the McMurray Formation, one outcrop and one subsurface. Carrigy has also done detailed work on the McMurray Formation including studies on grain size (Carrigy 1959b, 1966), the relationship of clay content to oil saturation (1962), the petrology of the Lower Member (1963a), differentiating the McMurray and Clearwater Formations (1963b), paleocurrent analysis (1963c), sedimentary structures (1967), and environmental interpretations (1971).

Detailed heavy mineral analysis of the McMurray Formation has been carried out by Mellon (1955, 1956). The heavy minerals have also been studied by Carrigy (1963a, 1963b, 1966).

The micropaleontology of the McMurray and Clearwater Formations has been studied by Mellon and Wall (1956) and the palynology by Singh (1964) and Vagvolgyi and Hills (1969).

Methods of Investigation

Field Work

At least one section from each of the twelve outcrops, except outcrop 8, was measured with a Jacob's staff and described in detail. Characteristics described include lithology and texture, scale of bedding, sedimentary structures and trace fossils, weathering characteristics, and oil saturation. Paleocurrent measurements were made with a brunton compass. Lithologic samples were taken at changes in lithology and generally at least every 6 metres of vertical section. Where sand beds were separated by thin partings of silt and shale, samples were taken of oil sand only.

Laboratory Analysis

Samples chosen for analysis were largely from two sections which have good exposure from at or near the base of the McMurray Formation to the Clearwater Formation. In addition, a number of samples were chosen from other sections for more complete lithologic coverage. Laboratory analysis of the field samples was carried out in the following steps:

1. The oil content of 49 samples was determined by soxhlet extraction. The samples were weighed before and after removal of the oil, and the weight percentage of oil was determined by difference.
2. Heavy mineral separation was accomplished by the use of the heavy liquid tetrabromoethane (specific gravity 2.965). The heavy minerals were slide mounted in Aroclor (refractive index 1.66) for petrographic analysis.

3. Grain size analyses were performed using seives at 1/2 Ø intervals, pipetting the clay and silt fraction.
4. Clay smears for x-ray diffraction analysis were prepared by pipetting the -2 micron fraction, allowing the water to evaporate until the clay was semi-solid; and smearing the clay on a glass slide.

Geological History

In the Athabasca oil sands area, subaerial erosion during the Pennsylvanian, Permian, Triassic and Jurassic Periods produced an irregular topography of Devonian limestone (Martin and Jamin 1963). Solution of the underlying Prairie Evaporite Formation (salt and anhydrite) caused collapse structures to form in the Waterways Formation. The result is a series of 'waves' in the Devonian surface with amplitudes of 15 to 30 metres and wavelengths of 0.1 to 1.5 kilometres (Carrigy, 1959a).

During pre-Cretaceous time, the Devonian strata were tilted to the west, producing dips of about 2.8 metres per kilometre (Martin and Jamin, 1963). The erosion surface thus truncates progressively younger Devonian rocks to the west.

The history of the McMurray and Clearwater Formations is one of a marine transgression. As the Cordilleran orogeny occurred in the west and the Coast Range mountains rose, the MacKenzie River Valley and northern Alberta areas sank, allowing the boreal sea to penetrate southward (Stelck, 1967). As base level rose, the rivers from the east dropped their loads in the lows on the Devonian erosion surface, such that the thickness of the McMurray Formation is inversely related to the elevation of the Devonian surface (Hume, 1949). With a continued rise in sea level, the Athabasca area became an epicontinental sea.

Post-Cretaceous tilting has resulted in an additional 1 to 1.3 metres per kilometre dip to the west (Martin and Jamin, 1963). Saline springs in the oil sands area and the presence of post-Cretaceous collapse, as indicated by the Bitumount basin, suggests that solution of the Prairie Evaporites is still occurring at present (Carrigy, 1959a).

CHAPTER 2

STRATIGRAPHY AND SEDIMENTOLOGY

Waterways Formation

The outcropping Devonian rock in the study area is the Moberly Member of the Waterways Formation. It is a buff to greenish yellow rubbly limestone with occasional resistant beds up to 3 metres thick. The resistant beds are often fossiliferous, containing abundant stromatoporoids, brachiopods, and bryozoa. The fossils in this member have been recorded by Norris (1963).

There are two forms of relief on the Devonian surface, one structural and one erosional. On the large scale, a gently undulating relief results from the solution of the underlying Elk Point evaporites. Bedding is seen to dip at low angles, indicating structural deformation (Fig. 4). On a more local scale, relief of more than 20 metres can occur within a horizontal distance of 50 metres. This rugged, often steep-walled relief results from erosion of the limestone in pre-Cretaceous time. Sinks in the limestone and evidence of collapse (see Lower Member, McMurray Formation) suggests that the Devonian surface had karst features.

The elevation of exposed limestone varies from about 277 metres above sea level on outcrop 3 to approximately 258 metres on outcrop 4 where it disappears below river level. It is present in most of the downstream outcrops and absent in those farthest upstream. The last exposure upstream occurs between outcrops 8 and 9.

Figure 4. Deformation 'waves' in limestone, outcrop 3 (left foreground). Solution of the underlying Elk Point evaporites has resulted in collapse of the Devonian limestone. The overlying McMurray Formation does not usually show any sign of deformation.

Large-scale collapse of limestone in post-McMurray time is indicated by formation heights on outcrop 11 and drill hole data (see Chapter 3, outcrop 11).

Generally, the Devonian/Cretaceous unconformity is a sharp contact between limestone and oil sand, but a well developed red paleosol is present on the limestone at outcrop 1. Red clay soil, composed of the oxidized insoluble impurities contained in the limestone, is a common feature of modern limestone landscapes.

McMurray Formation

McLearn (1917) defined the McMurray Formation as the freshwater sandstone underlying the widespread green sand of the basal Clearwater Formation. In the present study, the first presence of glauconite over trace amounts is taken as the base of the Clearwater Formation (Wabiscaw Member), though it is now known that the Upper McMurray carries a marine fauna (Mellon, 1955; Singh, 1964; Vagvolgyi and Hills, 1969). The Upper McMurray and Clearwater Formations have been dated on the basis of this microfauna as Middle Albian. Dating the lower parts of the formation has proven difficult due to the poor microfaunal content, but the whole of the McMurray Formation is probably Middle Albian (Vagvolgyi and Hills, 1969).

The type section for the McMurray Formation as designated by Carrigy (1959) is 5 km north of Fort McMurray on the east side of the river (Sec. 5, Twp. 90, Rge. 9 W4 Mer.). A supplementary subsurface type section, Socony-Vacuum Exploration Company Hole No. 27 (Sec [illegible] 91, Rge. 10, W4 Mer.) was also named by Carrigy ([illegible] Fig. 1).

The thesis covers a short stretch of outcrops which, at least superficially, resemble the type section of the McMurray Formation. Carrigy (1959a) divided the formation into three members - a Lower Member of conglomerates and a coarse-grained sand, a Middle Member of very fine to fine sands, and an Upper Member of horizontally bedded sands and silts. He also recognized within the Middle Member two different units - medium-grained sand thought to be of point bar origin, and fine-grained sand in beds with depositional dip (Carrigy, 1966, Table 5).

In the present report, Carrigy's Middle Member is divided into two units. Carrigy's 'medium sand' becomes the Middle A Member and the 'fine sand' is called the Middle B Member. The Upper Member is also divided into two units, an Upper A Member of horizontally bedded sandstones and siltstones, and an Upper B Member which is a characteristic marker bed of dark, structureless, very argillaceous oil sand.

The pre-McMurray detrital beds (Carrigy, 1966) are not exposed along the Steepbank River.

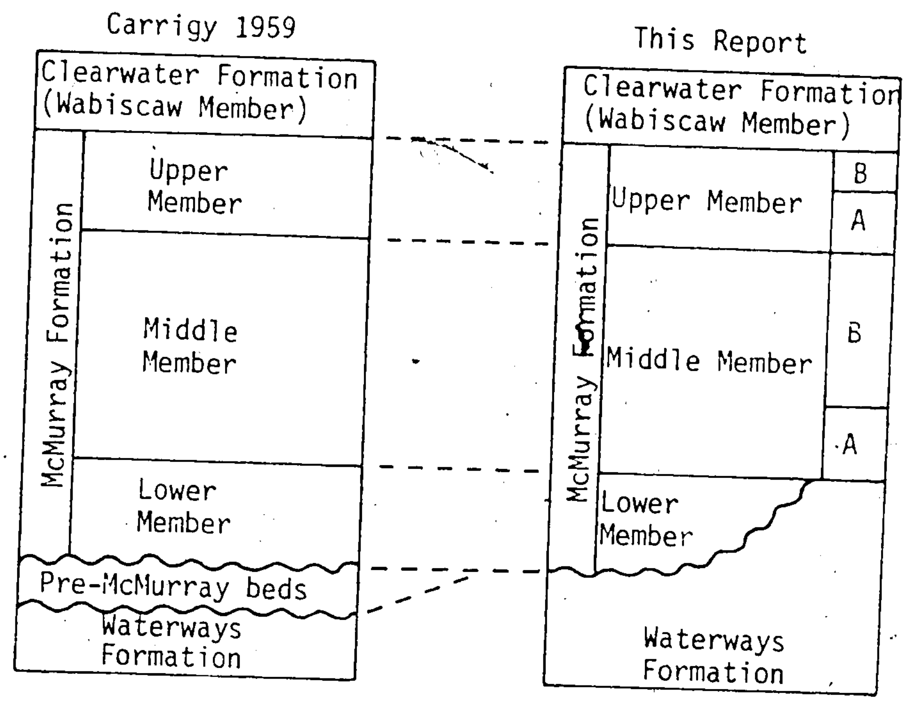


Figure 5. Local stratigraphy of the Athabasca oil sands outcrop area (Carrigy, 1959a) and the Steepbank River valley. In this report, the Middle and Upper Members have each been subdivided into two units. For simplicity in the text, these are referred to as the Middle A Member, Middle B Member, Upper A Member and Upper B Member.

1. Lower Member

General Lithology

The Lower Member of the McMurray Formation is generally composed of conglomerates and sandstones overlying the Devonian limestone, filling in depressions on the pre-Cretaceous erosion surface (Figs. 6, 7). This member is characteristically white to light grey in color compared to the black, fine-grained sands of the overlying Middle A Member. Bedding varies from well developed, with large scale planar cross-bedding, to virtually massive, with no apparent sedimentary structures.

Besides the typical light grey coarse sandstone and conglomerate there are a variety of other lithologies. Lenses of red-brown conglomerate are found interbedded with grey to brown sandstones . In places, red-brown conglomerate is composed almost entirely of disc-shaped clay ironstone concretions 2 to 10 cm in diameter. Elsewhere, grey shale overlies grey coarse sandstone and conglomerate which, in places, contains large white clay clasts.

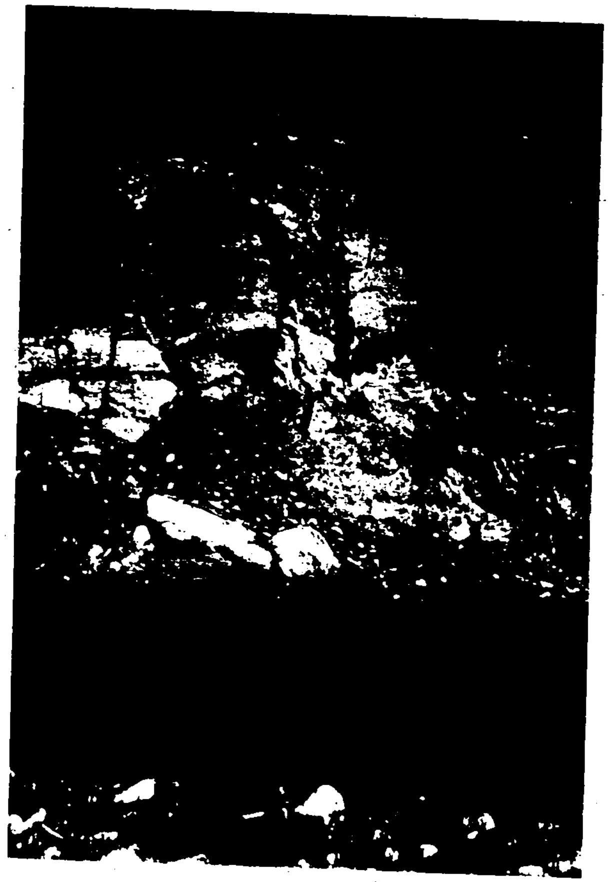
Sedimentary Structures

Large scale (decimetre to metre thick sets) planar cross-bedding is common in this member, the foresets of which are often composed of laminae of varying grain size.

Within the coarse sand in one location (outcrop 4) are 'pipes' which have apparently collapsed downward and been filled by the overlying shale (Fig. 8), indicating up to 2 metres of vertical movement. The bedding also shows 'waves' of 15 to 20 metres

Figure 6. Base of Lower Member, outcrop 1. At the top of the hammer is the base of the coarse-grained Lower Member sands of the McMurray Formation, overlying red paleosol of the Devonian limestone.

Figure 7. Lower Member in lows on the Devonian surface. In the left foreground is the Lower Member at the downstream end of outcrop 4. Two hundred metres farther, the limestone at the base of outcrop 3 (light area, right of centre) outcrops to a height of 25 metres above river level.



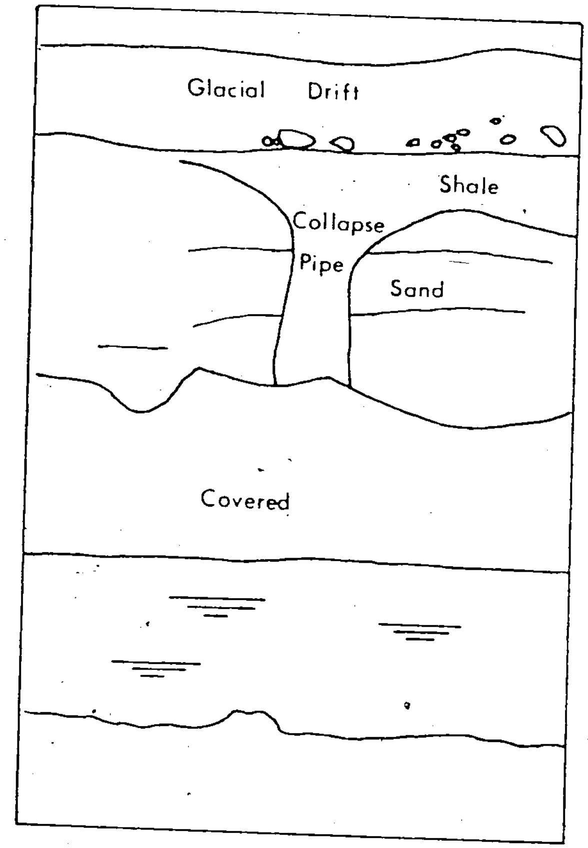


Figure 8. Collapse pipe in Lower Member, outcrop 4. Shale has slumped into a vertical-walled collapse structure in the underlying coarse sands. The collapse was probably a result of local solution of limestone by underground drainage.

wavelength and up to 2 metres amplitude. This structure is probably too small to have been caused by solution of the evaporites 160 metres below. Limestone outcrops nearby indicate the unconformity is close to the surface. These structures are interpreted to have been caused by the solution and collapse of the underlying limestone.

In another location (outcrop 8), a 20 metre wide 'hole' in the limestone is filled with sands of the Lower Member (Fig. 9). The inclined sides of the depression show a drop in elevation of 7 metres within a distance of a few metres. This steep-sided depression may have been a sink hole in the karst landscape of the pre-Cretaceous surface.

Texture

The Lower Member is characterized by its coarse grain size, poor sorting, and high clay content (Fig. 10).

The grain size of this member is the most varied of any member, ranging from conglomerate, containing pebbles and boulders, to clay. Medium to coarse sand is the most common grain size, with 6 to 10% clay content.

Carrigy (1959b) divided the McMurray Formation sands into three classes on the basis of sieve analysis and outcrop examination. Class I (coarse-medium sand) is composed of the conglomerates and sands of the Lower Member and is defined as follows:

1. Maximum grain size greater than 1 mm.
2. Median diameter not less than 0.13 mm (3 Ø).
3. More than 80% of the sample by weight coarser than 0.074 mm (3.75 Ø).

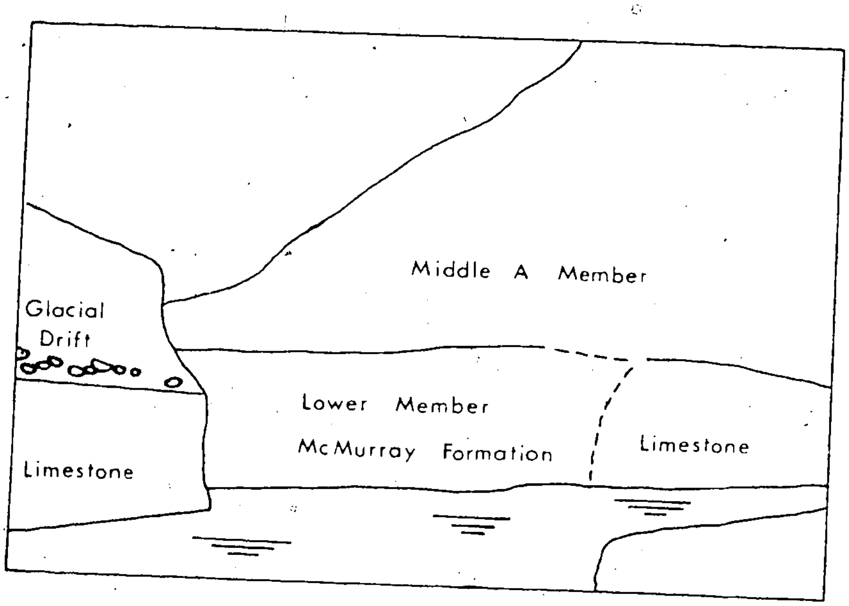
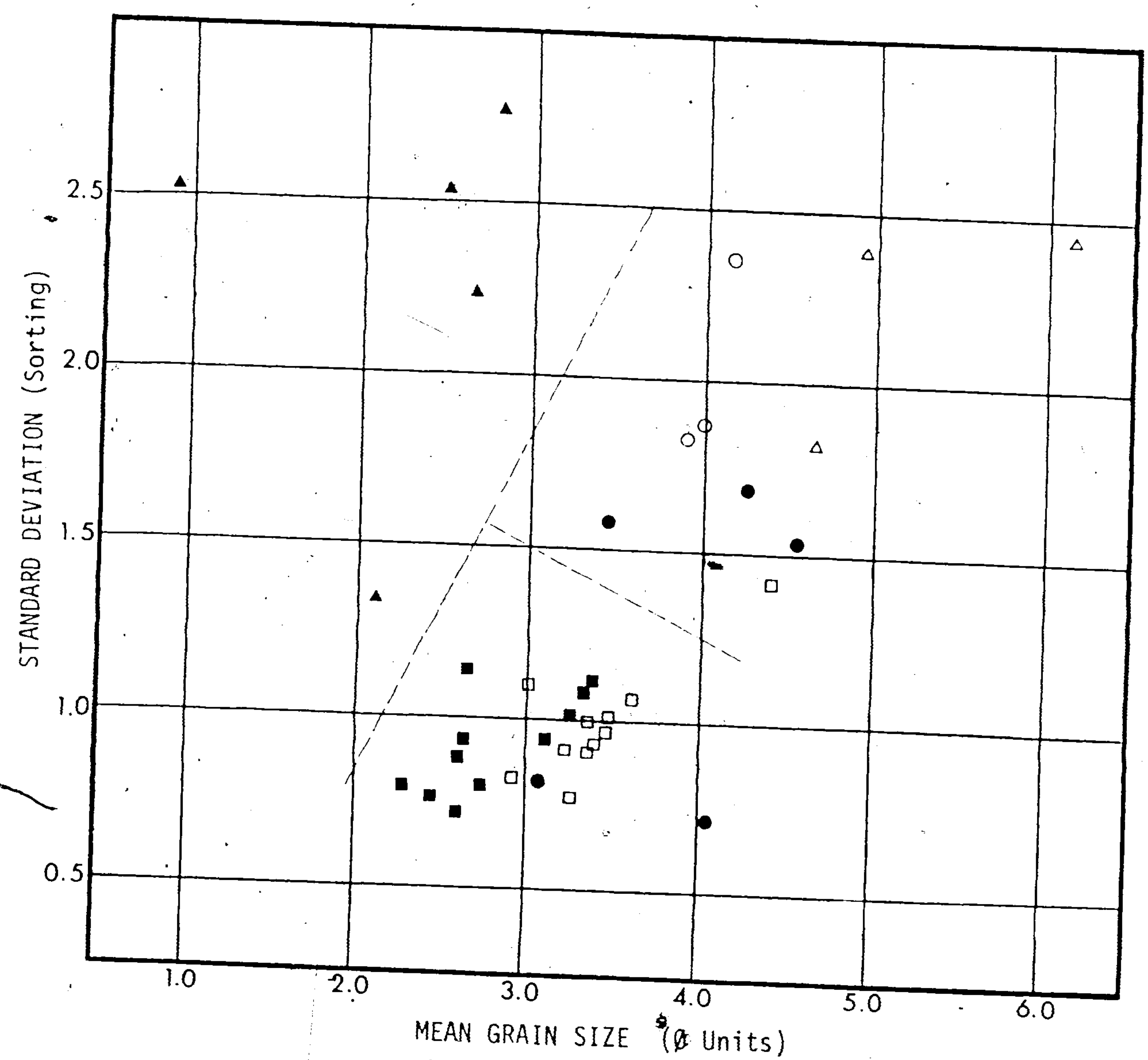


Figure 9. Lower Member sands filling a sink in the limestone surface, outcrop 8.

FIGURE 10.

Mean Grain Size
Vs
Sorting

for selected samples of the McMurray and Clearwater Formations



Legend

- ▲ Lower Member, McM Fm
- ■ Middle A Member, McM Fm
- □ Middle B Member, McM Fm
- ● Upper A Member, McM Fm
- ○ Upper B Member, McM Fm
- △ Clearwater Formation

The five samples analyzed from the Lower Member for this report fall within these limits.

2. Middle A Member

General Lithology

Overlying the Lower Member of the McMurray Formation is the Middle A Member, a generally thick bedded (0.5 to 1.5 metre), fine grained oil sand with no shale partings between the beds. The bedding is basically horizontal and can be obscure in fresh, oil rich sections. The Lower part of this member almost always has high oil saturation, often appearing black and massive. Higher in the member, oil saturation often drops, resulting in light grey oil sand with more prominent sedimentary structures.

In one location (outcrop 7), a wedge of shaly siltstone is present beneath and adjacent to the massive sands of the Middle A Member. This fine grained unit is composed of laminated sand, silt, and clay with no sign of burrows. It has apparently been channeled into by the overlying oil sands.

Sedimentary Structures

A characteristic feature of the Middle A Member is the presence of large scale trough cross-bedding (Fig. 11). Using the terminology of Allen (1963), 'large scale' cross-stratified units are those which are more than 5 cm thick. The trough sets are usually 30 cm to 1 metre thick, but can be up to 2 metres thick and 6 metres across in a section normal to flow. Sets of cross-strata often have shale rip-up clasts along the base. Because very high oil saturations are common in this member, the structure is often obscure.

The trough cross-bedding predominates in the lower part of the member, with ripple bedding common near the top, in the poorly saturated sands.

Figure 11. Large scale trough cross-bedding, Middle A Member, outcrop 5.

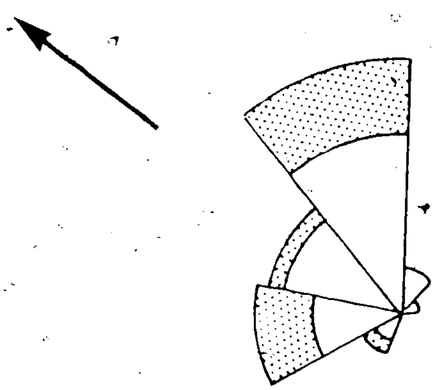


Figure 12. Paleocurrent rose diagram for Middle A Member (blank) and Middle B Member (stippled). Mean = 306°, s = 45°, 43 measurements.

Paleocurrent tion, as indicated by ss-bedding in this member and the Middle B Member, is calculate to e 306^{o} azimuth (Fig. 12) with a standard deviation of 45^{o}.

Texture

Though the sands of the Middle A Member tend to be somewhat coarser than those of the Middle B Member, overlap does occur and the two generally cannot be distinguished on the basis of texture. They both lie within Carrigy's Class II fine to very fine sands, with few exceptions. The definition of Class II sands is as follows:

1. Maximum size less than 0.3 mm (1.75 Ø).
2. Median size 0.18 to 0.09 mm (2.5 to 3.5 Ø).
3. More than 80% of the sample greater than 0.074 mm (3.75 Ø).

The Middle A and B Members are the best sorted sands in the formation and all lie within a relatively small range of values for both mean grain size and sorting (Fig. 10). Clay content is very low - 0.5% to 1.5% for the samples analyzed.

Medium to very coarse grained sands are locally present in this member, often associated with abundant carbonaceous material.

3. Middle B Member

General Lithology

This member comprises the bulk of the formation thickness in most outcrops. One to six decimetre thick oil sand beds are separated by thinner (0.5 to 10 cm) interbeds of grey shale or silt. This stratification is very well defined and dips at angles up to 12 degrees, resembling very large scale cross-bedding (Fig. 13). Bedding generally becomes thinner higher in the section. The top of the member is often reddish in color.

Especially in the zone of contact, sands of the Middle B Member are essentially indistinguishable from Middle A Member sands. The only truly diagnostic feature of the Middle B Member is the presence of the very large scale cross-beds.

Epsilon Cross-stratification

Perhaps the most conspicuous feature of the McMurray Formation as a whole is the inclined bedding of this member. These beds, called delta foresets by Carrigy (1971), meet the requirements of Allen's (1963) definition of epsilon cross-stratification, namely:

1. Almost invariably large in scale.
2. Underlain by a planar erosion surface.
3. Cross-strata in the set discordantly overlie the bounding surface.
4. Lithologically heterogeneous cross-strata.

The first criterion for epsilon cross-stratification is always met as 'sets' are generally 10 to 20 metres in thickness.

Figure 13. Outcrop 3. Limestone at the base of the outcrop is overlain by Middle A Member oil sand. The dipping beds in the centre of the outcrop are epsilon cross-strata, the point bar deposits of large meandering channels. At the top of the outcrop lie the horizontally bedded sands of the Upper A and B Members.

The second and third criteria are not apparent in all sections but, as figures 13 and 33 show, a planar basal erosion surface is present, with the epsilon cross-strata overlying horizontally bedded oil sand. The basal erosion surface is not marked by concentrations of coarse detritus, but this could be due to a lack of available sediment coarser than fine sand. For the discordant nature of the cross-strata to be apparent, the section face must be in a favourable position relative to the strike of the cross-strata, preferably at 90 degrees.

Wright (1959) predicted the possibility of such a structure and epsilon cross-stratification was first recognized and described by Allen (1965a). Since then, descriptions have been given by Moody-Stuart (1966), Beutner et al. (1967), Allen and Friend (1968), Steidtmann (1969), Allen (1970a), Cotter (1971), Land (1972), Elliot (1976), and Karl (1976). Allen (1965a) concluded that the structure is formed by lateral accretion on the inner bank, or point bar, of a channel meander bend. Erosion in the thalweg of the stream creates the erosion surface at the base of the epsilon set. Accretion occurs on the sloping surface of the point bar, each bed representing a time surface (Fig. 14). Heterogeneous beds are a result of variations in current velocity and discharge. All later authors have supported this interpretation to the extent that epsilon cross-stratification is now considered diagnostic of lateral accretion in meandering channels.

Where the true dip of epsilon cross-stratification can be determined, measurement of paleocurrent structures indicates

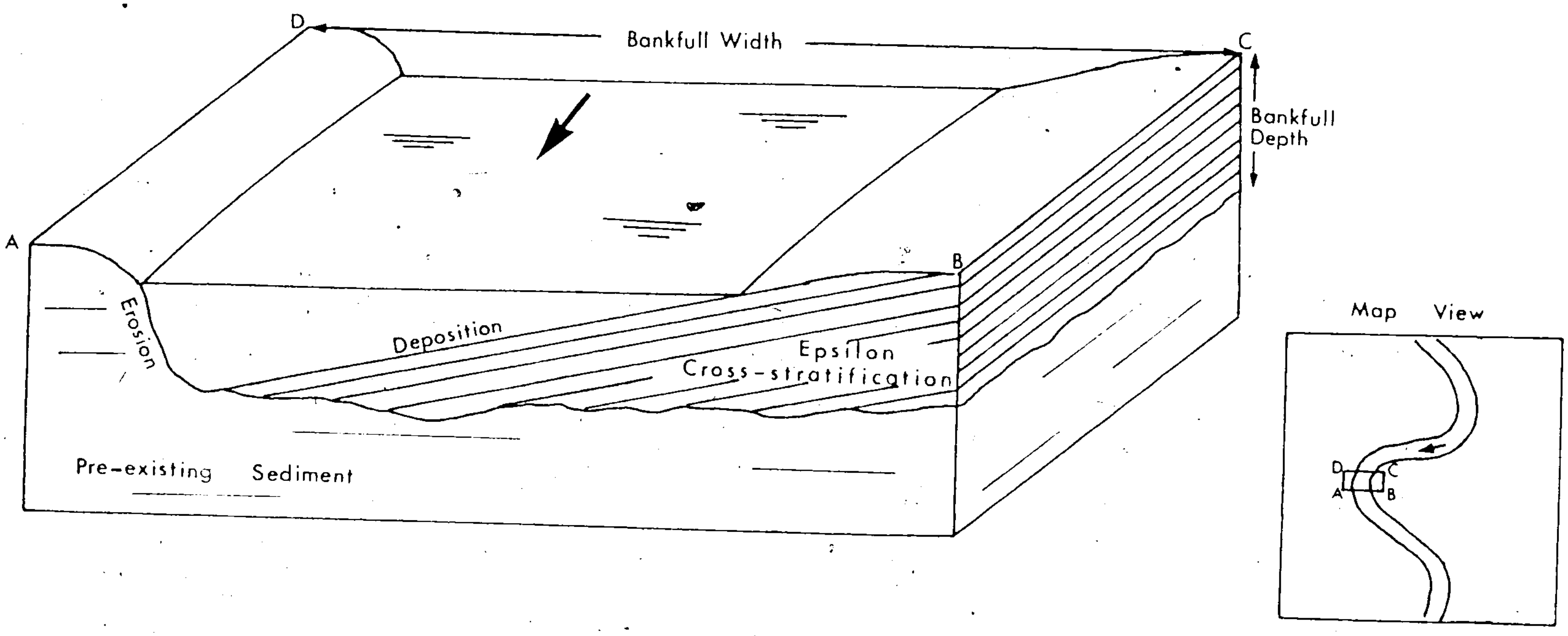


Figure 14. Origin of epsilon cross-stratification. Erosion occurs at the outer bank of a meander bend while accretion takes place on the sloping point bar surface.

flow which is approximately at right angles to the dip of the beds. Measurements were made on ripple marks on outcrop 3, where the true dip of the epsilon beds can be estimated to within 5 or 10 degrees as 35^{0} azimuth. True dip direction was determined for ten different ripple sets. The mean of these measurements is 303^{0} with standard deviation of 23^{0}. All ripple foresets dip in approximately the same direction. The section in which the ripples were measured is almost parallel to the strike of the epsilon cross-bedding such that the beds appear horizontal and ripples are seen in transverse section. Around the corner from this exposure, and at about 90 degrees to it, the apparent dip of bedding is approximately true dip. Here, smaller channel scours are seen in transverse section, indicating current flow normal to the dip of the epsilon cross-strata (Fig. 15).

The thicknesses of the epsilon sets in this area are the largest that have been described, most studies reporting thicknesses of from two to ten metres. If the thickness and width of epsilon cross-stratification sets are known, it is possible to estimate the size of the paleochannel (Moody-Stuart, 1966). The height of the epsilon cross-stratification set represents the depth of the channel at bankfull stage. The horizontal equivalent of the length of a single bed measured parallel to true dip from the top of the epsilon set to its base represents the width of the point bar. In Figure 16, 75 metres is the horizontal measurement of the point bar surface.

Allen (1966) estimated the size of lateral bars in low sinuosity streams to be two-thirds the channel width. This ratio

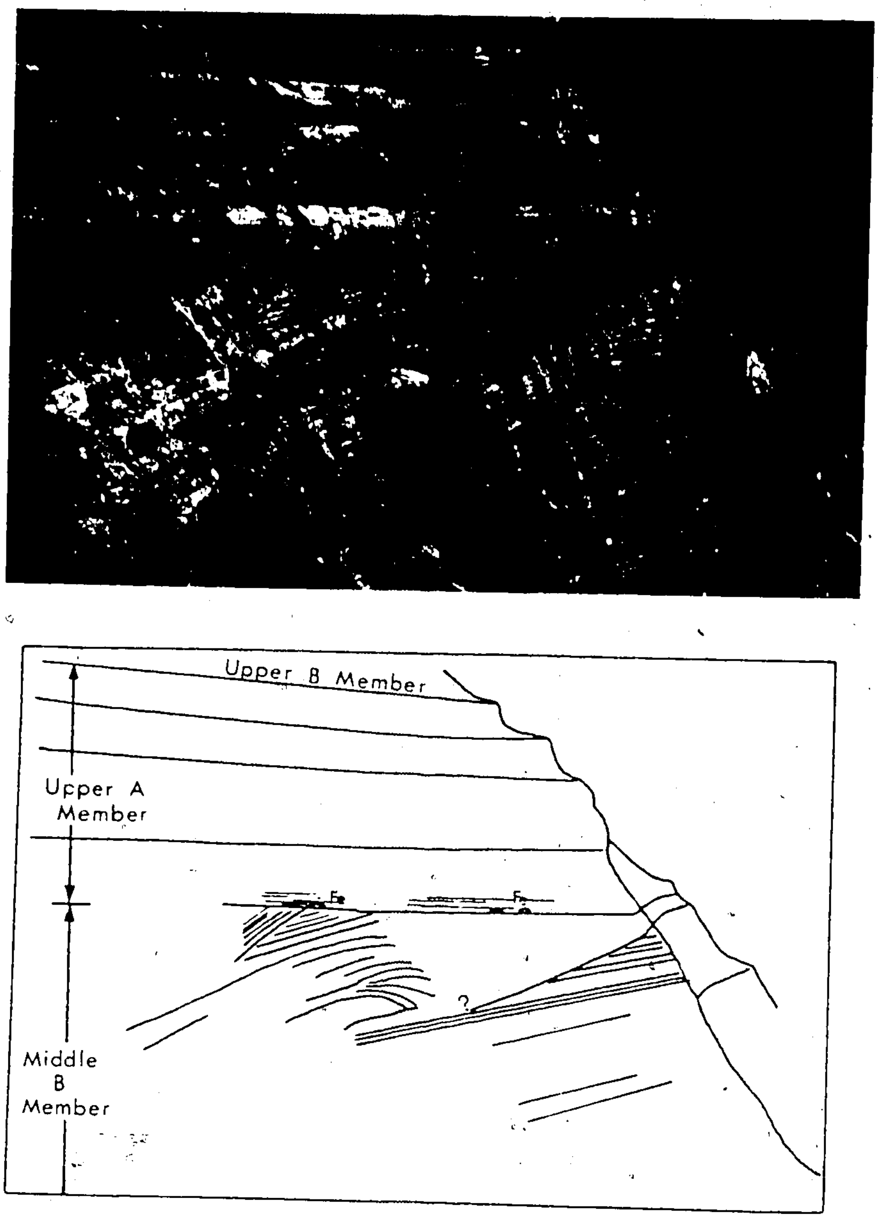


Figure 15. Epsilon cross-stratification, outcrop 3. Channeling is most extensive in longitudinal sections of epsilon bedding such as this. The base of the triangular covered area, right centre, is a sharp erosional surface. The base of another channel can be seen at left centre. A thin ironstone bed is present at the top of the epsilon cross-strata.

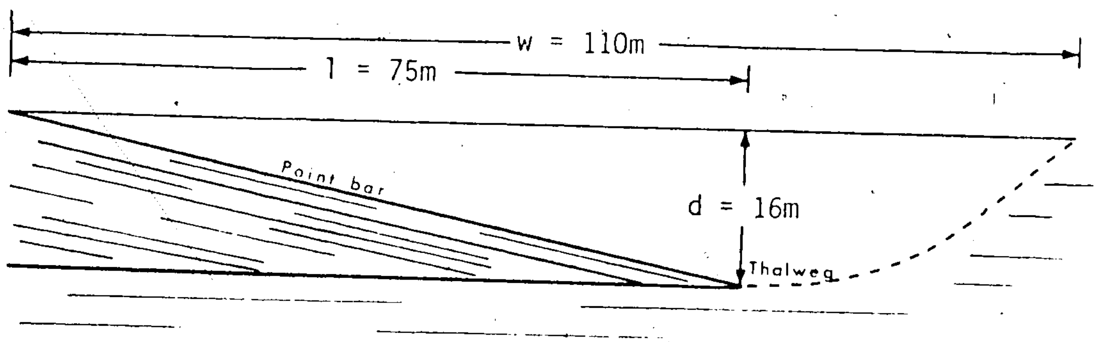


Figure 16. Paleochannel parameters, outcrop 3. Knowing the thickness (d) and dip of epsilon cross-stratification, the point bar width (l) and bankfull width (w) of the paleochannel can be estimated. See text for discussion.

was used by Moody-Stuart (1966) to represent the size of the point bar in a meandering stream. Cotter (1971) reviewed the studies of modern point bars and found the distance from inner bank to the thalweg of the channel to be about 0.6 to 0.8 the channel width. Cotter therefore also used the two-thirds relationship as an approximation.

Outcrop 3, as well as having excellent exposure, is the only outcrop where the true dip direction of the epsilon cross-beds can be estimated. Therefore, it is used as a model.

The thickness of the cross-strata set is 16 metres, which therefore approximates the depth of the paleochannel. The length of a single bed cannot be seen parallel to dip, but as the dip of bedding is approximately 12^{o}, the length of a bed, measured horizontally, is 16 m/Tan 12^{o} or about 75 metres (Fig. 16), representing the width of the point bar. If the relationship used by Moody-Stuart and Cotter holds for the channel represented here, it was on the order of 1.5 x 75 or 110 metres wide.

Leeder (1973) plotted bankfull depth against bankfull width for 57 modern meandering rivers of a wide range of sizes, and calculated the regression line and 95% confidence limits for the scatter of points. Bankfull depth and width were found to be not closely dependent variables with the result that scatter, and therefore standard deviations, are high. For a channel 16 metres deep, the width of the channel, with a 95% confidence level, is between 70 and 3400 metres. A stream 16 metres deep and 110 metres wide, as previously calculated, thus clearly falls within the realm of viability, although toward the lower limit of the width range.

The apparently low width/depth ratio of this paleochannel is a result of the relatively high dip of the point bar surface; that is, the epsilon cross-beds. Allen and Friend (1968, p. 54) found that "the surface dips of most modern point bars are generally so low that they would not be distinguishable as lateral deposits in ordinary exposures." In studying a number of modern point bars, Allen (1970) found dips of accretion slopes that were over 4^o for only two very small streams. This is apparently due to the fact that as a stream becomes larger, the dip of the accretion slope becomes smaller, just as channel width increases faster than channel depth. In the geologic record, epsilon cross-stratification is seemingly not common but, where present, dips are generally 4^o to 15^o (Allen, 1965; Moody-Stuart, 1966) and up to 20^o or 22^o (Beutner et al., 1967; Allen and Friend, 1968). In this study area, although dips of up to 25^o can be found in small channels within the main channel, the dip of epsilon cross beds is generally 10^o to 15^o. Leeder (1973) plotted point bar slope against size of channel for eleven reported examples of epsilon cross-bedding. He notes that dips of up to 12^o are still possible for rivers up to 20 metres in depth.

The channels of the Steepbank River area appear to have had a low width to depth ratio, as indicated by the high angle of dip of the epsilon cross-beds. The narrow channel may be partially a result of the nature of the bank material. Leopold et al. (1964) point out that channels with cohesive, silty banks are narrower than those with sand banks. Drilling in the Steepbank River area has shown that areas where silt and clay comprise most of the thickness of the McMurray Formation lie directly adjacent to the Steepbank River valley. This suggests that the channels of the Middle B Member were eroding into this fine-grained material, resulting in deep, narrow channels. Schumm (1968) states that the shape and sinuosity of channels is most dependent on the type of load being transported. Large suspended loads favour a deep, sinuous channel, while large bed loads create a shallow channel and a straight course. The width/depth ratio of this McMurray paleochannel is indicated to be less than 10, suggesting a largely suspended load and sinuous coarse. The normal load of the channel was probably largely silt and clay, while the sands were probably introduced as bed load during times of flood.

Other authors, notably Cotter (1971), have analyzed paleo-flow parameters such as channel sinuosity, meander length, and discharge on the basis of epsilon cross-bedding but the lack of more definite knowledge of channel width would make the validity of such numerical calculations questionable.

Other Sedimentary Structures

A ubiquitous structure in this member is small scale (1 to 3 cm) cross-laminations. These are asymmetrical ripple marks occurring within the sand beds of the unit, often comprising the complete bed. Due to the unconsolidated nature of the deposit, ripple marks can only be seen in cross-section, never on bedding planes. The three-dimensional shape, therefore, cannot be seen. Small-scale asymmetrical ripple marks indicate a current in the lower flow regime, just able to move grains along (Allen, 1965a). The sediment was apparently affected solely by a unidirectional paleocurrent with flow approximately parallel to the strike of the epsilon cross-strata.

Along with the ripple bedding is occasional medium scale cross-bedding 5 to 15 cm thick. Large scale trough cross-beds (30 to 60 cm thick) are present in some outcrops in the Middle B Member, but are not typical. They generally occur in zones of greater scour, in channels within a channel.

Biogenic Structures

This member is characterized by burrows 1 to 15 mm wide and usually 2 to 4 cm long. The burrows are cylindrical, unbranched, vertical to slightly inclined and have a lining of clay around the outside (Fig. 17). Some burrows flare towards the top. The clay walls, standing out as white to light grey against the dark matrix of oil sand, comprise up to one-half the diameter of the burrow. The burrows are concentrated in the silty/shaly beds and are generally more numerous higher in the section. Burrows are normally spaced a centimetre or more apart but sometimes can be so numerous as to result in complete bioturbation.

These burrows belong to the 'skolithus facies' of trace fossils (Seilacher, 1964) and represent dwelling burrows of an animal that could withstand rigorous living conditions. These conditions are indicated by the lack of other species of trace fossils, the lining of the burrow with a clay wall, and the association with ripple marks and erosion surfaces. Howard and Frey (1973), studying recent biogenic structures in Georgia

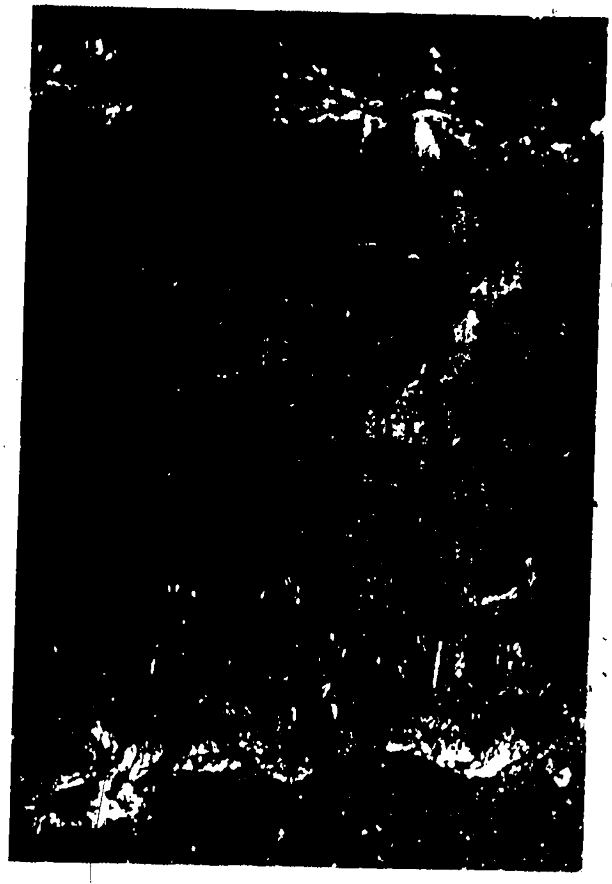


Figure 17. Small tubular burrows in the Middle B Member.

A) An oil sand bed between silt/shale partings, the characteristic bedding of the Middle B Member. Burrows at the base with ripple bedding throughout most of the bed. See B) for scale.

B) Abundant burrows showing light colored clay wall filled with oil sand.

estuaries, found very few species present. They found the freshwater reaches to be "dominated by a single species of burrowing oligochaete (resembling the familiar earthworm), and a few burrowing mollusks." They also found the diversity and abundance of biogenic structures to be greater on the sloping margins of the channel than in the deeper portions. In the Middle B Member, height in the section corresponds to higher positions on the point bar slope and density of burrowing does increase with height.

Polychaete worms commonly build vertical to slightly inclined dwelling tubes lined with an organic secreted layer. The freshwater forms are small (3 to 15 mm in length) and found in streams in close proximity to the sea (Chamberlain, 1975). X-ray radiographic pictures of polychaete worm burrows (Howard and Frey, 1973) show them to be long, thin tubes bearing a definite resemblance to those at the Steepbank River. The McMurray burrows are therefore interpreted on the basis of size, form, abundance, and depositional setting to be the dwelling tubes of suspension-feeding, freshwater worms.

Texture

The grain size and sorting of this member are very similar to the Middle A Member (Fig. 10). The sediment is generally very fine sand, with silty sand in places at the top of the member. Sorting, as in the Middle A Member, is good relative to the other members. The amount of clay in the sand beds is only 1 to 1.5%, disregarding the silt/clay interbeds.

In some places, notably outcrop 9, a slight but definite fining upward of grain size takes place within this member. This would be expected in a point bar deposit, as bottom to top in a vertical section represents moving from the depths of the channel towards the top of the point bar.

The range of values for both grain size and sorting is relatively small compared to the other members. This indicates fairly steady flow conditions for the deposition of the sands. The silt/shale beds indicate regular slackening of flow following flooding.

4. Upper A Member

General Lithology

The Upper A Member consists of horizontally bedded sands and silts overlying the dipping beds of the Middle B Member. This member is a sheet-like deposit, individual beds being traceable for much greater distances than the underlying members. The sediments are generally light in color due to poor oil saturation and often appear massive due to bioturbation. Bedding thickness varies from a few centimetres to a metre or more. This member is more resistant than the Middle B or Upper B Members and often stands in near-vertical bluffs. Isolated lenses of coal 10 to 30 cm thick are found in this member.

The Upper A Member is not present throughout the outcrop area. In the upstream outcrops, the Middle B Member is directly overlain by the Upper B Member.

Sedimentary Structures

The primary structure of the upper part of much of this member appears to be even, parallel laminations but generally all structure is destroyed by complete bioturbation. In the lower parts of the unit, ripple marks are present.

Large burrows, 10 to 15 cm long and 5 to 8 cm wide at the top, are found in the laminated sands. They are generally V-shaped, flaring at the top, with sand laminae pulled down along the sides of the burrow (Fig. 18). Howard and Frey (1973) found downward-pointing cones of disturbed sediment - a description which fits many of the large burrows found at the Steepbank River - to be the

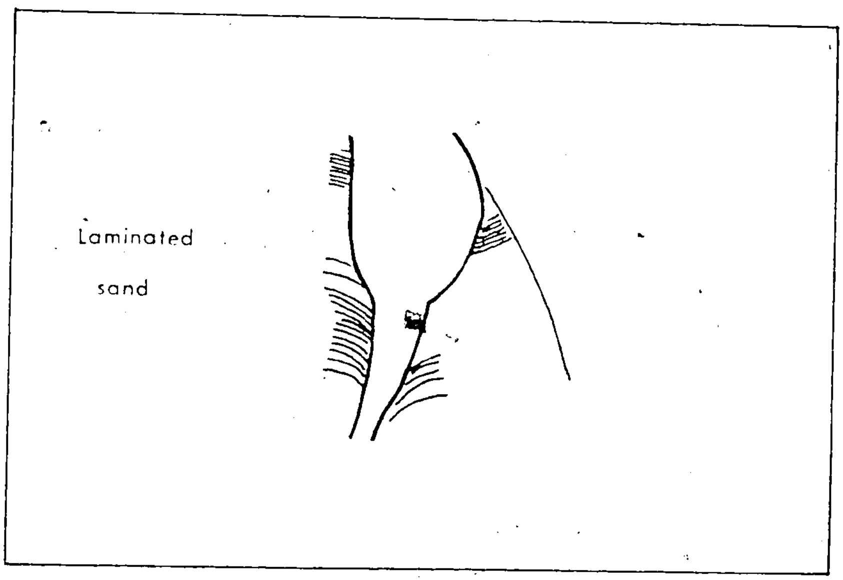


Figure 18. Large burrows in the upper A Member. The burrows are found in laminated sands, with the laminae pulled down at the [illegible] of the burrows. Most burrows are V-shaped although the one pictured here has a bulbous top.

result of the burrowing of small pelecypods in present day Georgia estuaries. Pelecypods may also have been responsible for the McMurray burrows.

Load casts are occasionally found associated with the laminated beds of the upper A Member.

Cross-bedding resembling the epsilon type is present at the top of this member in one location (Fig. 19). Though close observation was not possible due to inaccessibility, the structure appears to be the result of the meandering of a small channel. The set is about 2 metres thick, but has been truncated by the overlying Upper B Member.

Ironstone Beds

Moody-Stuart (1966) often found ironstone concretion horizons at the top of sets of epsilon cross-stratification. Since one of the characteristics of a meandering stream is the presence of a levee, and epsilon cross-stratification results from the meandering of a channel, the ironstone beds were taken as evidence of levees, possibly formed by leaching during soil formation.

In the Upper A Member of the McMurray Formation, horizons of ironstone are common, usually in the form of a series of concretions. The most continuous ironstone horizons are generally at or slightly above the top of the epsilon cross-bedding and may well represent a levee deposit. Several horizons of ironstone may be present and each may indicate a horizon of subaerial exposure. Not all ironstone beds represent levee deposits, however, as ironstone beds are also present in the Clearwater Formation and, less commonly, in the Middle B Member of the McMurray Formation.

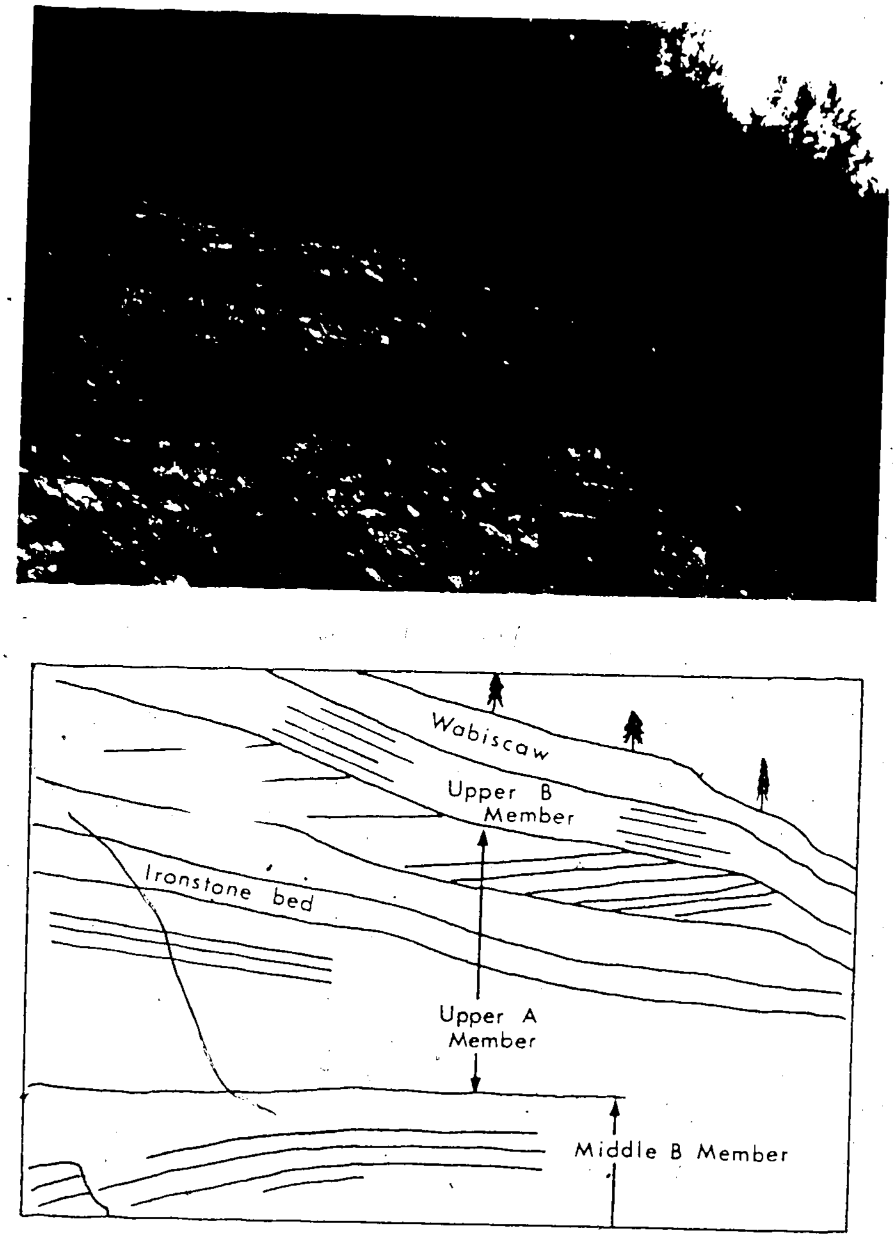


Figure 19. Top of outcrop 4, showing small epsilon cross-bed set of Upper A Member. The epsilon set is truncated at the top by the Upper B Member. The ironstone bed is continuous over the entire outcrop. Dipping epsilon beds of the Middle B Member are in the bottom left of the picture.

Texture

The texture of the Upper A Member is more varied than that of any other member. Sorting is generally poorer than the Middle Members, but two of the best sorted samples analyzed were from this unit. Grain size varies from sand similar to the Middle Members, to silt.

Analyzed samples from the lower parts of the member fall into Carrigy's Class II, fine-very fine sands, while those in the upper part of the member are Class III, very fine sands and silts, defined as follows:

1. Maximum size less than 0.3 mm (1.75 Ø).
2. Median grain size less than 0.12 mm (3.0 Ø).
3. Less than 80% of the sample coarser than 0.074 mm (3.75 Ø).

5. Upper B Member

General Lithology

The Upper B Member is generally characterized in outcrops as 2 or 3 metres of dark grey shaly oil sand at the top of the McMurray Formation. From a distance, this member resembles shale. In the upstream part of the area, it is easily identified, as it directly overlies the well-bedded sands of the Middle B Member. Downstream, however, it overlies finer grained, often bioturbated Upper A Member, to which it bears a closer resemblance.

Bedding is generally not visible in this member.

In places, the Upper B Member contains trace amounts of glauconite.

Sedimentary Structures

No structure is usually visible in the Upper B Member, apparently as a result of more or less complete bioturbation. In places this member has an erosional base, as shown by the truncation of the top of epsilon cross-bedding on outcrops 4 and 10.

Texture

The silty sands of this member have the finest grain size of the McMurray Formation and are very poorly sorted (Fig. 10). They contain a small percentage of grains larger than 0.3 mm, which results in their not fitting Carrigy's Class III, sands and silts. Clay content of the samples analyzed is 5 to 10%.

Clearwater Formation

Wabiscaw Member

General Lithology

The glauconite sand of the Wabiscaw Member, Clearwater Formation, can be distinguished by its green color, overlying the dark grey Upper B Member. The Wabiscaw often contains yellow ironstone concretions. This unit is always very recessive and good exposures are generally limited to steep, inaccessible cliffs. Amount of exposure rarely exceeds a metre or two in thickness. Bedding is generally obscure.

Texture

The Wabiscaw Member is composed of silty sands and sandy silts. The grain size is finer and the sorting poorer than the underlying Upper B Member of the McMurray Formation. Like the Upper B Member, the Wabiscaw contains a small percentage of coarse grains.

Clay content of the samples analyzed is 15 to 20%.

Formation / Member	General Lithology	Sedimentary Structures	Biogenic Structures	Oil Saturation (Weight%)
Clearwater Formation, Wabiscaw Member	Green, very argillaceous glauconitic sand.		Bioturbated	Trace
McMurray Formation: Upper B Member	Dark grey, very argillaceous oil sand. Commonly massive.		Bioturbated	2-4%
McMurray Formation: Upper A Member	Silt to fine sand, upper part light grey and resistant. Horizontally bedded.	One to two mm lamination. Ripples common.	Large V-shaped burrows. Commonly heavily bioturbated.	4-6%
McMurray Formation: Middle B Member	Very fine to fine sand. Oil sand (10-60 cm thick) separated by thinner partings of silt and shale.	Epsilon cross-bedding diagnostic. Ripples ubiquitous.	Tubular, clay-walled worm burrows.	8-15%
McMurray Formation: Middle A Member	Fine sand, locally medium or coarse. Bedding up to 1.5 m thick with little or no shale.	Trough cross-bedding predominates. Ripples common near top.		14-18%
McMurray Formation: Lower Member	Coarse sand to conglomerate. Light grey.	Large scale planar cross-bedding.		0-4%

Figure 20. Summary of field characteristics of the McMurray and Clearwater Formations.

Additional Properties of the McMurray and Clearwater Formation

1. Oil Saturation

Oil saturation values are based on both the analysis of samples (Appendix A) and field estimates.

Exposures of oil sand may have very different oil saturations than originally present, due to weathering and movement of oil under gravity. Weathering appears to affect only the outer few millimetres of the exposure. Flow under gravity, on the other hand, apparently covers vertical distances of at least a metre or two, and possibly much more, until the flow is stopped by an impermeable layer such as a shale bed. In this way, higher portions of an exposure may be depleted in oil, while lower parts are enriched. This effect is probably most important in the Middle A Member, which contains little shale, and less important in the Middle B Member, as the multitude of shale partings would keep migration to a minimum.

Carrigy (1962) has shown that oil saturation in the Athabasca oil sands varies inversely with the clay content. Grain size is a less important factor.

The Lower Member of the Steepbank River area has a consistently high clay content (6-10%) and, as a result, probably a consistently low oil saturation. Oil saturation varies from a trace to 4%. Carrigy (1963a) reports that the Lower Member (Class I) sands show a wide range of oil saturations with a mean of 12.47% by weight and are favorable petroleum reservoir rocks. This is apparently not the case in the Steepbank River area. The clay content of Carrigy's samples was not included in the report.

The trough cross-bedded sand of the lower Middle A Member contains the best oil saturation of any member, generally 14 to 16% and up to 18% by weight. As might be expected, clay content is low, generally less than 1.5%. Higher in the member, where smaller cross-beds and ripples are present, oil saturation is less, probably largely due to the downward migration of oil under the influence of gravity.

The gravity flow of oil is shown in the Middle B Member by the color of individual sand beds between thin shales. The oil sand often grades from dark at the bottom to light at the top. Analyses of samples revealed virtually no vertical changes in grain size or clay content within the beds to account for an initial difference in saturation. The Middle B Member generally has good saturation, 8 to 15%, in the sand beds between the unsaturated silt/clay partings.

The Upper A Member, because of its variable texture, has a fairly wide range in oil saturation, generally 4 to 6% but up to 10 or 12%. The usual low saturation may be a result of the bioturbation common in the member which produces a uniform clay-rich sand. The fine grain size in the member would also play a role.

The Upper B Member is consistently fine grained, shaly, and homogeneous due to biogenic reworking, resulting in oil saturations of 2 to 4%.

The Clearwater Formation is virtually oil-free, as it is throughout the Athabasca River Valley (Carrigy, 1963b).

2. Clay Mineralogy

The clay mineralogy of 18 oil sand samples was determined by x-ray diffraction methods (Fig. 21). Millot (1970) outlines the shortcomings of using sand samples instead of shale, and outcrop samples rather than subsurface cored samples. Water circulation during diagenesis, and weathering at outcrop result in a higher kaolinite to illite ratio than was originally present at deposition. Schooley (1975), in studying the Athabasca oil sands, found an enrichment of kaolinite in the sands compared to equivalent fine-grained sediments, indicating a diagenetic change in clay minerals. -sulting clay percentages in this report are therefore partly a resu t of diagenetic changes and are comparable only to other outcrop samples.

The general trend in the clay minerals is a reduction in kaolinite and an increase in illite with height in the section. The Lower Member contains 100% kaolinite in the sands but 80% kaolinite and 20% illite in the finer grained sediments, suggesting that diagenesis may have increased the kaolinite percentage. The Middle B Member contains 80 to 85% kaolinite and 15-20% illite in the sands. Both the Upper A and Upper B Members contain 60 to 70% kaolinite and 30 to 40% illite. In the Clearwater Formation, montmorillonite makes a sudden appearance, as does a smaller amount of chlorite. Kaolinite drops to 20 to 45% and illite remains at 30 to 40%.

Perhaps part of the increasing illite/kaolinite ratio with height is because there was more fresh water circulation in the

Figure 21. Percentages of clay minerals in selected samples of the McMurray and Clearwater Formations. Percentages determined by x-ray diffraction of -2 micron fraction.

Sample	Kaolinite	Illite	Chlorite	Montmorillonite
1-1	100			
3-1	100			
3-2	100			
3-6	80	20		
3-9	65	35		
3-11	65	35		
3-13	60	40		
3-14	65	35		
3-15	20	40	10	30
7-1	80	20		
7-2	85	15		
8-1	100			
9-1	100			
9-5	100			
9-8	85	15		
9-10	85	15		
9-12	70	30		
9-13	45	30	5	20

Stratigraphic Location of Samples

Clearwater Formation			3-15			9-13
McMurray Formation	Upper B Member		3-14			9-12
McMurray Formation	Upper A Member		3-13 3-11 3-9			
McMurray Formation	Middle B Member		3-6			9-10 9-8
McMurray Formation	Middle A Member		3-2	7-2 7-1		9-5
McMurray Formation	Lower Member	1-1	3-1		8-1	9-1

sands of the lower members. However, there is an increase of illite to kaolinite even when the fine-grained sediments of the Middle A Member are compared to the Upper Members. Millot (1970), in a survey of clay mineral abundances found that when modifications in mineralogy occur, it is generally an increase in illite and a decrease in kaolinite as one approaches the marine environment. This observation may explain some of the changes found at the Steepbank River.

The appearance of montmorillonite in the Clearwater Formation has been interpreted by Carrigy (1963b) as being due to the introduction of a partially volcanic source to the west, as montmorillonite is a common alteration product of volcanic ash. The lack of montmorillonite in the Upper B Member which, in other ways seems gradational with the Clearwater Formation, may be due to differential settling. Because montmorillonite is generally of smaller grain size than the other clays, it tends to settle out farther offshore (Lauff, 1967). It is also possible, however, that a change in source area occurred between deposition of the Upper B Member and the Clearwater Formation, possibly as a result of the increasing influence of marine currents.

3. Palynology

Nine fine-grained samples were chosen to be studied for the purpose of determining depositional environment as indicated by microflora. The microfossils were identified by Dr. C. Singh of the Alberta Research Council.

In the fine grained sediment of the Middle A Member, good recovery of numerous species of spores and pollen indicate a continental environment.

Only one sample of Middle B Member was studied. Large numbers of well-preserved spore and pollen species were recorded, indicating essentially continental conditions. Two specimens of acritarchs were present in the sample. This may indicate a marine influence but they may have been reworked from the Devonian strata. The possibility of marine influence remains open.

No sample of Upper A Member yielded good enough recovery to draw conclusions.

The Upper B Member is interpreted as marine due to the presence of several species of dinoflagellates. The Clearwater Formation, containing diverse and well-preserved dinoflagellates is also marine.

4. Heavy Minerals

Percentages of non-opaque heavy minerals were found for sixteen samples from six outcrops (Fig. 22). More than 200 grains were identified per sample.

The heavy mineral suite in the Steepbank River area is essentially the same as that from other parts of the Athabasca oil sands, as described by Mellon (1956) and Carrigy (1963a, 1966).

The Lower Member is generally characterized by such a high percentage of large pink garnets that the heavy mineral samples appear pink to the naked eye. The presence of pink garnet in this member has been noted by Carrigy (1963a). In sample 8-1, from the 'hole' in the Devonian limestone at outcrop 8, no garnet is present. One explanation for this anomaly is that the sample predates the rest of the Lower Member and the tapping of the source of garnet.

The other significant feature of the Lower Member heavy minerals is the high percentage of kyanite and staurolite relative to the amount of zircon and tourmaline. The kyanite and staurolite, along with the garnet, indicate a largely metamorphic source. The abundance of kyanite and garnet in this member, however, may be largely due to the grain size of the sample. These two minerals tend to have larger grain sizes, and may have been selectively sorted into the coarser sediments of the Lower Member.

The Middle A and B Members contain high percentages of zircon and tourmaline. Staurolite is abundant in the Middle A and lower Middle B Members, decreasing above this. Chloritoid, a common mineral in meta-sedimentary rocks, is generally more abundant in

Figure 22. Relative percentages of non-opaque heavy minerals in the Steepbank River area.

Sample No.	1-1	3-1	3-2	3-5	3-8	3-11	3-14	3-15	5-1	7-1	8-1	9-3	9-8	9-10	9-12	9-13
Zircon	5	24	48	72	17	33	40	28	43	47	39	49	40	71	61	45
Tourmaline	4	7	26	13	27	27	23	4	20	18	13	22	18	10	15	14
Chloritoid	0	0	5	5	42	24	7	2	14	13	1	3	14	5	4	15
Garnet	78	56	5	1	2	4	12	46	10	2	0	4	9	3	4	12
Rutile	2	1	1	5	4	5	2	8	5	5	6	1	3	7	7	5
Apatite	0	0	0	1	0	0	5	10	2	1	0	1	2	0	3	3
Staurolite	6	5	12	2	4	5	5	2	5	7	20	15	11	2	5	5
Kyanite	4	6	2	1	2	1	5	0	1	4	17	5	1	2	0	1
Others	1	1	1	0	2	1	0	0	0	2	4	0	2	0	1	0
Mean Grain Size of Bulk Sample in Ø Units	2.11	0.92	3.16	[illegible]	4.40	4.26	4.14	4.63	3.89	5.79	2.49	2.72	2.99	3.23	3.98	6.17

Stratigraphic Location of Samples

Clearwater Formation			3-15				9-13
McMurray Formation	Upper B Member		3-14	5-1			9-12
	Upper A Member		3-11				
	Middle B Member		3-8 3-5				9-10 9-8
	Middle A Member		3-2		7-1		9-3
	Lower Member	1-1	3-1			8-1	

the finer grained samples, regardless of stratigraphic position, from the base of the Middle A Member to the Clearwater Formation.

In sample 3-15 of the Clearwater Formation, there is a flood of garnet and a high percentage of apatite. To a lesser extent, garnet and apatite are abundant in sample 3-14 of the underlying Upper B Member of the McMurray Formation. In another Clearwater Formation sample (9-13), garnet is again higher than usual. This garnet/apatite anomaly was first noticed by Mellon (1956) in a sample from the Clearwater Formation of the subsurface type section. Mellon came to no conclusion as to its significance since he had only one sample of the glauconite sand. Apparently, this occurrence has regional extent.

Williams (1963) found that two distinct suites of non-opaque heavy minerals are present in the Mannville Group of central Alberta. The lower part of the Mannville Group is dominated by tourmaline and zircon, while the upper part, consisting of the Clearwater and Grand Rapids Formations, is dominated by apatite, garnet, zircon, and tourmaline, in that order. Mellon (1967) inferred a pyroclastic origin for the apatite, based on its idiomorphic habit and association with idiomorphic biotite. Both Williams and Mellon concluded that the provenance of the McMurray Formation was the Canadian Shield to the east and the beginning of Clearwater time marked the introduction of detritus from the Cordillera to the west. All evidence from the Steepbank River area supports these conclusions, from the metamorphic/sedimentary suite in the McMurray Formation to a sudden influx of garnet and idiomorphic apatite in the Clearwater Formation.

In studying the heavy minerals of the Athabasca oil sands, Mellon (1956) found tourmaline to be in much greater abundance than zircon. The difference between his results and those of this report may be attributable to the sample fraction chosen for study. Mellon studied the heavy minerals retained between the 100-mesh and 200-mesh sieves so that a large amount of zircon, which is commonly abundant in the finer grain sizes, may have been discarded. In this study, a portion of the bulk sample was used for heavy mineral separation.

CHAPTER 3

OUTCROP DESCRIPTIONS AND COLUMNAR SECTIONS

Outcrop 1

Outcrop 1 displays excellent exposure of the Waterways Formation limestone and the Lower Member of the McMurray Formation. The Middle A and B Members are poorly exposed, while the overlying Upper A and B Members are, in places, well exposed.

Twelve to twenty-five metres of limestone, above river level, are overlain by a red paleosol. Above this is the largest exposure of the Lower Member in the area. Bedding in the Lower Member often consists of large scale planar cross-bed sets with considerable lateral continuity. This cross-bedding indicates a paleocurrent direction of north to north-east. The member is white to dark grey in color in contrast to the darker color of the overlying Middle A Member.

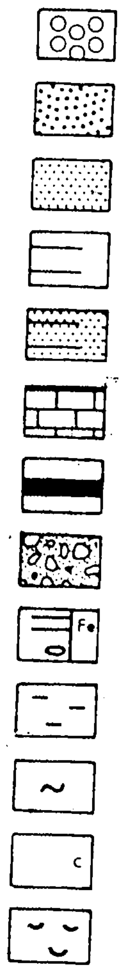
Outcrop 2

Poor exposure is present over this entire outcrop. Approximately 10 metres thickness of limestone is present, measured from river level, extending the length of the outcrop. Above the limestone lies about 6 metres of Lower Member; conglomerate at the base, and light grey coarse sand higher up. The rest of the outcrop, especially the Middle Members, is very poorly exposed.

Within the Upper A Member are ironstone concretions up to 1.5 metres in diameter.

Guide to Columnar Sections

Lithologic symbols



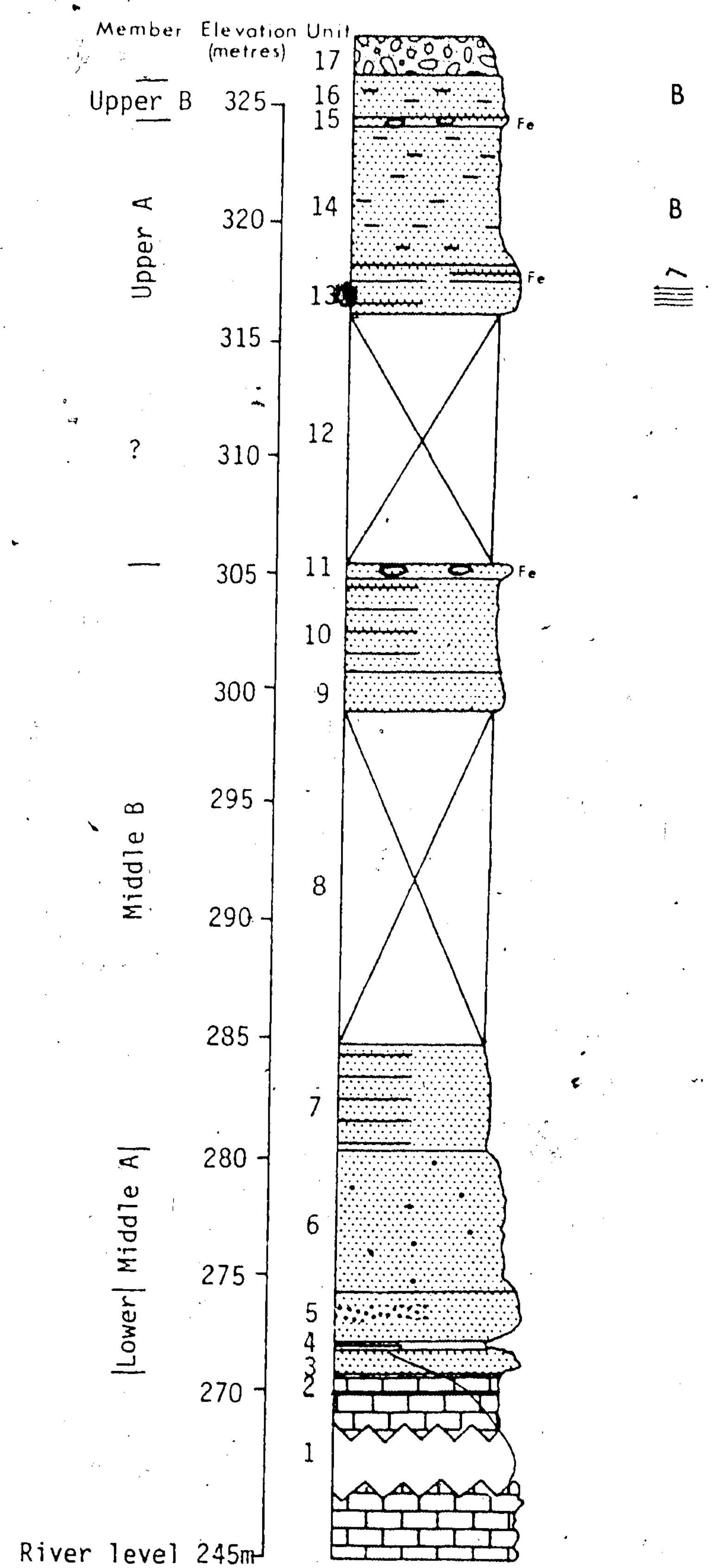
- Conglomerate
- Medium to coarse sandstone
- Very fine to fine sandstone
- Shale
- Sandstone with thin partings of siltstone or shale
- Limestone
- Coal
- Glacial drift
- Ironstone bed, concretions
- Argillaceous
- Glauconitic
- Carbonaceous
- Shale rip-up clasts

Sedimentary structures

- Epsilon cross-stratification
- Large scale trough cross-bedding
- Large scale cross-bedding undifferentiated
- Ripple bedding
- Parallel laminations
- B Bioturbation
- U Small tubular burrows
- V Large V-shaped burrows

Width of column indicates relative resistance to erosion. In the written descriptions, colour refers to weathered colour and oil saturations are field estimates in weight per cent.

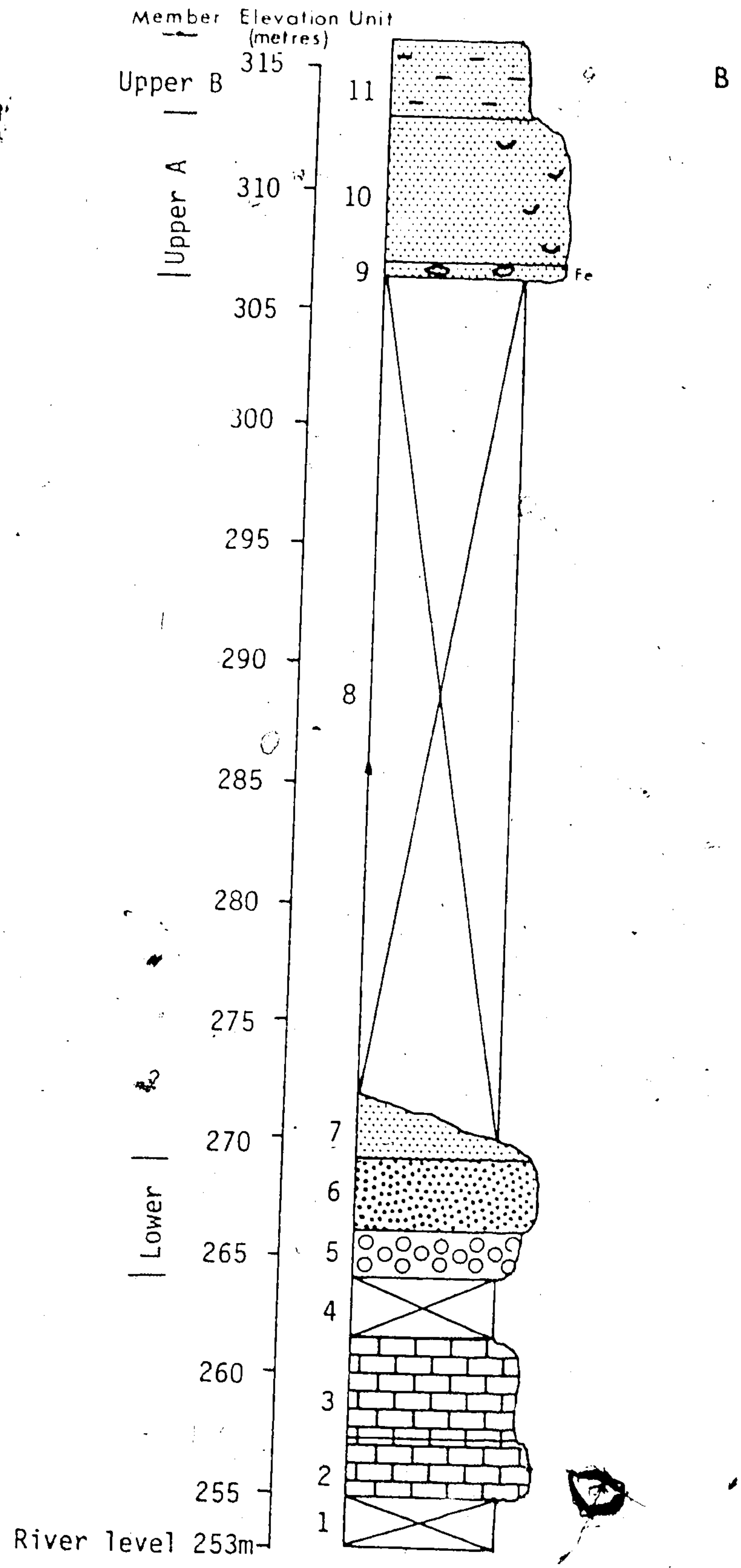
Figure 23. Guide to columnar sections.



Member
Elevation (metres)
Unit
Upper B
Upper A
?
Middle B
Lower
Middle A
325
320
315
310
305
300
295
290
285
280
275
270
River level 245m
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Fe
Fe
Fe
B
B

Figure 24. Columnar section of outcrop 1. (Downstream end of outcrop)

Unit	Thickness (metres)	Description
17	1.8	Glacial drift
16	1.8	Oil sand, grey-brown, very fine grained, very argillaceous.
15	0.3	Ironstone bed.
14	6.1	Oil sand, light grey, very fine grained, argillaceous; generally bioturbated; fractured and recessive; comminuted carbon to 3 mm long.
13	2.5	Oil sand, very fine grained, well defined bedding 10-30 cm; laminated in part, rippled towards top.
12	10.3	Covered.
11	0.6	Ironstone bed, red to yellow, resistant.
10	4.0	Oil sand, very fine grained, with shale partings.
9	1.5	Oil sand, very fine grained, apparently massive.
8	14.3	Covered.
7	4.6	Oil sand, very fine grained, well bedded with shale partings (1 to 2 cm thick) every 15 to 30 cm.
6	6.0	Oil sand, very fine grained, with occasional pebbles to 5 mm diameter; poor bedding, generally appears massive.
5	1.9	Oil sand, light grey, very fine to fine grained, interbedded with very coarse sand and conglomerate.
4	0.4	Shale, dark grey.
3	0.9	Oil sand, light grey, fine grained; poor bedding, homogeneous.
2	0.9	Paleosol, red.
1	24.4	Limestone, buff-yellow; recessive and rubbly with resistant ridges.



Member
Elevation (metres)
Unit
B
Upper B
Upper A
Lower
315
310
305
300
295
290
285
280
275
270
265
260
255
River level 253m
11
10
9
8
7
6
5
4
3
2
1
Fe

Figure 25. Columnar section of outcrop 2.
(Central ravine of outcrop)

Unit	Thickness (metres)	Description
11	3.4	Oil sand, very fine grained, argillaceous; bedding on scale of 5-10 cm; bioturbated; fiable; recessive; bottom 30 cm oxidized to yellow-brown.
10	6.1	Oil sand, light grey-green, very fine grained; abundant small shale clasts throughout; occasional beds of sandstone, poorly saturated and resistant, up to 5 cm thick; bedding 5 cm to 60 cm.
9	0.6	Oil sand, very fine grained, with large ironstone concretions parallel to bedding (50 cm diameter) in lower half of unit.
8	33.2	Covered.
7	3.4	Oil sand, black, very fine to fine grained; well-defined bedding 5 to 30 cm thick; poor exposure.
6	2.7	Oil sand, light grey, medium to coarse grained, with abundant pebbles to 5 mm; resistant, cliff-forming unit over entire outcrop.
5	2.4	Conglomerate, red brown, sand matrix with pebbles 2 to 10 cm diameter; mostly disc-shaped clay-ironstone pebbles lying parallel to bedding; within unit are several beds of sand; unit in lenses varying somewhat in stratigraphic position over outcrop; up to 6 metres thick.
4	2.4	Covered.
3	4.6	Limestone, green-yellow, micritic, recessive.
2	2.4	Limestone, yellow-grey, fossiliferous, resistant.
1	2.1	Covered.

Outcrop 3

Outcrop 3 (Figs. 13, 15), a very large exposure, is perhaps the closest approach to an ideal section in the study area. There is excellent exposure of all units except the Lower Member. Over most of the outcrop, limestone is present from river level to a height of about 20 metres and the Lower Member is absent. This Devonian high, however, does not extend beyond the limits of the outcrop. At the downstream end of the outcrop, the limestone drops appreciably in elevation and the Lower Member of the McMurray Formation occupies the low on the unconformity surface.

The exposure of the Middle B Member (epsilon cross-stratification) is particularly good in this outcrop, both because the true dip of the epsilon beds can be estimated (35 to 40° azimuth), and because much of the outcrop is well-weathered. Weathering emphasizes sedimentary structures such as ripple bedding and burrows. The Upper A Member is also particularly well exposed and accessible.

Outcrop 4

This is another large outcrop but with only fair exposure (Fig. 27). It has more complex geometry than outcrop 3.

Limestone is present only at each end of outcrop 4, most of the outcrop being occupied by the Lower Member from river level to a height of 6 to 18 metres. In a conglomerate of the Lower Member at the upstream end of the outcrop are large clasts, one angular sandstone boulder measuring 45 cm across. Clasts of this size have not been previously reported from the McMurray Formation.

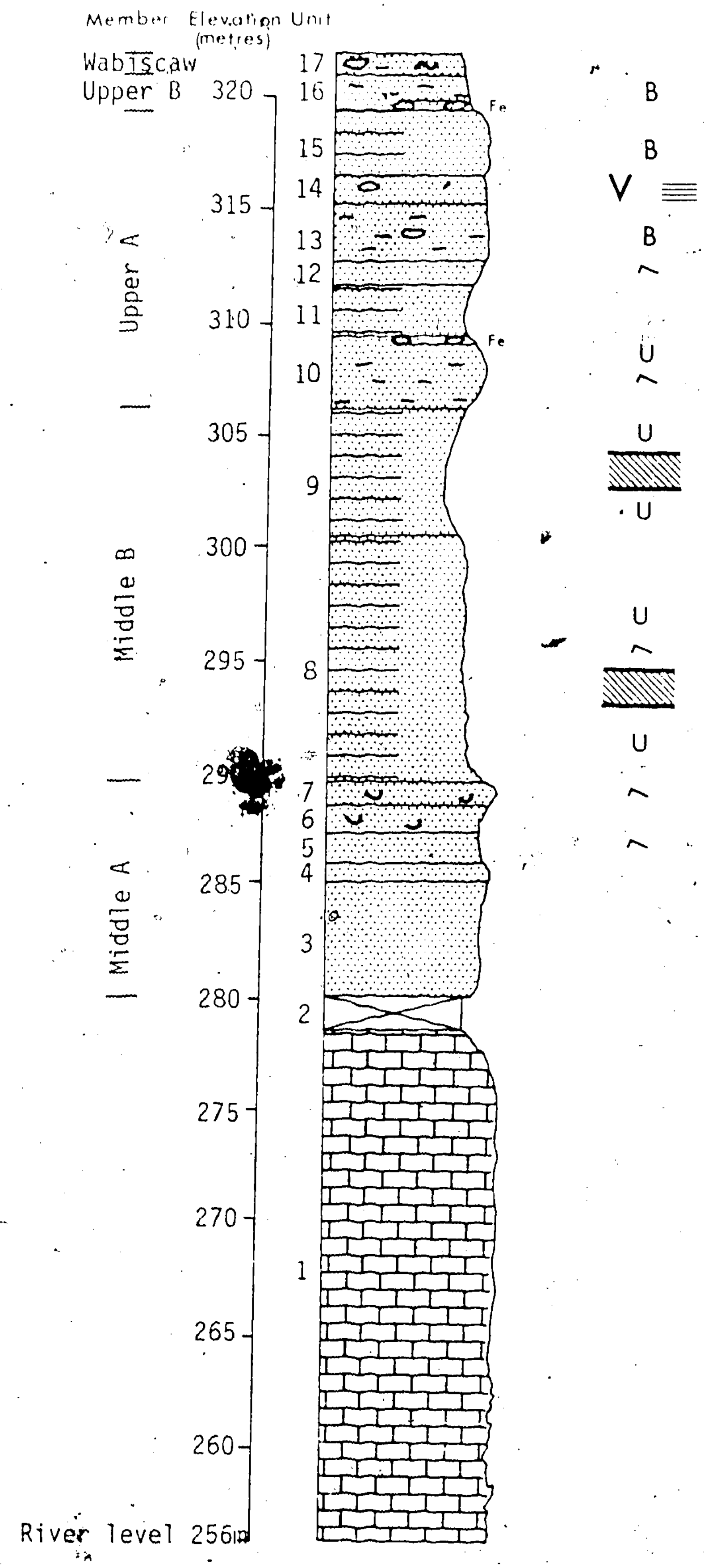

Member Elevation Unit (metres)
Wabiscaw
Upper B
Upper A
Middle B
Middle A
320
315
310
305
300
295
285
280
275
270
265
260
River level 256m
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Fe
Fe
B
B
B
U
U
U
U
U

Figure 26. Columnar section of outcrop 3.
(Centre of outcrop. Cliff immediately downstream from Large grove of trees.)

Unit	Thickness (metres)	Description
17	0.6	Sandstone, very light green-grey, very fine grained, very argillaceous, glauconitic; contains ironstone concretions.
16	1.8	Oil sand, dark grey, very fine grained, very argillaceous; ironstone bed 30 cm from base.
15	3.7	Oil sand, light grey, very fine grained, interbedded with shale; very uniform bedding, up to 30 cm of oil sand separated by up to 8 cm of shale; bioturbated.
14	1.2	Oil sand, very light grey, very fine grained, laminated to rippled in part; large burrows at top, occasional concretions.
13	2.4	Oil sand, light grey very fine grained to silty, very argillaceous; bioturbated.
12	1.2	Oil sand, light grey, very fine grained; trough ripples throughout; medium scale cross-beds at top (5 cm sets).
11	2.4	Oil sand, red-brown to grey, very fine grained, very silty and shaly, interbedded with shale, very sandy; fissile and recessive unit.
10	3.1	Oil sand, dark grey at base to light grey at very fine grained, argillaceous; poorly defined bedding due to lack of shale beds; burrows abundant along bedding planes; ripples present, medium scale cross-bedding (5-10 cm) at base.
9	5.8	Oil sand, red-brown to grey, very fine grained, very argillaceous; discontinuous laminations.
8	10.7	Oil sand, dark grey to black, very fine grained, interbedded with shale and siltstone; oil sand generally rippled; bedding very distinct, with clean sand beds 10 to 30 cm thick separated by beds of shale 1 to 10 cm thick; individual sand beds often grade from dark at bottom to light on top, and from massive at bottom to rippled on top.
7	1.2	Oil sand, light grey, very fine grained, top half rippled throughout; shale rip-up clasts in lower part.
6	1.2	Oil sand, black, fine grained, with abundant shale rip-up clasts throughout, mostly a few millimetres but up to 10 cm.
5	1.2	Oil sand, light grey, very fine to fine grained; tr gh ripples throughout; medium scale cross-bed (5 cm thick) at top.
4	0.9	Oil sand, light grey, very fine to fine grained; resistant; bedding not continuous laterally.
3	4.[illegible]	[illegible] sand, black, very fine grained; looks massive from distance but bedding 1 to 5 cm; cliff-forming unit.
2	1.8	Covered.
1	22.6	Limestone, green-yellow, fine grained, rubbly.

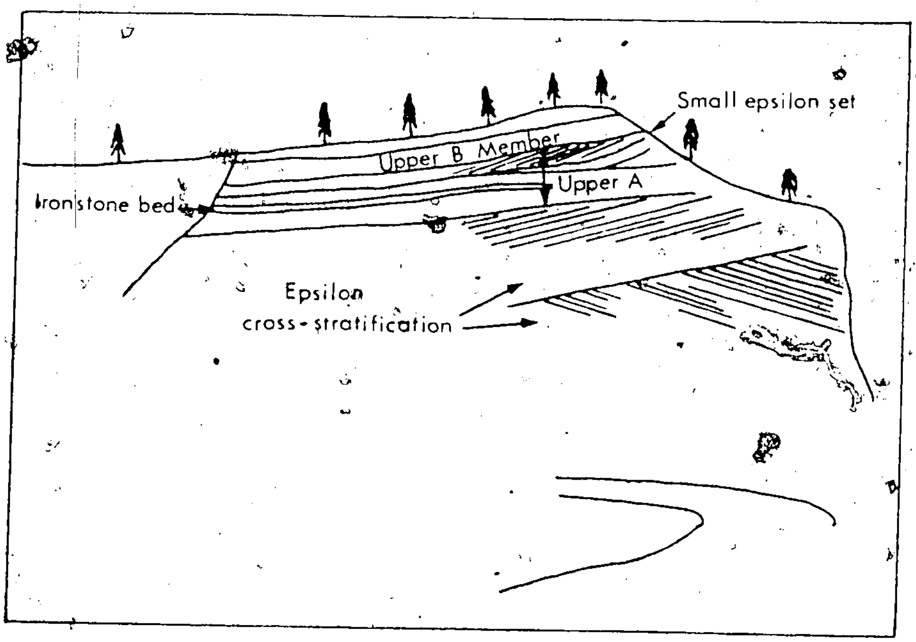
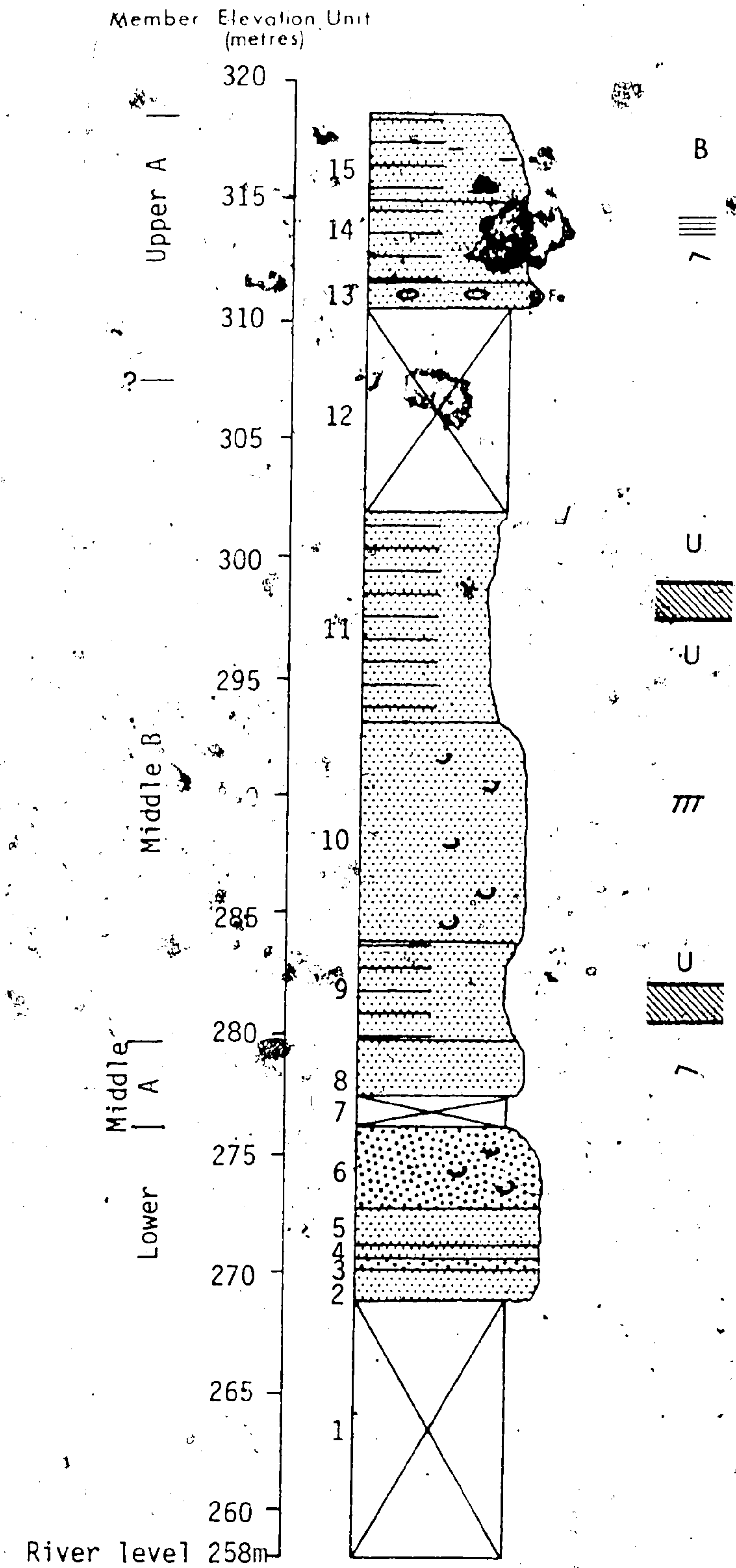


Figure 27. Outcrop 4. Two sets of Middle B Member epsilon cross-stratification are present, dipping in opposite directions. A continuous ironstone bed overlies these, followed by a small epsilon cross-bed set (see Fig. 19).



Member Elevation Unit
(metres)
320
315
310
305
300
295
285
280
275
270
265
260
River level 258m
Upper A
Middle B
Middle A
Lower
?
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Fe
B
U
U
U

Figure 28. Columnar section of outcrop 4. (Upstream end of outcrop)

Unit	Thickness (metres)	Description
15	3.7	Oil sand, very fine grained, argillaceous, interbedded with shale, bedding 2-8 cm thick; heavily burrowed.
14	3.4	Oil sand, very fine grained, interbedded with shale, bedding 5 to 30 cm; laminated in part, rippled in part, bioturbated in part.
13	0.9	Ironstone bed, continuous across outcrop; ironstone concretions and oil sand oxidized to brown.
12	8.5	Covered.
11	8.8	Oil sand, very fine grained, interbedded with shale, 15 cm to 60 cm of oil sand separated by up to 5 cm of shale; burrowed, especially along shale beds; laminations of varying oil saturation within individual sand beds; at some locations channels in this unit contain large scale cross-beds (30 to 60 cm thick).
10	9.2	Oil sand, dark grey to black, very fine grained; cliff-forming unit, cross-bedded in places, apparently massive in places; occasional beds 2 to 30 cm thick with abundant shale rip-up clasts; clasts generally a few millimetres to a few centimetres, but up to 10 cm.
9	4.3	Oil sand, dark grey, very fine grained, interbedded with shale on scale of 10 to 30 cm, clean sand and shale; burrowed.
8	2.1	Oil sand, dark grey, very fine grained, bedding on scale of one metre but internally laminated; trough ripples throughout.
7	1.1	Covered.
6	3.4	Oil sand, light grey, very coarse grained with abundant shale clasts and pebbles up to a few millimetres; resistant.
5	1.5	Oil sand, light grey, fine grained with occasional grains up to 2 mm diameter; apparently massive.
4	0.3	Oil sand, light grey, very fine grained with beds of very coarse sand to pebbles.
3	0.6	Oil sand, light grey, coarse to very coarse grained, with abundant pebbles to 2 cm along bedding planes.
2	1.2	Oil sand, light grey, fine grained; poor bedding, essentially massive.
1	10.7	Covered.

The Middle B Member is more complex in this outcrop than in outcrop 3, as there are two sets of epsilon cross-stratification dipping in opposite directions. Mo- y-Stuart (1966) also found two superimposed sets and believed i- e likely to be the result of the chance superposition of two -nder belts rather than the return sweep of a rapidly aggrading stream.

Massive oil sand of what at first appears to be the Middle A Member is present overlying the southward-dipping set. The lower set, present at both ends of the outcrop, appears to be channeled into by the overlying massive oil sand which often contains abundant shale rip-up clasts. The fact that the massive unit overlies an epsilon set suggests that it is a deeper-channel facies of the upper epsilon cross-stratified unit.

The apparent dip of the lower set of epsilon cross-bedding, judged to be close to the true dip, is 12 to 15^{o}, with a dip direction of about 80^{o} azimuth. The apparent dip of the upper set in the Middle B Member is at a maximum 8 to 10^{o}, dipping south-west, at the north end of the outcrop. The apparent dip of this set decreases towards the south, probably because the strike of the cliff face approaches the strike of the bedding.

Overlying the Middle B Member is the horizontally bedded Upper A Member, dipping very slightly to the north, opposite to the dip of the epsilon cross-bedding below. The beds immediately overlying the epsilon unit are bioturbated sands with occasional laminations, topped by an ironstone horizon extending the length of the outcrop. Overlying the ironstone and forming the top unit of the Upper A Member is a cross-bed set, interpreted to be a smaller-scale version of epsilon cross-stratification, about 2 metres thick (Fig. 19).

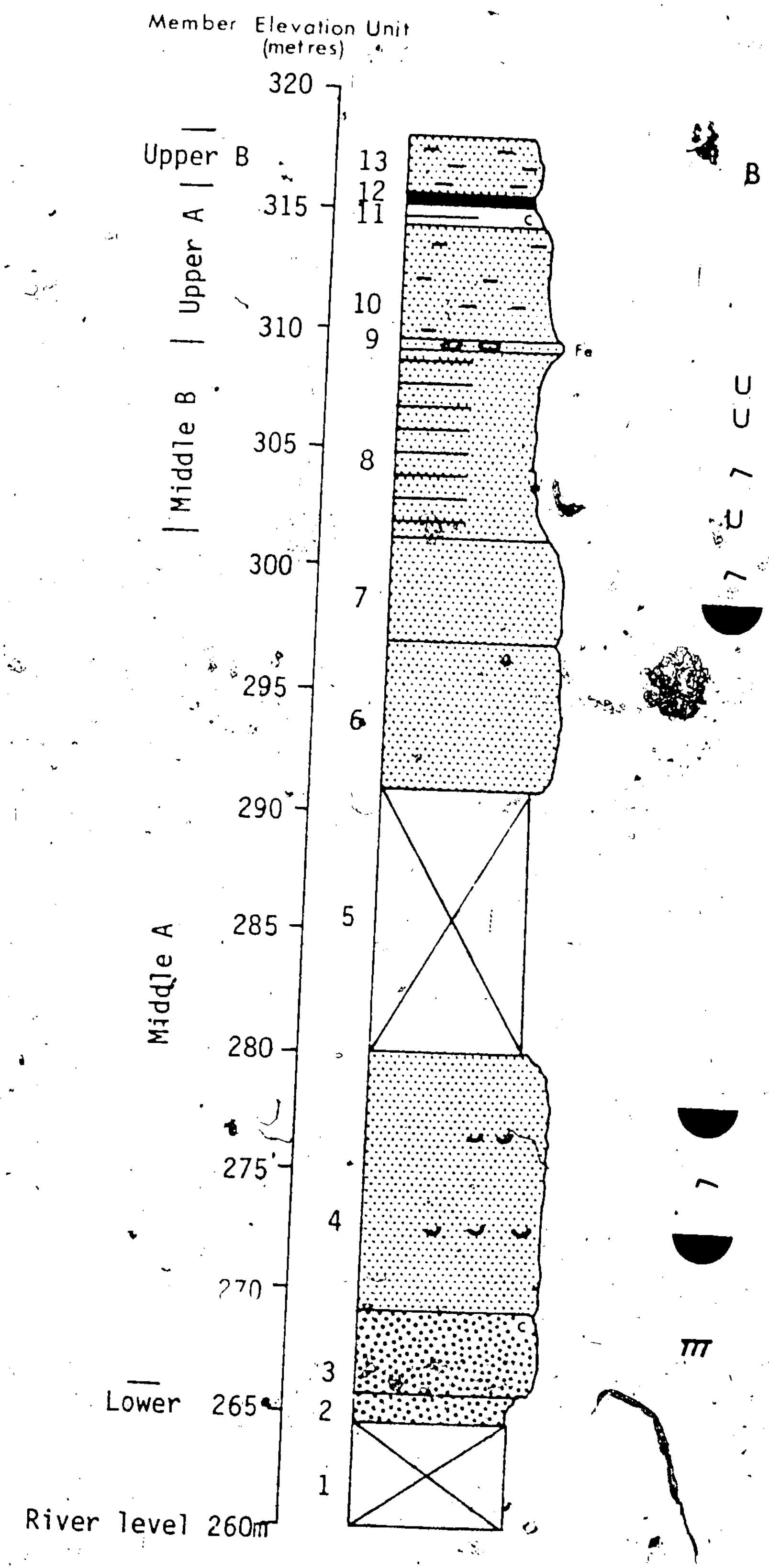
At the top of the outcrop, the Upper B Member and the glauconite sands of the Clearwater Formation ar present.

Outcrop 5

This outcrop contains an excellent exposure of Middle A Member trough cross-beds, both because of their orientation (the cliff face cuts a transverse section through the troughs) and the high degree of weathering of the surface. Exposure of the Middle A Member is very poor but the Upper Members are well exposed on a ridge upstream from the main outcrop.

The sets of trough cross-bedding in the Middle A Member are generally 30 to 60 cm thick, but sets near the base are up to 1.5 m thick and 6 m across in transverse section. Thickness of the trough sets decreases upward. The Middle A Member is very thick in this outcrop, at the expense of the Middle B Member which is only 10 metres thick. At the top of the Middle B Member is an ironstone bed which is fairly continuous over the entire outcrop, a distance of approximately 300 metres.

A bioturbated sandstone overlies the ironstone bed which is in turn overlain by a 30 cm thick bed of coal. This coal is covered with a powdery coating of sulphur. Above the coal is a completely bioturbated, almost unsaturated, grey silty sandstone. This is interpreted to be Upper B Member which, because it has a low oil content, is light in color.



Member
Elevation (metres)
Unit
320
315
310
305
300
295
290
285
280
275
270
265
River level 260m
Upper B
Upper A
Middle B
Middle A
Lower
13
12
11
10
9
8
7
6
5
4
3
2
1
Fe
B

Figure 29. Columnar section of outcrop 5.
(Upstream end of outcrop. Top 10 metres measured on ridge to the east.)

Unit	Thickness (metres)	Description
13	2.4	Sandstone, grey with yellow patches, very fine grained, argillaceous, with thin (1 to 2 mm) lenses and laminations of black shale; yellow patches apparently due to sulphur staining on grains; completely bioturbated.
12	0.3	Coal, fissile, with coating of sulphur powder.
11	0.9	Shale, brown at base to black at top grading into coal; lithified, very fissile.
10	4.9	Oil sand, very light grey, very fine grained, very shaly; apparently nearly completely bioturbated.
9	0.3	Ironstone bed, continuous over most of outcrop; varies from iron staining to concretions.
8	7.6	Oil sand, dark grey, very fine to fine grained, interbedded with thinner partings of shale; burrows at [illegible] unit, becoming more abundant up-section; [illegible]s common.
7	4.6	[illegible]ight grey, very fine to fine grained, cross-[illegible]roughout, from ripple beds (1 cm thick) to t[illegible]sets up to 50 cm thick; laminated in part.
6	6.1	Oil sand, light grey, very fine grained; generally horizontally bedded, but bedding obscure; hand specimen appears massive.
5	10.7	Covered.
4	10.9	Oil sand, fine grained, trough cross-bedded throughout, troughs from 30 cm to 1.5 m thick; shale clasts at base of some troughs (clasts average 1 mm thick x 4 mm long); some troughs internally rippled.
3	3.4	Oil sand, fine to coarse grained; cross-bedded throughout, sets 3 to 50 cm; at top of unit a few thin bands (to 3 cm) of shaly carbonaceous material, occasional small wood fragments.
2	0.9	Oil sand, light grey, very fine to coarse grained, pebbles and clasts of clay to 1 cm; very poorly sorted; unconsolidated.
1	4.6	Covered.

Outcrop 6

Outcrop 6 is a small, poor exposure. The Middle A Member begins at river level, as no limestone or Lower Member is exposed at this outcrop. As in outcrop 5, the trough cross-beds can be very large. On the top of one of these sets, a few of the small burrows characteristic of the Middle B Member were found, an anomaly not repeated elsewhere in the study area. The Middle A Member at this outcrop displays other unusual features. Large scale planar cross-beds with alternating medium and coarse laminae in the foresets are present, as well as abundant carbonized wood fragments up to 10 cm through and 60 cm long.

The contact between the Middle A and B units is [illegible] sharply defined in this exposure. The epsilon cross-bedding of this member appears to be dipping north to north-west. At the top of the Middle B Member, 15 cm of coal is overlain by completely bioturbated light grey silty sand, similar to that at the top of outcrop 5.

Outcrop 7

Exposure on this outcrop is excellent (Fig. 31), though largely inaccessible. Limestone is present across the outcrop from river level to a height of about 6 metres and the Lower Member is absent.

The Middle A Member at this outcrop is unique in that it includes a unit of interlaminated sand, silt, and shale which has been channeled into by the overlying trough cross-bedded oil

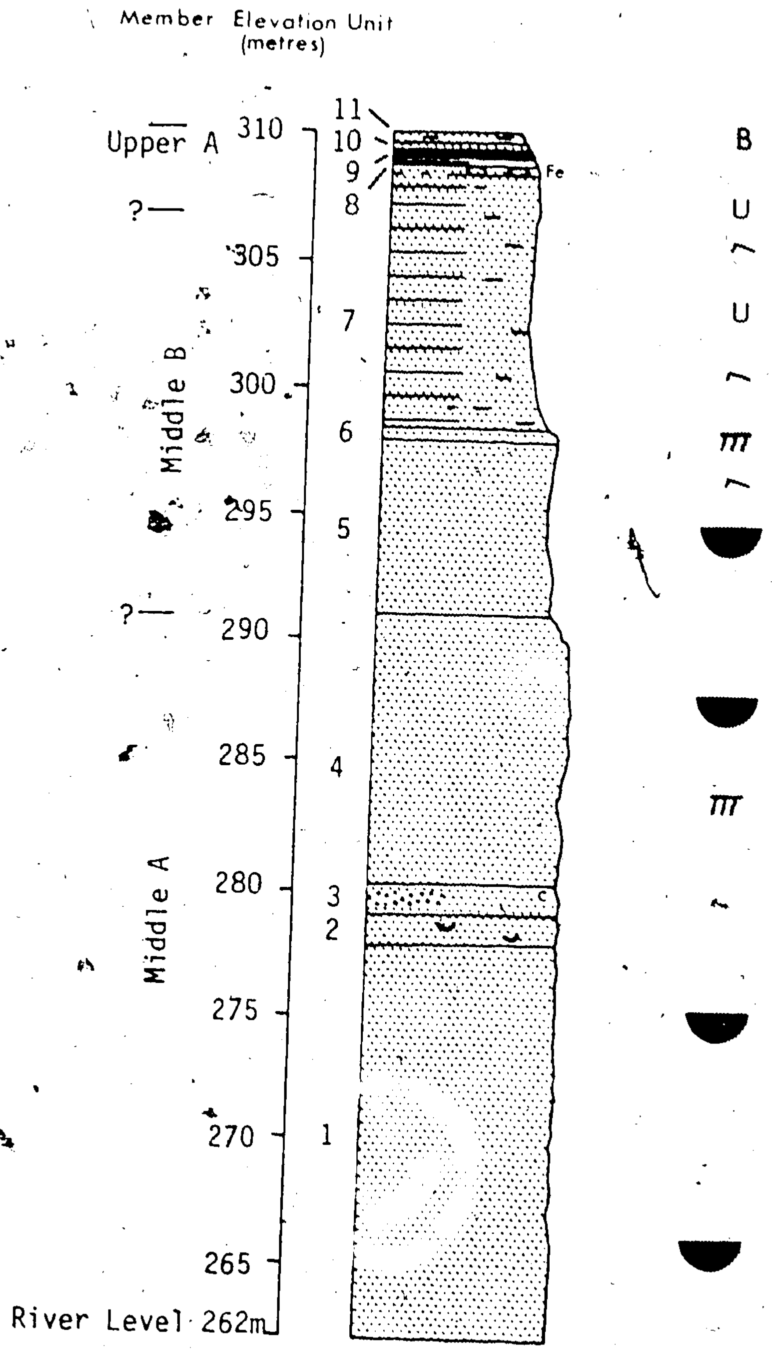
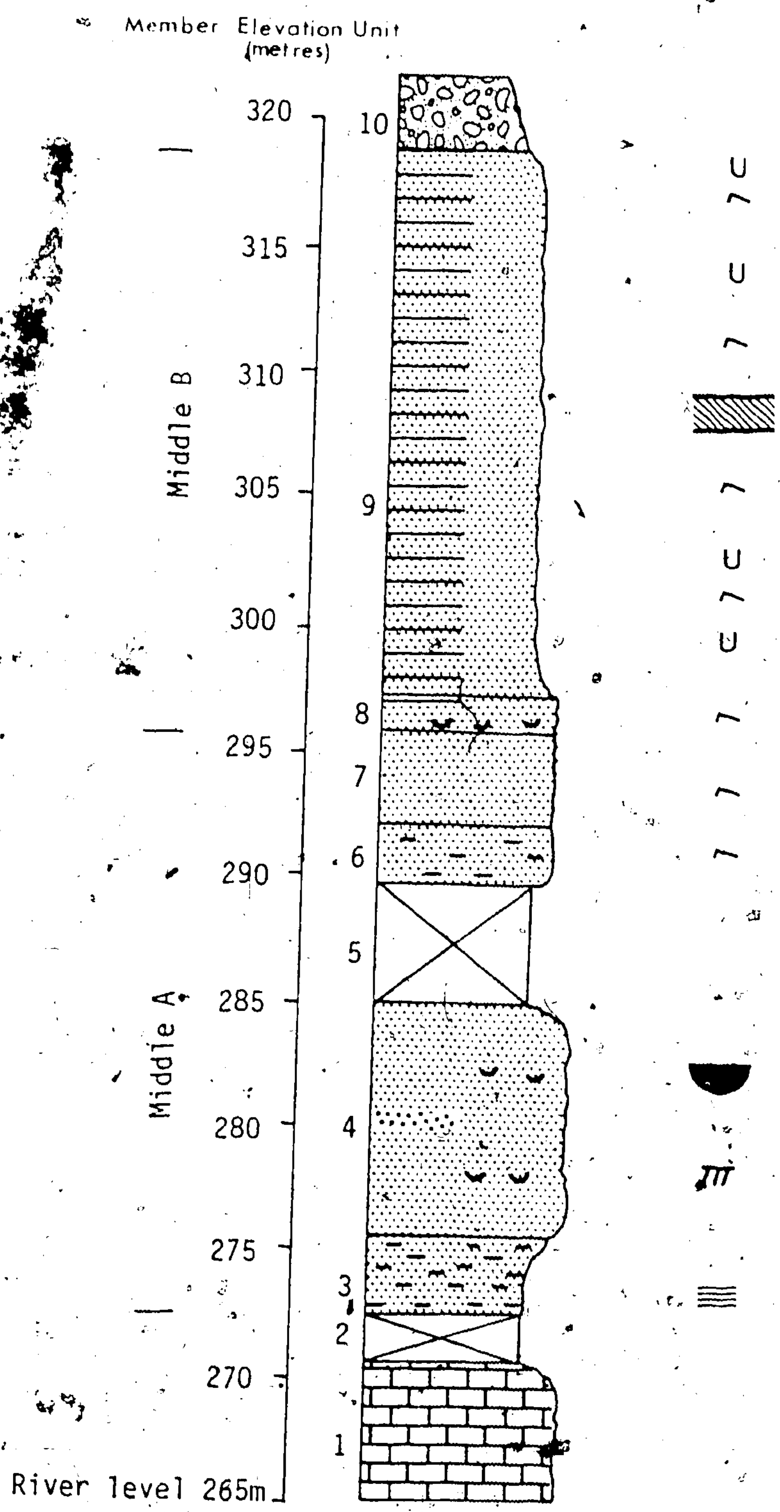

Member
Elevation (metres)
Unit
Upper A
Middle B
Middle A
?
310
305
300
295
290
285
280
275
270
265
River Level 262m
11
10
9
8
7
6
5
4
3
2
1
Fe
c
B
U
U

Figure 30. Columnar section of outcrop 6.
(Central ravine of outcrop)

Unit	Thickness (metres)	Description
[illegible]	0.6	Sandstone, very light grey, very fine grained, very argillaceous; apparently bioturbated; crumbly and very recessive.
10	0.3	Sandstone, yellow-brown, very fine grained; in places cemented into ironstone bed.
9	0.12	Coal, lignite to sub-bituminous.
8	0.3	Shale, grey to brown, soft; no fissility.
7	10.7	Oil sand, grey to brown-grey, very fine to fine grained; very argillaceous, beds 5 to 15 cm, interbedded with shale and silt beds 2 cm thick; well-defined bedding; occasional ripple bedding and medium scale cross-beds; burrows present, especially in lower parts of beds; poor exposure.
6	0.3	Sandstone, light brown, very fine to fine grained; resistant bed containing 50 cm cross-bed set.
5	6.7	Oil sand, black to grey, very fine to fine grained; cross-bedded or rippled throughout individual beds; bedding up to 60 cm thick.
4	10.7	Oil sands, black, very fine to fine grained, cross-bedded throughout, trough cross-beds up to 1.2 metres thick.
3	1.2	Oil sand, black, very fine to fine grained; abundant carbonaceous material in seams and pockets; zones of medium to very coarse oil sand.
2	1.2	Oil sand, light grey, fine grained, with large shale clasts (5 to 8 cm in diameter), light grey, rounded; top 8 cm of unit is medium to coarse sand with some cut and fill structures.
1	15.9	Oil sand, dark grey, fine grained; bedding 5 centimetres to 60 cm, poorly defined; cross-bedded throughout, sets average 30 cm thick; one trough set at least 1.5 metres thick; shale clasts in some sets; burrows seen at top of one cross-bed set, but very rare.

Figure 31. Outcrop 7. Interlaminated shale, silt and very fine sand overlies the limestone at bottom right of the outcrop. This is the only occurrence of shaly sediments in the Middle A Member. The apparent dip of epsilon bedding in the Middle B Member changes with height in the section (see text for discussion).



Member Elevation Unit
(metres)
320
315
310
305
300
295
290
285
280
275
270
River level 265m
Middle B
Middle A
10
9
8
7
6
5
4
3
2
1

Figure 32. Columnar section of outcrop 7.
(Lower 11 metres measured in centre of outcrop.
Remainder of section measured at upstream end.)

Unit	Thickness (metres)	Description
10	2.8	Glacial drift
9	21.6	Oil sand, grey to brown-grey, very fine to fine grained, interbedded with shale; oil sand beds 5 cm to 50 cm, shale beds 1 cm to 15 cm; alternating series of rippled beds, shale beds, burrowed beds, and medium scale (7-10 cm thick) cross-bed sets; shale beds clean, generally completely bioturbated; many beds of oil sand grade from dark and massive at base to lighter and rippled at top; above 302 m, bedding is thinner (5-15 cm), with higher percentage of shale; above 310 meters, burrows more abundant.
8	1.2	Oil sand, grades from dark at the base to light at the top, very fine to fine grained; shale fragments at base, rippl[illegible] through top 3/4 of unit; 8 cm shale bed at t[illegible]
7	3.7	Oil sand, light grey, very fine to fine grained; abundant ripples, also massive beds; 5-10 cm of shale at top; beds of oil sand are not separated by beds of shale as in overlying units.
6	2.4	Oil sand, light grey, very fine grained, argillaceous; bedding 2 to 30 cm; very well developed ripple [illegible] throughout.
5	4.6	[illegible]
4	9.1	[illegible] black, fine grained; bedding on scale of 1 metre, poorly defined; cross-bedded throughout, sets 15 cm to 2 m thick; shale rip-up clasts to 10 cm present along bedding, often separating cross-beds; some sets separated by medium to coarse sand, occasional beds about 30 cm thick contain lenses and pockets of clean, light grey shale.
3	3.4	Oil sand, red-brown, very fine to fine grained, interbedded to interlaminated with shale, grey; bedding on scale of millimetres to 5 centimetres; no burrows, channeled into by overlying oil sand.
2	1.8	Covered.
1	5.5	Limestone, green-grey, rubbly; oxidized zone at top is in places hard ironstone.

sands, the top of the shaly unit becoming lower in the upstream direction. This unit is apparently not burrowed and could be interpreted either as overbank deposits associated with Middle A Member channel sands, or else as an earlier deposit which was largely eroded away by the channels of the Middle A Member. The Middle A Member is thick at this outcrop (25 metres) with trough cross-bedding at the base and poorly saturated ripple-marked sandstone at the top.

The inclined bedding of the Middle B Member is very well exposed but the Middle A/Middle B Member contact is not well defined. This is probably because of the nature of the lower parts of the Middle B Member. The deepest part of the Middle B Member paleochannel, with its greater energy, would stand a good chance of producing preservable scour and fill structures cut into the underlying Middle A Member. The resultant lenticular scour and fill bedding, beneath the epsilon cross-bedding of the higher parts of the point bar, may resemble the Middle A Member sands.

At the base of the Middle B Member at the location where the section was measured is a 1.2 metre-thick bed of oil sand with clay clasts at the base, ripples throughout the bulk of the bed, and a 7 cm bed of clay at the top. Samples taken from this bed indicate virtually no vertical change in grain size or clay content.

The thickness of the epsilon cross-stratification sets, and therefore the depth of the paleochannel, is about 25 metres.

The dip of the cross-stratification changes upward through the section (Fig. 31). At the base, the dip is very low, becoming greater up section to a maximum of about 12^{0}, and returning to a low angle near the top. This change may be the result of the exposure of different apparent dips of epsilon cross-stratification. Because the paleochannel was migrating, the apparent dip of the point bar surface, as seen in cross-section, would vary as the orientation of the channel changed relative to that of the cross-section. Thus the low-dip beds at the base of the Middle B Member are seen almost in strike section while those at a higher angle are seen very close to true dip. Alternative explanations for these changes in dip are 1) that the paleochannel had a large flat channel floor resulting in the low dip beds at the base and as the channel migrated the steeper beds higher on the point bar came to overlie them, or 2) the migration of the channel brought it into contact with material more resistant to erosion (silt and shale instead of sand) which resulted in a deeper, narrower channel and thus a higher dip to the point bar.

No units above the Middle B Member are present in the outcrop, but the top of the outcrop on the downstream end is heavily burrowed with apparent dips approaching horizontal. These beds may be transitional to the missing Upper A Member. The top of the outcrop is truncated by Pleistocene erosion and is overlain by glacial drift.

Outcrop 8

This is a large outcrop but so much of it is obscured by talus that a section was not measured. Limestone is present at the base of the outcrop except for the 20 metre length where it is replaced by the Lower Member as discussed in Chapter 2, 'Lower Member.'

Outcrop 9

Outcrop 9 is well exposed but is largely unweathered, resulting in obscure sedimentary structures. The base of the outcrop is mostly covered but, where exposed, grey to reddish poorly saturated sands of the Lower Member are present.

Standing on the outcrop, the Middle A/Middle B contact is difficult to pick, but from a distance, the discordance in bedding can be seen (Fig. 33).

The Middle B Member in this outcrop is very different from that of other outcrops in that it displays characteristics more like those of the Middle A Member. Except for the top thinner-bedded 4.5 metres of the member, large scale trough cross-beds (30-60 cm thick sets) are common and no burrows are present. The presence of trough cross-bedding in the higher parts of the Middle B Member, which is generally characterized by ripple bedding, indicates deposition of the sands in a higher flow regime than is usual for the member.

At the downstream end of the outcrop, thick (10 to 50 cm) grey shale beds are present between oil sand beds (Fig. 34). In places, the shale is rhythmically interbedded with very fine sand and silt laminae which, having slight oil saturation, are brown. Locally, these shales have been eroded and incorporated

Figure 33. Outcrop 9.

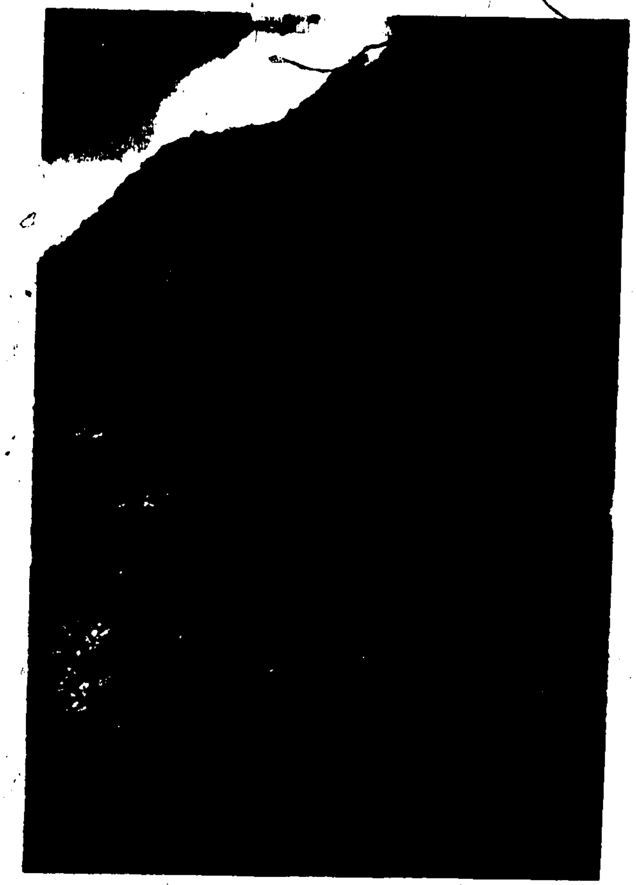
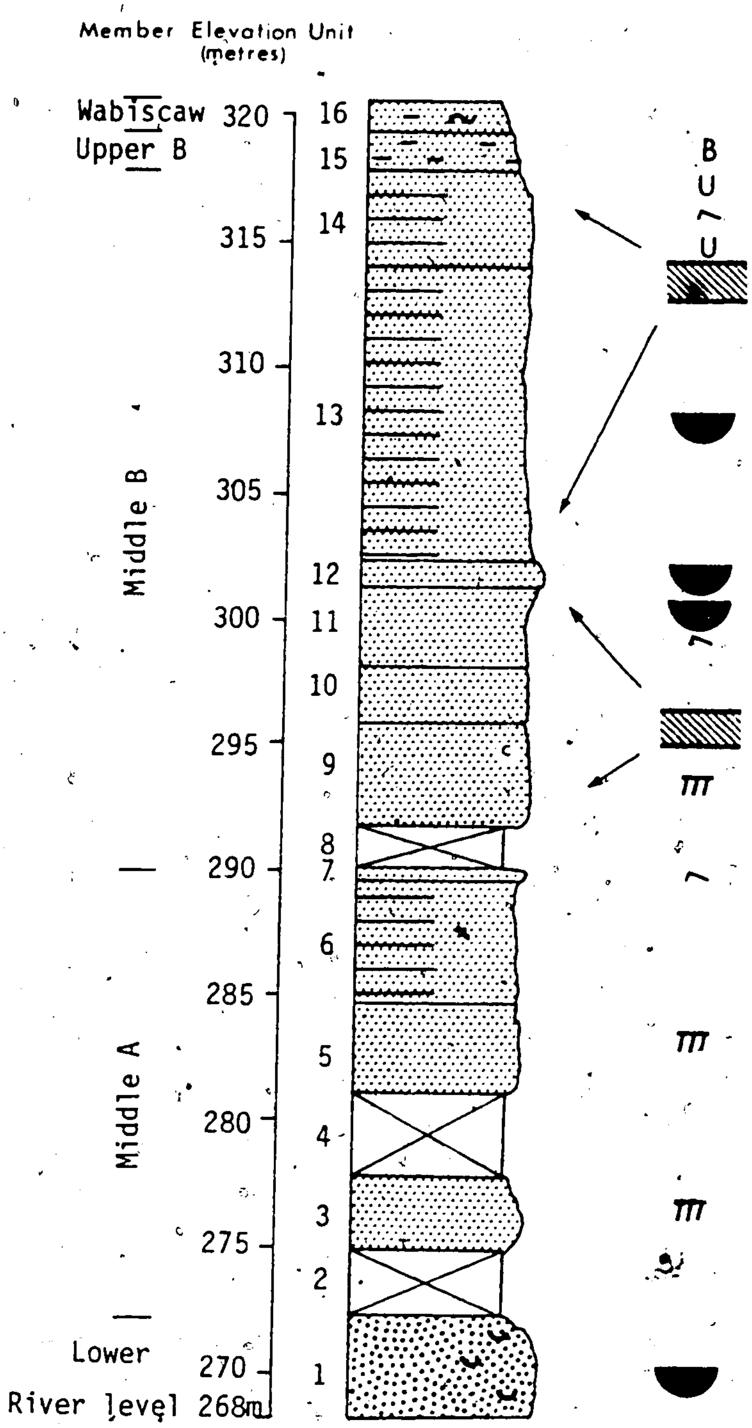


Figure 34. Thick shale units (light colored, laminated) separating oil sand beds (dark, blocky) within epsilon cross-stratification, outcrop 9. Lowest thick shale unit is approximately 60 cm thick.



Member
Elevation (metres)
Unit
Wabiscaw
Upper B
Middle B
Middle A
Lower
River level 268m
320
315
310
305
300
295
290
285
280
275
270
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

Figure 35. Columnar section of outcrop 9.
(Ravine at upstream end of outcrop)

Unit	Thickness (metres)	Description
16	1.5	Sandstone, very fine grained, very argillaceous, glauconitic.
15	1.5 —	Oil sand, dark grey, very fine grained, very silty and argillaceous; apparently bioturbated.
14	3.9	Oil sand, light grey to reddish brown, very fine to fine grained, all beds less than 30 cm thick, interbedded with shale beds 2-5 cm thick; occasional trough cross-bedding in 30 to 60 cm thick sets.
13	11.3	Oil sand, dark grey, fine grained, beds 10 cm to 15 cm thick, interbedded with shale beds 2-5 cm thick; occasional trough cross-bedding in 30 to 60 cm thick sets.
12	1.2	Oil sand, light grey, fine grained, cross-bedded throughout; resistant.
11	2.7	Oil sand, black, fine grained, trough cross-bedded throughout; occasional shaly beds; occasional ripples.
10	2.1	Oil sand, black, fine grained; at top of unit are medium scale (10 cm thick set) cross-beds.
9	3.9	Oil sand, black, fine grained, generally cross-bedded; bands of shale and carbonaceous material; carbonaceous material up to 15 cm thick or a series of thinner beds with oil sand between.
8	1.5	Covered.
7	0.6	Oil sand, light grey, fine grained, rippled at top; resistant shelf across outcrop.
6	4.9	Oil sand, dark grey, fine grained, interbedded with shale, 5-15 cm thick oil sand beds separated by up to 1 cm of shale.
5	3.4	Oil sand, dark grey, fine grained, non-argillaceous; cross-bedding present.
4	3.4	Covered.
3	2.8	Oil sand, black, fine grained, cross-bedded.
2	2.7	Covered.
1	4.3	Oil sand, reddish to light grey, medium to coarse grained, bedding poorly defined; small (2-5 mm) clay clasts throughout much of exposure. Trough cross-bed sets 20 cm to 60 cm thick.

into the overlying oil sand as rip-up clasts. In places, ripple-marked oil sand beds grade upwards into the laminated shale without a distinct break. These thick shale beds occur quite deep in the paleochannel, as can be determined by their position within the epsilon cross-bedding, and represent the finer-grained sediments deposited during low water stages of the stream.

The top of the Middle B Member is bedded on a smaller scale (10 cm), burrowed, and weathered reddish brown, as is often the case at the top of this member. The epsilon cross-bedding comprising the Middle B Member is approximately 25 metres thick in this outcrop, indicating a paleochannel 25 metres deep. The epsilon beds have an apparent dip of about 5^{o} to the north-west along the cliff face.

The Upper B Member, a dark grey, very shaly oil sand, directly overlies the Middle B Member.

Outcrop 10

The bulk of this outcrop is poorly exposed. Upstream from the main outcrop, inclined bedding of the Middle B Member is seen to be truncated at the top by the Upper B Member (Fig. 36). This shows that there is, at least in some places, erosion preceeding the deposition of the Upper B Member. The apparent dip of the epsilon cross-stratification in this location is 10^{o} in a direction 260^{o} azimuth.

One of the few accessible exposures of the glauconite sand of the Clearwater Formation is at this section.

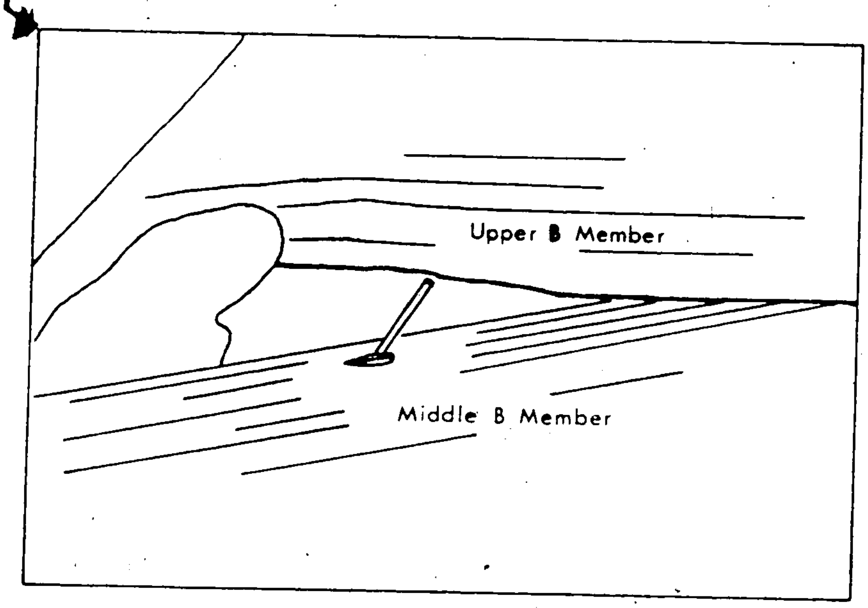
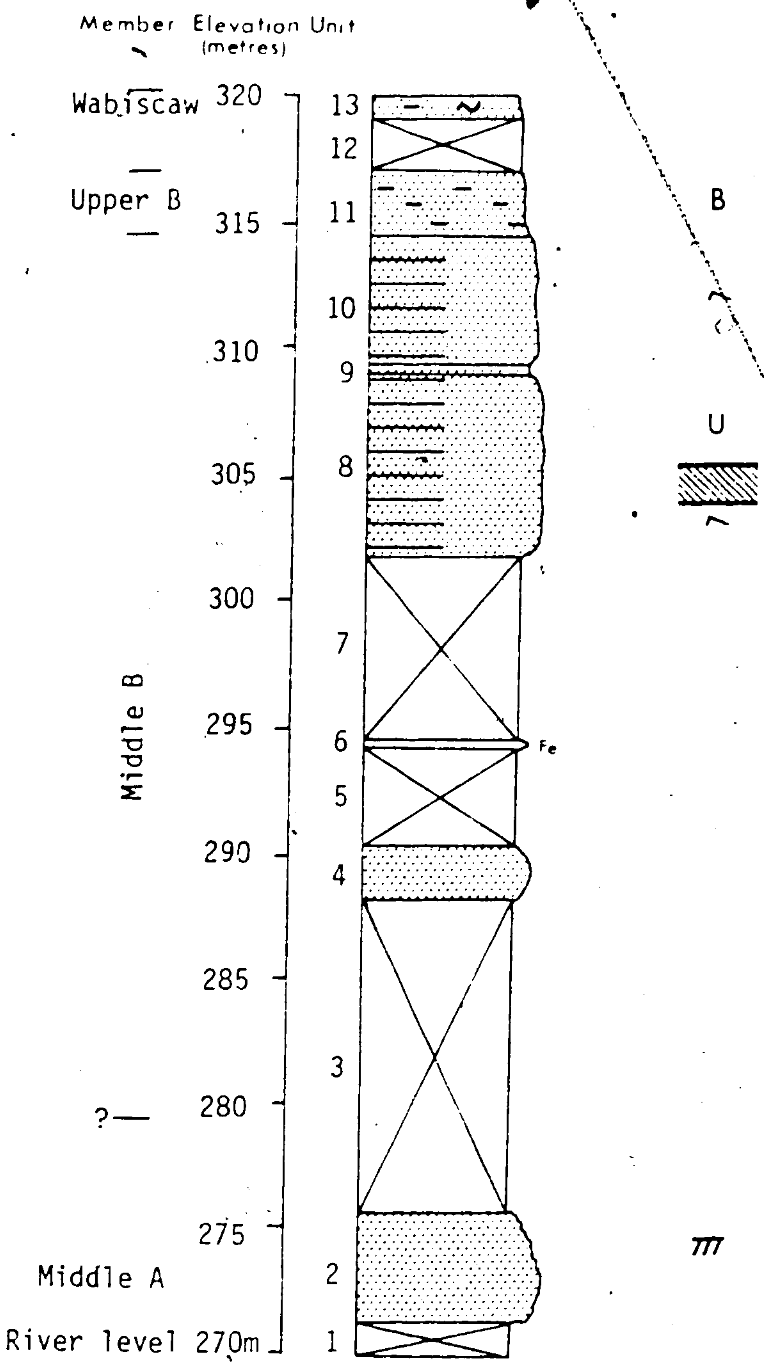


Figure 36. Truncation of Middle B Member epsilon cross-bedding by erosional base of Upper B Member, outcrop 10. Bedding in the Upper B Member is horizontal.



Member
Elevation (metres)
Unit
Wabiscaw
Upper B
Middle B
Middle A
River level 270m
320
315
310
305
300
295
290
285
280
275
13
12
11
10
9
8
7
6
5
4
3
2
1
Fe
B
U
?

Figure 37. Columnar section of outcrop 10.
(Upstream end of outcrop)

Unit	Thickness (metres)	Description
13	1.2	Sandstone, very fine grained, very silty and argillaceous; glauconitic.
12	1.8	Covered.
11	2.4	Oil sand, grey, very fine grained, very argillaceous; thin laminae of shale throughout the oil sand, bedding (partings) on scale of 5-8 cm; looks like shale from distance; apparently bioturbated.
10	5.2	Oil sand, very fine to fine grained, interbedded with shale, grey, fissile; bedding on scale of 2 to 30 cm; at top is 30 cm thick bed of light brown oil sand, rippled throughout.
9	0.3	Oil sand, poorly saturated, interbedded with shale and shaly oil sand, bedding 2 to 5 cm thick.
8	7.3	Oil sand, light grey, very fine to fine grained, beds 60 cm to 1 m, interbedded with shale, beds 2-3 cm; rippled throughout, laminated in part, occasional burrows in unrippled shalier beds; resistant unit; less saturated, lighter near top; occasional beds and lenses of grey shale; bedding has apparent dip of 8-10°.
7	7.3	Covered.
6	0.3	Ironstone bed; good jointing.
5	3.9	Covered.
4	2.1	Oil sand, dark grey, very fine to fine grained, bedding on scale of 15 cm to 1 m; structures not visible; poor exposure.
3	13.1	Covered.
2	3.6	Oil sand, dark grey, fine grained, cross-bedded, apparently planar bedding on scale of 30 cm to 1 m, often based on zones of small shale clasts; little shale present.
1	1.5	Covered.

Outcrop 11

Examination of this small outcrop indicated that the top of the McMurray Formation is approximately 18 metres lower than at surrounding outcrops. Drilling results from the Steepbank River (Government of Canada 1949) show that the elevation of the Devonian limestone is about 20 metres lower in a hole drilled near outcrop 11 (245 m A.S.L.) than in holes drilled near outcrops 9, 10 and 12 (265 $\pm$ 5 m A.S.L.). The most probable explanation for this anomaly is post-McMurray collapse of both the limestone and overlying McMurray Formation, probably due to solution of the Elk Point evaporites. This type of collapse, on a much larger scale, has been interpreted by Carrigy (1959a) to be the cause of the Bitumount basin (Twp. 96, Rges. 10 and 11) where collapse has occurred in post-Cretaceous times.

Epsilon cross-bedding in this outcrop has an apparent dip of up to 15^{o} to the north-west. The dip of an individual bed lessens considerably as one follows it 'up the point bar' (Fig. 38).

Outcrop 12

Outcrop 12, another large, well-exposed outcrop, is dominated by a cross-cutting bed extending the length of the outcrop (Figs. 40, 41). The bed begins as a thin, horizontal bed at the top of the Middle B Member in the downstream part of the outcrop. As it is followed upstream, it cuts through older beds at an angle of about 15^{o}, becomes much thicker (4.5 metres) and eventually horizontal again. The entire bed is laminated to rippled

Figure 38. Outcrop 11.

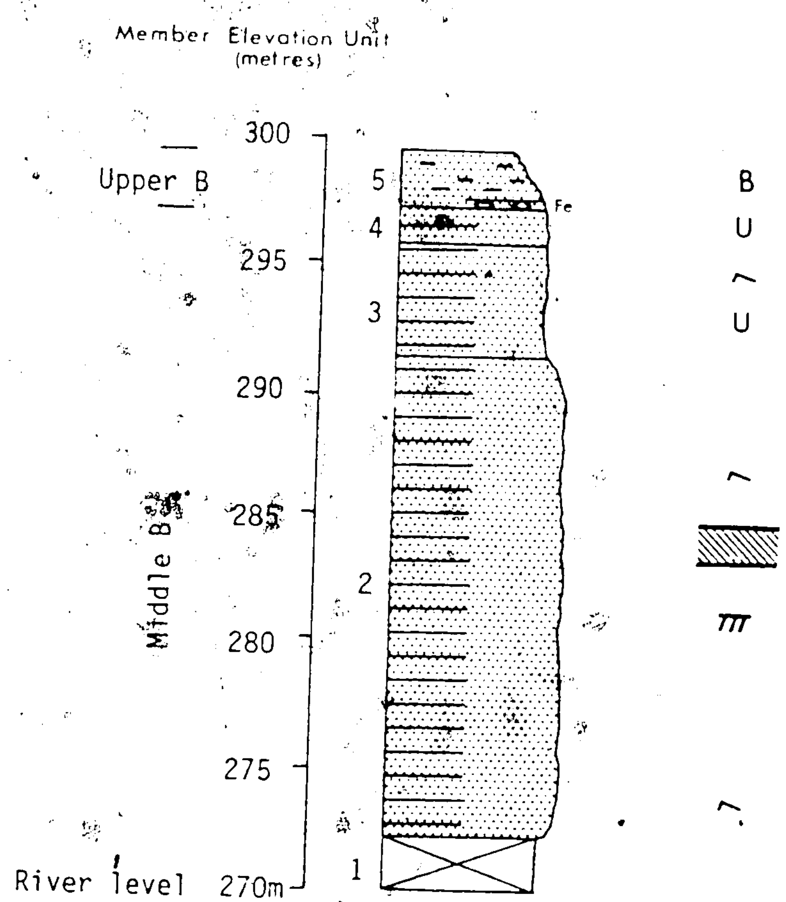

Member
Elevation (metres)
Unit
Upper B
Middle B
River level
300
295
290
285
280
275
270m
5
4
3
2
1
Fe
B
U
U

Figure 39. Columnar section of outcrop 11.
(Downstream end of outcrop)

Unit	Thickness (metres)	Description
5	2.1	Oil sand, dark grey, very fine grained, very silty and argillaceous, very recessive; apparently bioturbated.
4	1.2	Oil sand, brown-grey, very fine to fine grained, beds 2 to 15 cm thick, interbedded with shale beds 2-5 cm thick; abundant burrows, in places bioturbated; more shale towards top; in places, ironstone bed at top.
3	4.9	Oil sand, very fine grained, beds 20 cm to 1 m thick, interbedded with shale up to 10 cm thick; generally rippled with some burrows in shalier zones.
2	18.9	Oil sand, very fine grained, beds to 1 m, interbedded with shale beds up to 60 cm; ripple bedding with some medium to large scale cross-beds (sets to 60 cm); lower beds have depositional dip.
1	2.1	Covered.

Figure 40. Outcrop 12, downstream end. Cross cutting bed at upper left extends the length of the outcrop (see Fig. 41).

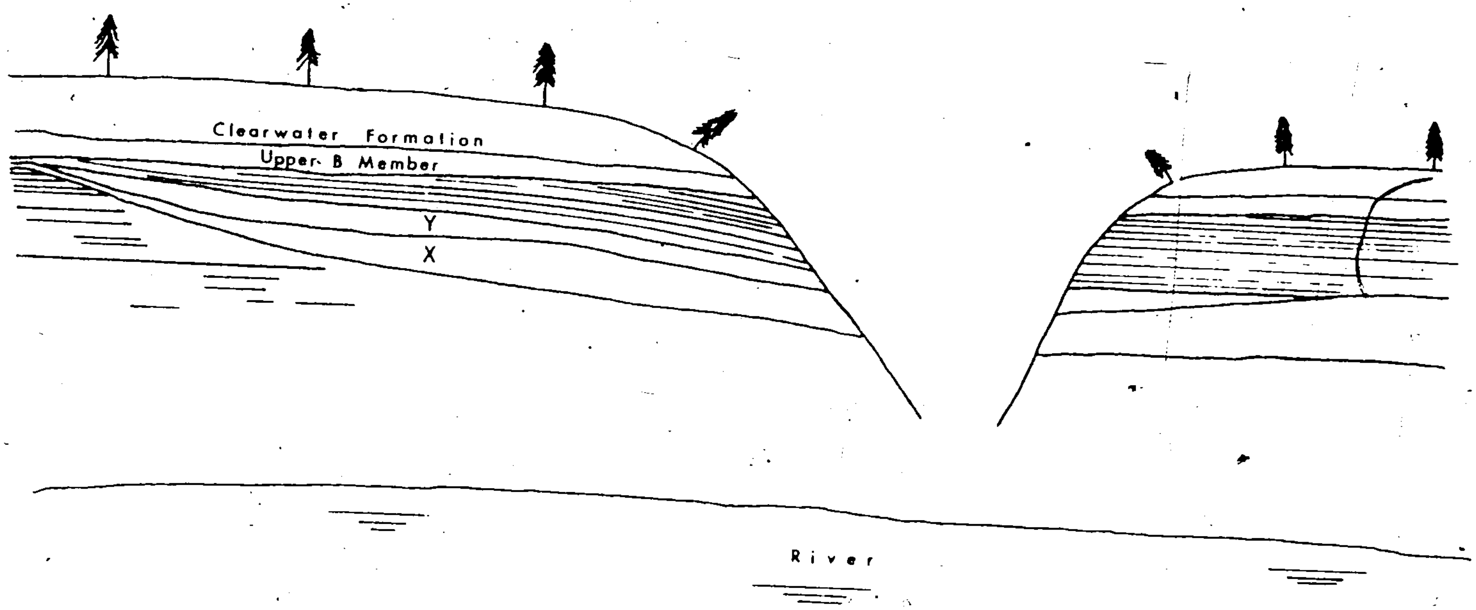


Figure 41. Outcrop 12. The cross-cutting bed (X) constitutes the first sediments deposited by a Middle B Member channel which cut through previous Middle B sediments. Overlying this is another thick, rippled channel-fill sand (Y) followed by a set of epsilon cross-stratification.

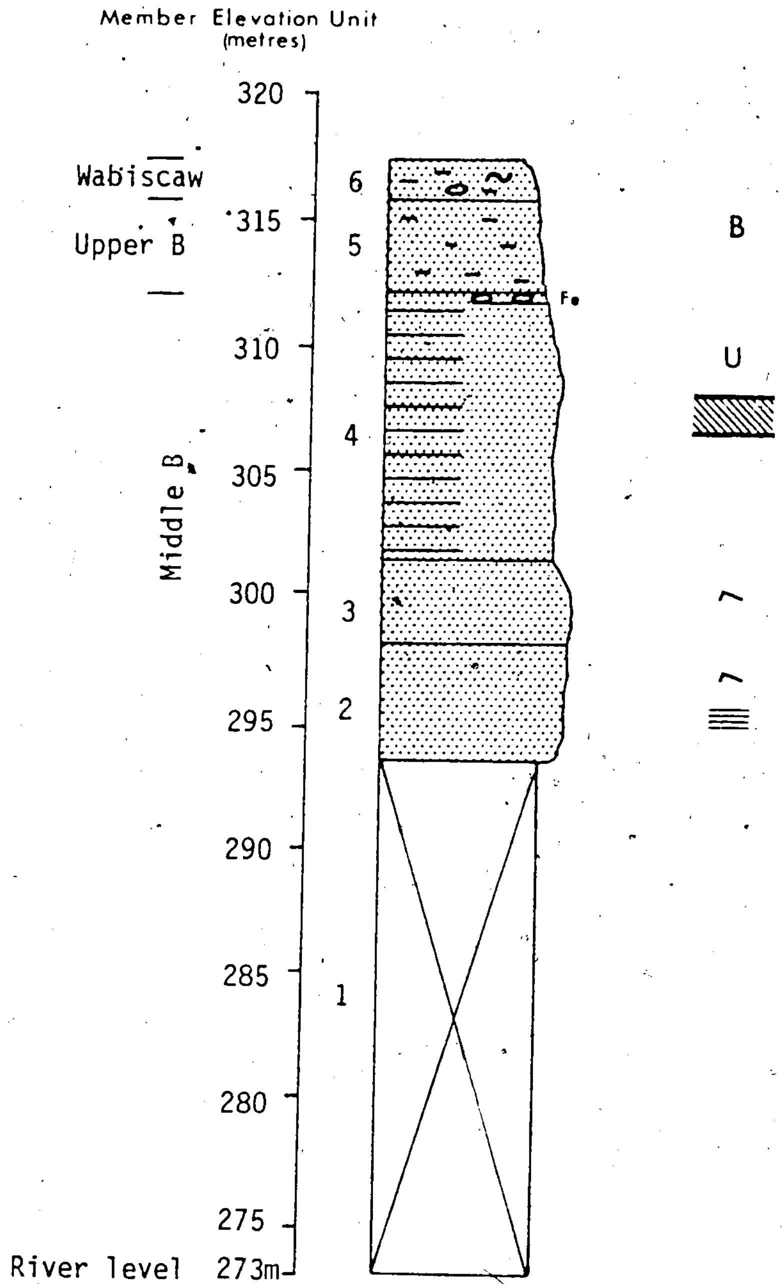

Member Elevation Unit
(metres)
320
Wabiscaw
6
315
Upper B
5
Fe
B
310
U
4
Middle B
305
300
3
2
295
290
285
1
280
275
River level 273m

Figure 42. Columnar section of outcrop 12.
(Central ravine of outcrop)

Unit	Thickness (metres)	Description
	1.2	Sandstone, very fine grained, very argillaceous, slightly glauconitic; some ironstone beds.
5	3.9	Oil sand, dark grey, very fine grained, very argillaceous; from distance looks like shale; fissile, bedding 5-10 cm.
4	10.4	Oil sand, very fine grained, argillaceous, bedding 5 cm to 60 cm, interbedded with shale beds up to 5 cm thick; burrows apparently present but obscure; medium scale cross-bedding present; ironstone bed at top.
3	3.4	Oil sand, light grey, very fine to fine grained; ripple bedded throughout; less shaly than underlying unit.
2	4.3	Oil sand, light grey, very fine to fine grained; laminated to rippled throughout; no internal bedding.
1	20.7	Covered.

throughout. Above this bed is another thick (3 m), wedge-shaped bed which has apparently scoured into the lower bed. Concordantly overlying these two units is a set of epsilon cross-stratification resulting from deposition on the point bar of the same channel. This epsilon set wedges out to the west where the original channel margin is high in the section. The paleochannel was 18 metres deep and the current direction, judging from the ripple marks, was approximately south to south-west.

The top of the epsilon cross-stratification is again reddish and an ironstone bed is present, in places, at the Middle B/ Upper B contact.

Drilling Results

Several wells drilled north of the Steepbank River are composed largely of silt and clay, just as Carrigy's subsurface type section is mostly fine-grained material compared to his outcrop type section which is almost totally sand-size material. The lack of fine-grained sections in outcrop is probably due to their recessive nature but it is also possible that the present Steepbank River preferentially cuts through oil sand rather than the perhaps more cohesive silts and clays. Paleocurrent directions indicate the present Steepbank River flows in the same direction as the drainage of Cretaceous time. It is possible that the Steepbank River follows the meander belt of a Cretaceous channel.

The closest available cored well to the outcrop area (location in Fig. 2) is about 1 km east of outcrop 3

(SOBC FL 1-74 1-1, 14-29-92-9W4). This well consists mostly of argillaceous oil sand interlaminated with shale with only occasional small intervals (0.5 to 1.5 m) of good oil sand. The average oil saturation is about 3% by weight. The core is described in Appendix C.

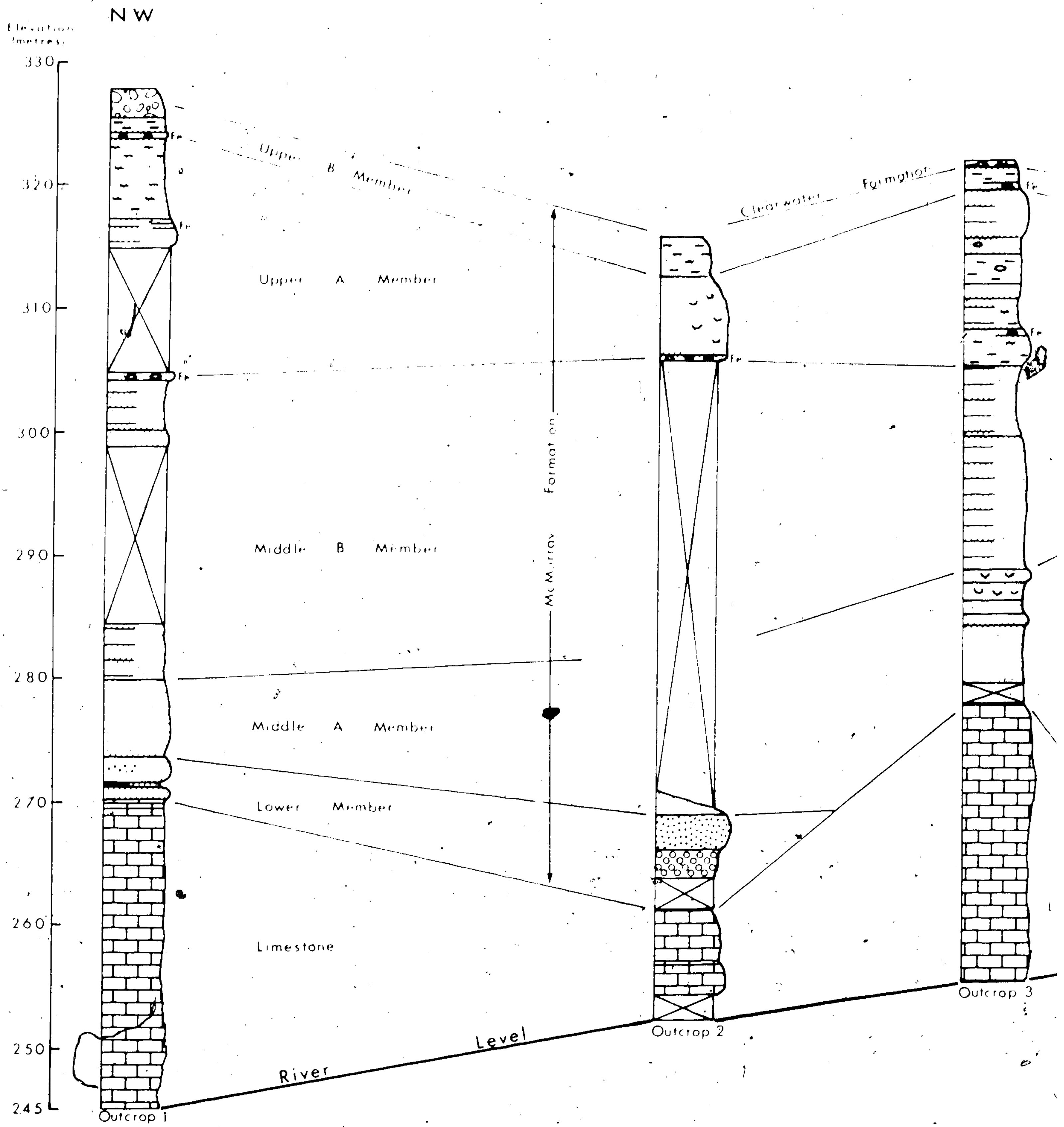
Structural Cross-section

In the structural cross-section of the Steepbank River area (Fig. 43), an attempt has been made to correlate the members of the McMurray Formation. In places, it is difficult to differentiate the Middle A and Middle B Members, especially in poorly exposed outcrops and where, because of the orientation of the outcrop, there is no apparent dip to the epsilon cross-beds of the Middle B Member. In the Upper Members, unlike the underlying fluvial sands, individual beds are much more extensive. The Upper B Member, the base of which may be nearly a time surface, is the most consistent unit in the outcrop area.

It is not known to what extent post-McMurray collapse has occurred, and therefore how closely the present structure resembles that at the time of deposition. As previously discussed, outcrop 11 has undergone post-McMurray collapse, and less obvious downward movement may have occurred at other outcrops, for example, outcrop 6.

Outcrop 4 was omitted because joining outcrop 3 to 4 produces a line perpendicular to the line of cross-section which runs essentially southeast-northwest.

Elevations were determined by estimating river level elevation at each outcrop from 1:50,000 NTS maps. These estimates are thought to be accurate to within 2 metres.



NW
Elevation (metres)
330
320
310
300
290
280
270
260
250
245
Upper B Member
Clearwater Formation
Upper A Member
McMurray Formation
Middle B Member
Middle A Member
Lower Member
Limestone
River Level
Outcrop 1
Outcrop 2
Outcrop 3

STRUCTURAL CROSS-SECTION, STEEPBANK

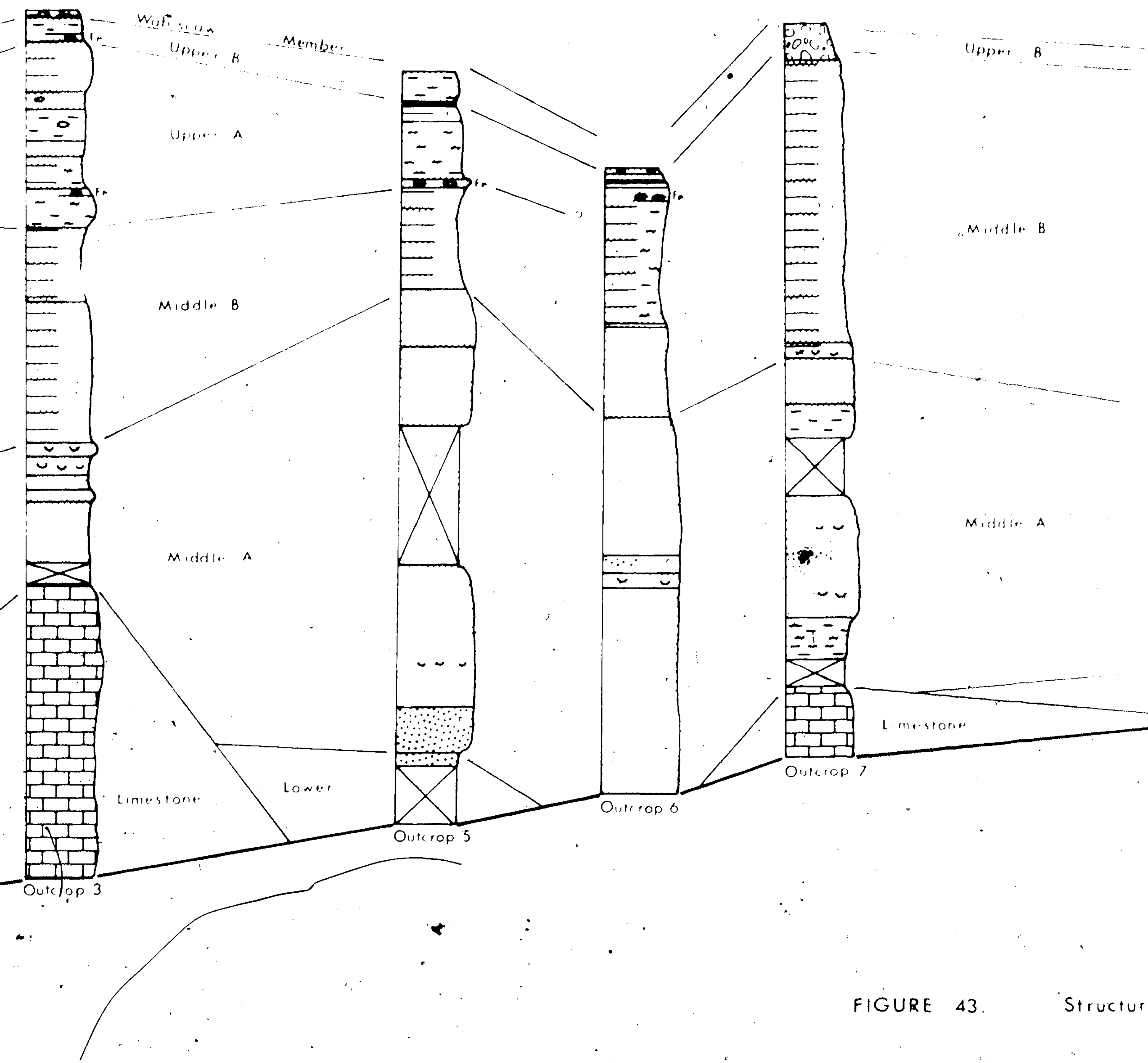


FIGURE 43. Structur

OSS-SECTION , STEEPBANK RIVER VALLEY

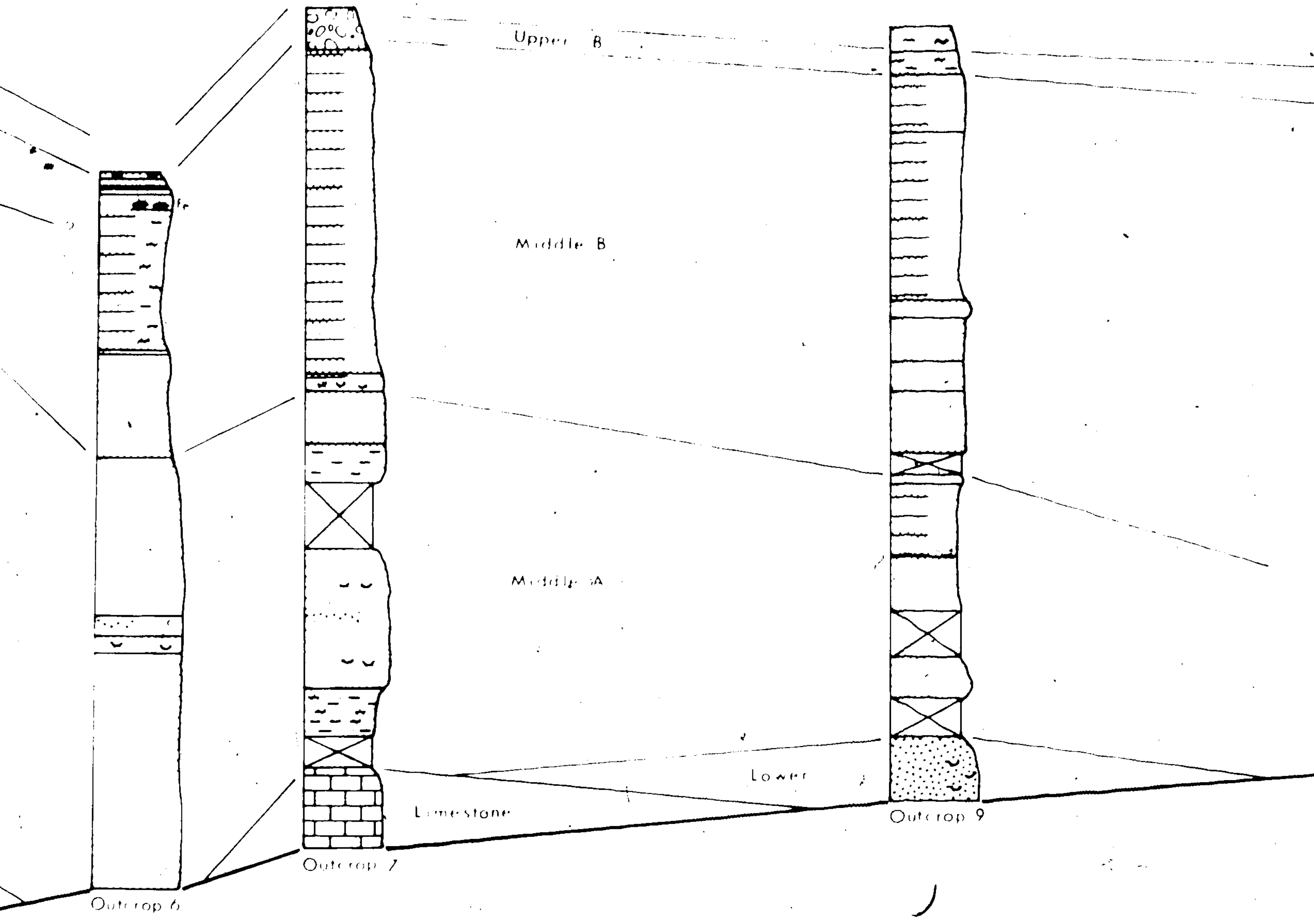
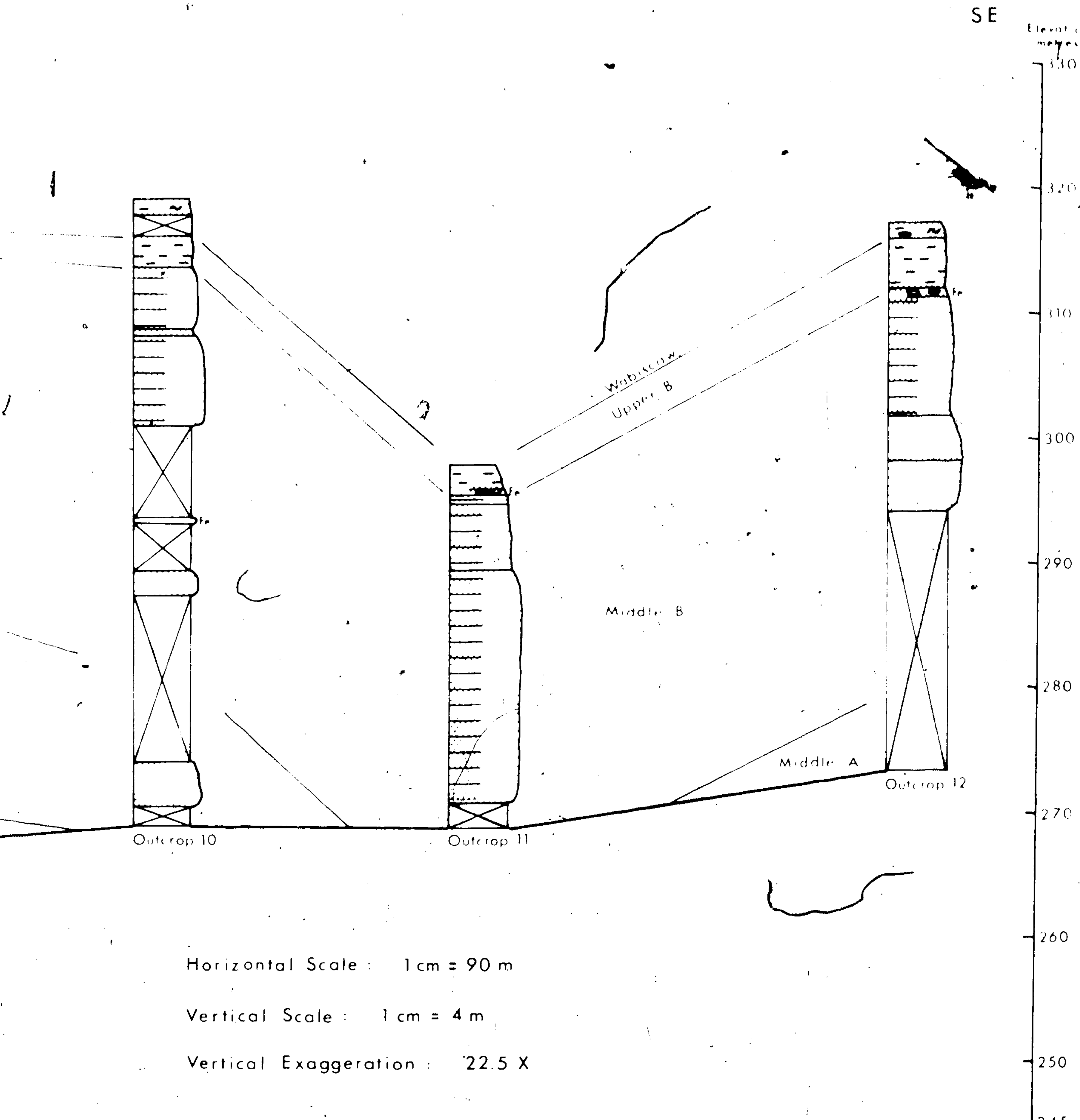


FIGURE 43. Structural cross-section, Steepbank River valley

3 of



Horizontal Scale : 1 cm = 90 m

Vertical Scale : 1 cm = 4 m

Vertical Exaggeration : 22.5 X

valley.

CHAPTER 4

DEPOSITIONAL ENVIRONMENTS

In early Cretaceous time in the Athabasca oil sands area, a well-developed drainage system was present on the limestone landscape (Carrigy, 1973b). Many karst features are present in the Steepbank River area and elsewhere in the Athabasca oil sands, indicating substantial underground drainage. During this time of relatively low sea level, the rivers flowing to the north were capable of transporting a load of coarse sand and gravel. The 'backwater effect' (Blatt et al., p. 586) of a rise in sea level results in deceleration of flow and an increase in water depth for distances far upstream from base level. As the boreal sea transgressed, therefore, the rivers lost some of their transporting capability and deposition began. The rugged local topography was thus subdued by the sediments of the Lower Member.

The Middle A Member is interpreted to be the blanket sand of a fluvial channel complex. Large-scale trough cross-stratification is generally present at the base of the member, with set thicknesses decreasing with height in the section. Above the trough cross-beds, ripple bedding is often the dominant structure. This succession of sedimentary structures results from a lowering of flow regime. The change of bedform from dunes to ripples in response to lowering flow regime has been well established both by flume studies (Simons et al., 1965) and in studies of modern rivers (Allen, 1965b). The environment of deposition of this member is envisaged to be fluvial systems on a plain of low relief.

The epsilon cross-stratification of the Middle B Member indicates point bar deposition in deep meandering channels which may have been in close proximity to the sea. The amount of marine influence in these channels has not been firmly established. Land and Hoyt (1966) attempted to find some criteria to distinguish fluvial from estuarine point bar deposits. They concluded that, as processes of deposition are very similar, the only diagnostic properties of estuarine point bars are the presence of marine fossils and the traces of abundant life. As previously discussed, the burrows of the Middle B Member are interpreted to be the work of fresh water worms but Chamberlain (1975) notes that even fresh water polychaetes are normally found close to the sea. The sediments of the Middle B Member are interpreted to represent the deposits of meandering channels on a coastal plain, possibly distributaries on a delta floodplain.

The Upper A Member of horizontally bedded sands and silts, overlying the channel sands of the Middle B Member, has a wide range of textures, reflecting more varied processes of deposition than the other members. Several different depositional environments are probably represented. The upper beds of this member, the laminated to bioturbated sands, are more continuous over the downstream part of the study area than the lower beds of the member. A model for the deposition of the upper part of this member must accommodate the presence of laminated sands, widespread bioturbation, local occurrences of coal, and small channels as indicated by epsilon cross-bedding. Laminated sands have been reported in a wide variety of environments from the upper flow regime of channels to beach deposits, and are not in themselves diagnostic. A unifying model incorporating all the evidence, however, is based on Van Straaten's (1959) description of a typical tidal flat environment. The tidal flat area is generally comprised of three identifiable sub-environments - salt marshes above mean high tide, tidal channels below mean low tide, and the tidal flat proper between the two. In the Steepbank River area, the salt marsh is thought to be represented by the coal deposits, the epsilon cross-bedding representing what is thought to be a tidal channel can be seen on outcrop 4, and the bulk of the member, the laminated to bio-turbated sands, are thought to be the deposits of the tidal flat proper. Epsilon cross-bedding is very common in modern tidal flats (Reineck and Singh, 1973). In fact, modern epsilon cross-bedding was first recognized in this environment. Van Straaten (1959) describes the sedimentary structures of the tidal flat proper as smooth, even laminae, sometimes showing ripple marks. Burrowing is common and on the higher parts of the tidal flats, which are generally sandy deposits, all traces of lamination are often obliterated. The upper Upper A Member is therefore believed to represent an upper tidal flat environment.

The lower part of the Upper A Member is only well exposed at two outcrops and generalities about its lithology cannot be made. However, one might expect coastal plain sediments such as levee, floodbasin, and crevasse splay deposits to overlie the channel sands of the Middle B Member. The presence of ironstone beds, laminated to thinly bedded silts, clays and sands, occasional bioturbation, and worm burrows characteristic of the channel sands below do not contradict this interpretation.

The Upper B Member of the McMurray Formation is believed to represent the first truly marine deposit in the study area. Palynological evidence indicates this member is marine. The base is erosional in places, if not throughout the area. This is typical of transgressive deposits (Visher, 1965), the erosion being the result of wave action. Oomkens (1971) found such a transgression plane in the Rhone delta overlain by a thin bed (less than one metre) which was completely homogenized by burrowing marine forms. Howard (1971) describes the offshore facies of Upper Cretaceous sediments of Utah as highly bioturbated siltstones which, other than a 'somewhat shaly appearance' contain no sedimentary structures due to complete biogenic reworking. Both these descriptions fit the Upper B Member. The depositional environment is interpreted to be near offshore. The trace occurrences of glauconite in this member suggest that it is transitional to the overlying glauconite sands of the Clearwater Formation.

The Wabiscaw Member of the Clearwater Formation is interpreted, on the basis of its fine grain size and glauconite content, to have been deposited in deeper water than the Upper B Member, in an environment of little turbulence and slow rate of sedimentation.

Implications for Future Recovery

The environmental model as outlined in this study does not hold true everwhere in the Athabasca oil sand deposit, as shown by the occurrence of the largely silt/shale sections in many cored drill holes. These can be in close proximity to a good oil sand deposit. The presence of epsilon cross-bedding, however, indicates that many of the favorable oil sand deposits are related to the meandering of large channels. An important consequence of this model is the possibility of tracing oil sand deposits along meander belts rather than considering them to be small, isolated deltas built into lakes and lagoons (Carrigy,1971). Besides aiding in the exploration for oil sand deposits, predicting the trend of the oil sand body may be helpful in the field of injection well/ recovery well *in situ* techniques where prediction of path of fluid flow could be very important.

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APPENDIX A Summary of Sample Analyses

Sample	Mean Grain Size Ø	Standard Deviation	Oil Saturation	Percentage Clay	Textural Classification (Shepard 1954)
1-1	2.11	1.30	3.9	6.5	Sand
2-1	2.67	2.24	0.4	6.6	Sand
3-1	0.92	2.54	3.6	7.6	Sand
3-2	3.16	0.95	15.1	0.9	Sand
3-3	3.33	1.08	7.5	1.4	Sand
3-4	3.27	1.02	10.7	1.1	Sand
3-5	3.45	0.97	12.8	1.0	Sand
3-6	3.28	0.89	8.1	1.0	Sand
3-7	3.60	1.07	8.4	1.2	Sand
3-8	4.40	1.41	12.2	3.9	Silty Sand
3-9	3.45	1.59	9.4	3.7	Sand
3-10	3.09	0.82	10.9	0.7	Sand
3-11	4.26	1.69	4.3	4.7	Silty Sand
3-12	4.02	0.71	9.2	1.8	Silty Sand
3-13	4.56	1.54	3.6	5.1	Silty Sand
3-14	4.14	2.37	2.4	11.1	Silty Sand
3-15	4.63	1.81	0.3	6.0	Silty Sand
3-16	4.91	2.39	Trace	14.6	Silty Sand
3-17	3.08	0.97	5.4	1.1	Sand
3-18	3.03	0.94	12.4	1.0	Sand
5-1	3.89	1.84	0.5	5.8	Sand

APPENDIX A (Continued)

Sample	Mean Grain Size Ø	Standard Deviation	Oil Saturation	Percentage Clay	Textural Classification (Shepard 1954)
6-1	2.66	0.94	15.5	0.8	Sand
7-1	5.79	2.28	3.9	16.6	Sandy Silt
7-2	5.10	1.83	5.9	7.1	Sandy Silt
7-3	2.66	1.14	17.4	1.2	Sand
7-4	3.38	1.11	5.8	1.6	Sand
7-5	3.45	1.10	14.5	1.3	Sand
7-6	3.42	1.04	13.1	1.2	Sand
7-7	3.40	1.02	10.0	1.4	Sand
7-8	3.45	1.08	4.8	1.6	Sand
7-9	3.44	1.08	13.5	1.2	Sand
7-10	3.45	1.04	10.0	1.4	Sand
7-11	3.33	1.00	13.1	1.2	Sand
7-12	3.37	0.91	12.5	1.1	Sand
8-1	2.49	2.54	2.2	7.7	Sand
9-1	2.82	2.79	3.1	9.7	Sand
9-2	2.30	0.80	?	0.5	Sand
9-3	2.72	0.80	14.8	0.4	Sand
9-4	2.47	0.76	13.1	0.5	Sand
9-5	2.59	0.74	12.6	0.6	Sand
9-6	2.62	0.88	4.0	0.9	Sand
9-7	2.91	0.84	13.5	0.7	Sand

APPENDIX A (Continued)

Sample	Mean Grain Size Ø	Standard Deviation	Oil Saturation	Percentage Clay	Textural Classification (Shepard 1954)
9-8	2.99	1.10	7.3	1.5	Sand
9-9	3.08	0.94	15.1	1.1	Sand
9-10	3.23	0.92	12.0	1.0	Sand
9-11	3.48	1.01	9.8	1.5	Sand
9-12	3.98	1.86	3.7	5.8	Silty Sand
9-13	6.17	2.43	Trace	20.6	Sandy Silt
9-14	6.27	2.15	2.0	21.0	Clayey Silt

Appendix A (Continued)

Locations of samples

Sample Number *	Text Reference
1-1	Appendix D, section 1-A, unit 10.
2-1	Figure 26, unit 5.
3-1	Appendix D, section 3-B, unit 5.
3-2	Figure 27, unit 3.
3-3	Figure 27, unit 5.
3-4	Figure 27, unit 7.
3-5	Figure 27, unit 8.
3-6	Figure 27, unit 8.
3-7	Figure 27, unit 8.
3-8	Figure 27, unit 9.
3-9	Figure 27, unit 10.
3-10	Figure 27, unit 12.
3-11	Figure 27, unit 13.
3-12	Figure 27, unit 14.
3-13	Figure 27, unit 15.
3-14	Figure 27, unit 16.
3-15	Figure 27, unit 17.
3-16	Appendix D, section 3-A, unit 14.
3-17	Appendix D, section 3-A, unit 3.
3-18	Appendix D, section 3-A, unit 4.
5-1	Figure 30, unit 13.
6-1	Figure 31, unit 1.
7-1	Figure 33, unit 3.
7-2	Figure 33, unit 3.
7-3	Figure 33, unit 4.
7-4	Figure 33, unit 6.
7-5	Figure 33, unit 8, 295.7 m elevation.
7-6	Figure 33, unit 8, 296.0 m elevation.
7-7	Figure 33, unit 8, 296.3 m elevation.
7-8	Figure 33, unit 8, 297.0 m elevation.
7-9	Figure 33, unit 9, 303.0 m elevation.
7-10	Figure 33, unit 9, 303.1 m elevation.
7-11	Figure 33, unit 9, 310.0 m elevation.
7-12	Figure 33, unit 9, 317.0 m elevation.
8-1	Lower member of outcrop 8.
9-1	Figure 36, unit 1.
9-2	Figure 36, unit 3.
9-3	Figure 36, unit 5.
9-4	Figure 36, unit 6.
9-5	Figure 36, unit 6.
9-6	Figure 36, unit 7.
9-7	Figure 36, unit 9.
9-8	Figure 36, unit 10.
9-9	Figure 36, unit 12.
9-10	Figure 36, unit 13.

Sample Number	Text Reference
9-11	Figure 3[illegible] [illegible]it 14.
9-12	Figure 36, unit 15.
9-13	Figure 36, unit 16.
9-14	Thick shale beds of outcrop 9, Middle B Member

* First number refers to outcrop number.

APPENDIX B Weight Percentages of Size Fractions

Sample No.	Sizes in Ø Units: -3.0	-2.0	-1.0	-0.5	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	8.0	Passing
1-1			0.16	0.65	1.43	3.89	7.87	11.81	32.17	20.89	8.83	0.43	1.87	0.60	2.85	6.55
2-1		0.52	0.88	1.23	1.64	1.51	2.39	4.92	20.65	33.97	17.59	3.25	1.20	0.68	2.97	6.60
3-1	1.13	8.14	27.49	8.44	3.32	1.55	1.19	1.46	6.78	12.00	11.59	2.64	1.15	0.84	4.66	7.61
3-2									0.05	2.90	55.80	27.57	6.81	2.33	3.61	0.92
3-3							.009	.03	.06	1.27	41.49	37.04	11.07	3.04	4.57	1.41
3-4									0.01	0.55	50.26	32.19	7.87	3.28	4.75	1.09
3-5				0.04	0.03	0.01	0.03	0.03	0.04	0.26	22.51	51.53	14.74	5.12	4.66	1.02
3-6								0.01	0.03	0.96	36.38	43.16	12.50	4.09	1.83	1.05
3-7				0.02	0.04	0.17	0.54	1.22	2.53	1.94	15.43	43.42	20.76	6.50	6.23	1.21
3-8							0.01	0.02	0.06	0.07	0.51	10.30	46.45	23.04	15.67	3.86
3-9			0.06	0.01	0.02	0.03	0.05	0.07	0.25	6.27	52.31	21.45	5.24	2.33	8.19	3.72
3-10								0.01	0.11	2.53	58.95	26.52	7.27	1.96	1.97	0.73
3-11				0.01	0.02	0.06	0.11	0.18	0.34	1.20	9.81	29.92	26.21	7.92	19.46	4.74

APPENDIX B (Continued)

Sample No.	Sizes in Ø Units -3.0	-2.0	-1.0	-0.5	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	8.0	Passing
3-12				0.01				0.01	0.02	0.07	0.53	9.26	61.80	17.41	9.05	1.83
3-13							0.01	0.02	0.03	0.06	0.75	10.66	36.22	29.07	18.11	5.06
3-14				0.02	0.02	0.05	0.18	0.37	0.72	5.69	43.66	19.17	2.91	2.69	13.38	11.15
3-15				0.03	0.09	0.18	0.37	0.48	0.69	1.30	3.13	13.67	36.89	9.36	27.82	5.99
3-16						0.01	0.01	0.02	0.06	0.20	6.32	39.70	12.37	4.71	22.02	14.59
3-17								0.04	0.13	5.23	61.74	22.62	4.94	1.40	2.78	1.13
3-18									0.04	8.01	63.00	18.19	5.47	2.00	2.27	1.03
5-1			0.02		0.01	0.02	0.66	0.14	0.24	1.55	36.20	27.04	11.99	5.07	11.82	5.82
6-1								0.02	0.87	58.09	28.00	5.65	2.48	2.26	1.79	0.85
7-1							0.02	0.09	0.33	1.84	11.67	8.65	3.78	4.45	52.61	16.55
7-2				0.04	0.08	0.17	0.36	0.53	0.68	0.99	5.44	14.85	13.62	15.40	40.89	7.13
7-3					0.01	0.08	0.36	1.00	4.89	56.69	24.53	4.26	2.18	1.24	3.58	1.19
7-4								0.01	0.03	1.84	37.17	37.50	14.02	3.46	4.39	1.58

APPENDIX B (Continued)

Sample No.	Sizes in Ø Units -3.0	-2.0	-1.0	-0.5	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	8.0	Passing
7-5									0.02	2.77	38.05	24.13	20.18	8.31	5.25	1.30
7-6									0.02	2.61	33.82	31.82	20.15	6.14	4.20	1.24
7-7									0.01	2.29	29.86	38.25	20.88	4.29	3.05	1.37
7-8									0.01	1.17	26.62	44.48	18.09	4.02	4.02	1.60
7-9									0.01	1.41	34.76	37.42	13.65	5.24	6.36	1.15
7-10									0.01	1.38	23.55	48.62	17.53	3.45	4.04	1.42
7-11									0.02	0.64	40.19	37.98	12.05	4.28	3.67	1.18
7-12				0.01	0.03	0.04	0.09	0.17	0.24	1.14	23.88	52.03	15.62	3.24	2.40	1.1076
8-1	0.68	0.68	0.82	0.97	2.05	4.56	8/25	11.90	16.55	28.87	12.42	1.88	0.57	0.39	3.73	7.68
9-1			0.68	1.09	1.98	3.38	5.05	11.46	31.44	15.91	6.69	2.08	1.03	0.68	8.86	9.66
9-2							0.01	0.23	33.23	42.62	18.16	2.66	0.94	0.46	1.24	0.45
9-3								0.01	0.98	39.41	45.02	9.29	2.00	0.68	2.16	0.44
9-4						0.01	0.04	0.07	8.59	59.23	25.64	3.02	1.48	0.50	0.87	0.54

APPENDIX B (Continued)

Sample No.	Sizes in Ø Units -3.0	-2.0	-1.0	-0.5	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	8.0	Passing
9-5							0.01	0.02	2.52	59.85	27.29	4.68	1.44	0.54	3.02	0.64
9-6						0.01	0.02	0.06	2.62	52.99	32.97	7.34	1.40	0.44	1.30	0.86
9-7									0.18	17.81	58.51	16.10	3.71	1.24	1.71	0.75
9-8						0.01	0.03	0.12	0.45	21.56	51.97	14.83	4.76	1.90	2.92	1.46
9-9								0.02	0.07	7.93	55.79	22.63	8.00	2.36	2.15	1.05
9-10									0.01	2.00	42.78	38.72	10.53	2.51	2.40	1.04
9-11									0.02	0.20	17.58	54.54	18.20	4.26	3.10	1.50
9-12						0.02	0.03	0.06	0.50	3.78	27.02	29.40	13.94	4.85	14.57	5.82
9-13				0.01	0.01	0.03	0.12	0.22	0.53	0.96	3.41	14.61	16.11	7.22	36.17	20.62
9-14			0.01						0.01	0.09	1.53	5.74	8.10	10.19	53.36	20.97

Appendix C

Supplementary Measured Sections

Outcrop 1, section 1-A
(Blend in river at upstream end of outcrop.)

Unit No.	Height Above River Level (metres)	Unit Thickness (metres)	Description
1	0-14.3	14.3	Limestone, pale yellow-green, more or less covered above lowest 2 m; red oxidized paleosol at top.
McMurray Formation, Lower Member			
2	14.3-14.8	0.5	Sandstone, weathers light grey, very coarse grained; beds of conglomerate, especially at base, pebbles to 5 cm diameter, medium to well rounded; clasts of clay and quartz pebbles; thin, discontinuous beds of fine sandstone present; oil saturation 2 to 4%.
3	14.8-15.8	1.0	Sandstone, weathers light grey, very coarse grained to conglomerate, interbedded with medium grained sandstone; large (to 10 cm) shale clasts at base; bedding on scale of 1 to 5 cm; large scale, planar, heterogeneous cross-bedding present.
4	15.8-16.3	0.5	Sandstone, very coarse grained to conglomeratic (grains to 4 mm), poorly sorted; bedding not apparent.
5	16.3-16.7	0.4	Sandstone, very coarse grained to conglomeratic at base becoming finer grained and more argillaceous towards top; lighter grey than underlying unit.
6	16.7-18.0	1.3	Sandstone, weathers dark grey, medium to very coarse grained; bedding on scale of 30 cm with each bed of different grain size; weathered beds often grade from dark grey at the base to white at the top; oil saturation 4-6%.
7	18.0-19.2	1.2	Sandstone interbedded medium and coarse grained; medium grained beds weather grey, coarse beds white, producing striped appearance; bedding on scale of 2 to 4 cm.

Unit No.	Height Above River Level (metres)	Unit Thickness (metres)	Description
8	19.2-20.1	0.9	Sandstone, weathers light grey, fine to very coarse grained; finer grained beds usually well sorted and have better oil saturation (6 to 8%); bedding on scale of 2 to 30 cm.
9	20.1-22.3	2.2	Sandstone, weathers light grey, fine to medium grained, beds 15 cm to 60 cm thick, interbedded with siltstone and shale beds 5 to 10 cm thick.
10	22.3-25.3	3.0	Sandstone, weathers light grey, fine to medium grained, bedding discontinuous with lenses of argillaceous sandstone weathering white; occasional grains to 5 mm; rare clay clasts; in places, ripple marks at top.
11	25.3-26.2	0.9	Sandstone, fine grained to conglomeratic, occasional pebbles to 4 cm; generally very poorly sorted with occasional beds of medium sorted fine sandstone; abundant shale rip-up clasts at the top.
12	26.2-26.5	0.3	Sandstone, weathers light grey, fine to medium grained; bedding 2 to 4 cm thick.

Top of Lower Member

Outcrop 3, section 3-A
(Prominent ridge in center of outcrop.)

1	0-18.3	18.3	Limestone, pale greenish yellow, fine grained, rubbly.
2	18.3-20.7	2.4	Covered.
McMurray Formation, Middle A Member			
3	20.7-32.3	11.6	Oil sand, very fine to fine grained; cross-bedded at base, upper 2 metres rippled throughout and weathering light grey. Sample 3-17.
Middle B Member			
4	32.3-48.2	15.9	Oil sand, much darker than underlying unit, very fine to fine grained, well bedded, 10 to 30 cm thick beds of oil sand separated by 2 to 5 cm partings of shale; burrows first appear at 32.8 metres, becoming more abundant with height. Sample 3-18.
5	48.2-48.3	0.1	Ironstone bed.

Unit No.	Height Above River Level (metres)	Unit Thickness (metres)	Description
6	48.3-~~39.2~~	0.9	Shale, light grey, interbedded with very fine sand on scale of 2 to 5 cm; extreme burrowing.
Upper A Member			
7	49.2-52.3	3.1	Oil sand, very fine grained, interbedded with shale; poor exposure.
			Sandstone, light grey, very fine grained; resistant, apparently completely bioturbated.
9	52.7-52.8	0.1	Ironstone bed.
10	52.8-57.9	5.1	Oil sand, very fine grained, interbedded with shale; poor exposure.
11	57.9-58.0	0.1	Ironstone bed, discontinuous.
12	58.0-66.4	8.4	Oil sand, weathers very light grey, very fine grained, argillaceous; poorly bedded, burrowed to bioturbated, some zones rippled. Large V-shaped burrows 5 to 8 cm wide at top, 10 cm long.
Upper B Member			
13	66.4-69.2	2.8	Oil sand, weathers dark grey, very fine grained, very argillaceous; yellow-green coloration in pockets up to 2 cm; ironstone bed at 66.9 metres.
Clearwater Formation, Wabiscaw Member			
14	69.2-69.8	0.6	Sandstone, weathers brown to green, very fine grained; very argillaceous, contains glauconite; occasional ironstone concretions. Sample 3-16.

Outcrop 3, section 3-B
(Downstream end of outcrop where Lower Member is present.)

Unit No.	Height Above River Level (metres)	Unit Thickness (metres)	Description
1	0-6	6.0	Covered.
2	6-7.0	1.0	Limestone, yellow to red brown, rubbly.
3	7.0-7.5	0.5	Shale.
Lower Member			
4	7.5-10.4	2.9	Sandstone, red brown, fine to medium grained, elevation not uniform.
5	10.4-11.6	1.2	Sandstone, medium to very coarse grained, and conglomerate; very discontinuous bedding; in places, conglomeratic part has pebbles and shale clasts up to 8 cm diameter.
Middle A Member			
6	11.6-20	8.4	Oil sand, black, fine grained, cross-bedded throughout, bedding on the scale of 1 to 1.5 m.

Unit No.	Height Above River Level (metres)	Unit Thickness (metres)	Description
Outcrop 4, Section 4-A (Downstream end of centre grove of trees.)			
Lower Member			
1	0-7.0	7.0	Sandstone, light grey, coarse grained.
2	7.0-12.2	5.2	Covered.
Middle A Member			
3	12.2-16.8	4.6	Oil sand, black, very fine to fine grained; cross-bedding throughout; very little shale.
4	16.8-24.4	7.6	Covered.
Middle B Member			
5	24.4-31.7	7.3	Oil sand, black, very fine to fine grained; apparently massive, very little shale; occasional zones of abundant shale clasts in beds up to 30 cm thick.
6	31.7-36.2	4.5	Covered.
7	36.2-42.7	6.5	Oil sand, very fine to fine grained; well bedded, with thin partings of shale and siltstone; first burrows at 36.2 metres.
Upper A Member			
8	42.7-51.8	9.1	Oil sand, very fine grained, with shale partings; poor exposure; in places completely bioturbated, in places finely laminated.
9	51.8-52.1	0.3	Ironstone bed; continuous over most of outcrop.
Remainder of section inaccessible, the following measurements are approximations.			
10	52.1-56.5	4.4	Oil sand, upper 2 metres apparently epsilon cross-bedding of small channel.
Upper B Member			
11	56.5-58.5	2.0	Oil sand, dark greenish-grey, with iron stained bed 50 cm from base.
Clearwater Formation, Wabiscaw Member			
12	58.5-60.0	1.5	Apparently glauconitic sand, green.
Outcrop 6, section 6-A (Upstream end of outcrop.)			
1	0-16.8	16.8	Covered.
Middle A Member			
2	16.8-23.8	7.0	Oil sand, fine grained; trough cross-bedded throughout, shale clasts often at base of sets, sets up to 30 cm thick; ripple marks common in beds up to 60 cm thick; wood fragments.

Unit No.	Height Above River Level (metres)	Unit Thickness (metres)	Description
Middle B Member			
3	23.8-34.5	10.7	Oil sand with thin partings of shale; bedding 5 to 60 cm; beds have apparent dip of 11°; burrows at base of unit, but rare; at top of unit are trough cross-bed sets 20 to 30 cm thick, topped by ripples.
4	34.5-38.1	3.6	Oil sand interbedded with shale on a scale of 2 to 10 cm; very recessive, burrowed; 60 cm thick ironstone bed at 35.0 metres.
5	38.1-41.2	3.1	Oil sand, light grey, very fine; with no definite shale beds; apparently completely bioturbated.

Covered above 41.2 metres.

Outcrop 12, section 12-A
(Downstream end of outcrop.)

Unit No.	Height Above River Level (metres)	Unit Thickness (metres)	Description
McMurray Formation, Middle A Member			
1	0-4.5	4.5	Oil sand, fine grained; apparently massive, no shale partings.
2	4.5-9.0	4.5	Oil sand, dark grey at base grading upwards to very light grey, fine grained; large scale (30 to 50 cm thick) cross-bedding at base, upper 2 metres rippled throughout.
3	9.0-10.7	1.7	Covered.
4	10.7-12.5	1.8	Oil sand, fine grained, bedding on scale of 60 cm; generally rippled.
5	12.5-16.8	4.3	Covered.
6	16.8-18.0	1.2	Oil sand, fine grained, rippled throughout, 10 cm thick cross-bedding at top.
Middle B Member			
7	18.0-38.0	20.0	Oil sand, fine grained; burrows begin in this unit, common in beds up to 5 cm thick in lowest 3 m of unit, decreasing in abundance above this; most beds rippled, some medium scale cross-bedding to 50 cm thick; bedding on scale of 10 to 30 cm.
8	38.0-38.2	0.2	Ironstone bed.
Upper B Member			
9	38.2-44.2	6.0	Oil sand, light grey, very argillaceous, bedding poorly defined, 4 to 8 cm; fresh surface shows dark grey shale laminations and brown sandy pockets; oil saturation 2 to 4%.

Appendix C (Continued)

Description of Core
Well name: SOBC FL 1-74 1-1
Location: 14-29-92-9W4
KB: 333.2 m GRD: 332.0 m

Unit No.	Top of Unit Elevation (metres)	Thickness (metres)	Description
1	309.45	.91	Oil sand, very fine grained, argillaceous, with streaks of shale, grey, up to 5 mm thick; mottled texture; oil saturation varies with mottling.
2	308.54	.16	Oil sand, very fine grained, interlaminated with silt, light brown, and shale, grey; not mottled.
3	308.38	1.67	Shale, dark grey, fissile; occasional thin (2 mm) blebs of silt.
4	306.71	.46	Shale, light brown, silty, fissile; blebs and streaks of silt and very fine sand, becomes siltier towards base.
5	306.25	.30	Oil sand, very fine grained, very argillaceous, interbedded with shale, light grey.
6	305.95	1.99	Lost core.
7	303.96	2.40	Oil sand, very fine grained, interlaminated to interbedded (to 2 cm thick) with shale, light grey, silty; beds of oil sand have good saturation but average is low, contorted bedding 303.35 to 303.65.
8	303.23	.49	Shale, light grey to light brown, sandy; sandier towards base; slight oil saturation.
9	302.74	2.59	Oil sand, very fine grained, interlaminated with shale, light grey, sandy; 50% sand, 50% shale; laminations average 1 mm thick; mottled in part; 5 cm oil sand bed at 300.30 m with burrows into underlying 6 cm bed of shale.
10	300.15	.45	Oil sand, dark brown, very fine grained; in upper part laminated with shale; cross-bedding, 15^{0} dip, good saturation in lower part.
11	299.70	3.05	Lost core.
12	296.65	.61	Oil sand, very fine grained, argillaceous, interlaminated with shale, sandy, light grey to light brown.

Unit No.	Top of Unit Elevation (metres)	Thickness (metres)	Description
13	296.04	.31	Shale, light grey, mottled, with patches of oil sand in places.
14	295.73	.30	Oil sand, very fine grained, silty and argillaceous, poor saturation.
15	295.43	1.28	Oil sand, very fine grained, argillaceous, interlaminated with shale, light grey; laminations a few mm thick; occasional shale breaks of 1-2 cm; well laminated to mottled.
16	294.15	1.47	Shale, light grey, silty, interbedded with interlaminated shale and oil sand; well laminated.
17	292.68	1.25	Oil sand, very fine grained, very argillaceous; interlaminated with shale to mottled.
18	291.43	.42	Oil sand, dark brown to black, very fine grained, well laminated (1 to 2 mm); very good saturation (15%).
19	291.01	.31	Shale, light grey, interlaminated (0.1 to 1 mm) with oil sand, very fine grained; even parallel laminations; 1.5 cm yellow concretion at 290.85 m.
20	290.70	.61	Oil sand, very fine grained, mottled to interlaminated with shale, light grey.
21	290.09	.30	Shale, light grey, occasional carbonaceous material.
22	289.79	.46	Shale, light grey, with mottles and stringers of oil sand, abundant carbonaceous material, one bed of carb. material 1 cm thick; one large (4 cm x 1 cm) oblong siderite module.
23	289.33	2.29	Shale, light grey to light tan, silty and sandy in places; disseminated carbonaceous material throughout, especially in sandy zones; occasional patchy oil saturation in sand lenses.
24	287.04	.76	Oil sand, very fine grained, with high oil saturation (15%); well laminated, occasional grains to 5 mm diameter; occasional carbonaceous material, disseminated and in partings.
25	286.28	.46	Shale, light grey, interbedded (0.5-3 cm thick) with oil sand.
26	285.82	.76	Shale, light grey, sandy in places, even parallel laminations; occasional stringers of oil sand; siderite concretion at top.
27	285.06	.61	Lost core.

Unit No.	Top of Unit Elevation (metres)	Thickness (metres)	Description
28	285.45	1.22	Shale, as above.
29	283.23	1.83	Shale, light grey, sandy in places, interbedded to interlaminated with oil sand; well laminated to mottled and disrupted; disseminated carbonaceous material in sandy zone; soft sediment deformation has apparently occurred.
30	281.40	.45	Shale, light grey, with zones of poorly saturated oil sand and carbonaceous material; apparently soft sediment deformation.
31	280.95	.22	Oil sand, very fine grained, laminated to homogeneous.
32	280.73	1.31	Shale, light grey, sandy in part, interlaminated to mottled with oil sand; bioturbation and soft sediment deformation; top of unit deformed by overlying sands; most laminations at angle of about 20°.
33	279.42	.76	Shale, sandy, as above but with even parallel lamination.
34	278.66	.31	Shale, as above but with patchy, rather than laminated, oil saturation, disrupted laminations.
35	278.35	.42	Shale, as above, with even parallel laminations; oil saturated in sandy laminae.
36	277.93	1.19	Shale, light grey, sandy in part, with scattered patchy oil saturation in sandy zones but no beds of oil sand.
37	276.74	3.72	Shale, light grey, interlaminated to interbedded (0.1 mm to a few cm thick) with oil sand, very fine grained; shale is fissile with fine laminations.
38	273.02	.76	Lost core.
39	272.26	1.62	Oil sand, black, fine to medium grained with a few coarse grains; bedding, where present, is alternating laminae of medium and fine sand; cross-bedding at 10° to 30° dip; occasional shale clasts 1 to 2 cm diameter.
40	270.64	1.28	Shale, light grey to tan, sandy; even parallel laminations; occasional thin (1-2 mm) stringers of sand, some saturated; at base is 4 cm hard streak (fine to medium sandstone) with large (6 cm x 1 cm) flat concretion; underlain by 2 cm of carbonaceous material, sandy.

Unit No.	Top of Unit Elevation (metres)	Thickness (metres)	Description
41	269.36	.67	Oil sand, black, very fine to medium grained, some coarse near top; bedding obscure; occasional pebbles to 5 mm diameter.
42	268.69	1.74	Shale, light grey, with stringers and lenses of sandstone, very light grey, very fine grained, with occasional oil saturation; occasional concretions (2 mm - 1 cm diameter).
43	266.95	.79	Lost core.
44	266.16	.31	Oil sand, black, fine to very coarse, apparently homogeneous; limestone breccia and concretions at base.
45	265.85	1.40	Shale, light grey, with streaks and lenses of hard, red yellow silty zones (borders not always distinct).
46	264.45	.33	Limestone fragments.

Appendix D.

Descriptions of Heavy Minerals

Zircon

Zircon, the most abundant mineral in most of the samples, varies from very well rounded grains from reworked sediment to first-cycle euhedral prisms. The euhedral crystals are generally larger than the rounded grains. Zircon grains are almost always clear and inclusion-free, except for some grains with a red-brown stain, as also noted by Mellon (1956). Most grains with this staining are still identifiable, however, by crystal form, parallel extinction, bright interference colors, and the fact that only zircon grains were observed to have the stain. A large number of these stained grains are euhedral and zoned. The large percentages of zircon in some samples are due to floods of small (less than 0.1 mm), rounded grains.

Tourmaline

Tourmaline grains can be prismatic, very well rounded, or irregularly fractured. Black inc ions are common, often parallel to the crystal length. The color of tourmaline grains is generally pleochroic from colorless or yellow through shades of brown. Pink grains pleochroic to very dark green or blue are less common. The grains are usually prismatic. Rarely found are blue grains pleochroic to a deeper blue.

Chloritoid

This platy, bluish mineral is generally filled with black inclusions to the point of being opaque. Such grains are almost black under crossed nicols. The less common inclusion-free flakes exhibit marked blue-green pleochroism and anomalous blue birefirngence. Chlorite, present in some samples, is distinctly green and has a refractive index lower than the 1.66 of the aroclor mounting medium while chloritoid has a refractive index higher than 1.66

Garnet

Angular pink and clear garnet with no inclusions is the most common form of garnet. These grains show fresh conchoidal fractures. Many grains, usually more rounded, have a sugary pitted surface.

Staurolite

Staurolite grains are pleochroic from light to dark golden yellow, generally with clear inclusions, though black inclusions are common. Many grains have 'swiss-cheeze' texture. Grains are generally irregular in shape and may show step-like fracture surfaces. Well-rounded grains often have a pitted appearance.

Kyanite

Generally easily identified by its cleavage, low interference colors and inclined extinction, kyanite grains are often much larger than other grains in the same sample. The grains are almost always fresh in appearance.

Apatite

Apatite grains are usually prismatic in shape, clear, and unaltered.

Rutile

A minor but consistent part of the heavy mineral suite, rutile varies in color from light yellow to the more common dark red-brown. Most grains exhibit oblique striations. Some rutile grains are needle-like, being very long relative to their width.