EDMONTON GEOLOGICAL SOCIETY 1996 FIELD TRIP

FORT McMURRAY / OIL SANDS AREA

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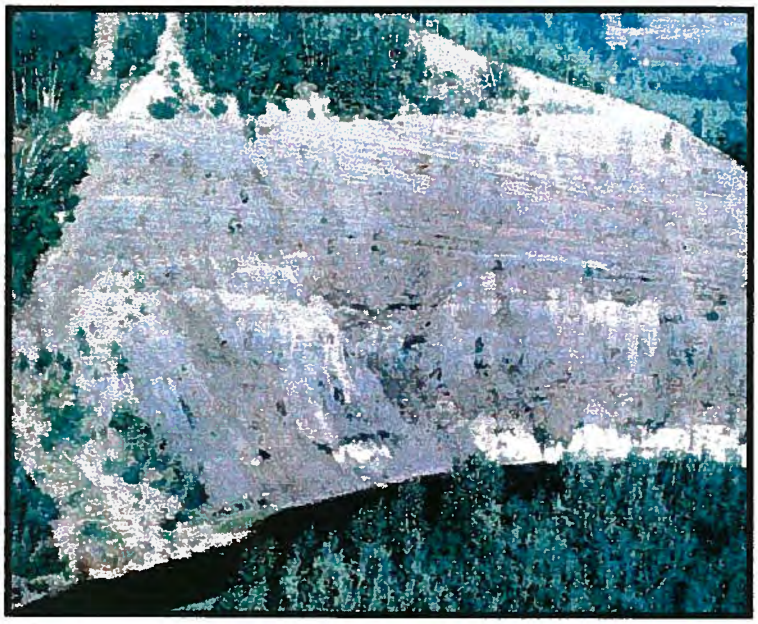
SEPTEMBER 1996



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APPENDICES

The McMurray Formation: Reservoir Heterogeneities Exposed in Outcrop

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Introduction

The Athabasca Oil Sands Area in northeast Alberta contains the largest oil sands deposit (142 x 10^9 m^3, 892 x 10^9 bbls) in the world (ERCB, 1991). The primary objective of this three day field trip is to introduce participants to the sedimentology and reservoir characteristics of the Lower Cretaceous McMurray Formation, which contains the bulk of the oil sands resource. Participants will have the opportunity to examine McMurray Formation reservoirs exposed in outcrop and to gain insight into commercial mining and pilot stage *in situ* operations (Figure 1).

The itinerary is as follows:

September 20, Friday
PM - Depart 14:30 hrs (Petroleum Plaza, North Tower, 9945 - 108 St.) and 16:30 hrs (SuperStore parking lot, 4950 - 137 Ave [the Superstore Gas Station is the meeting place]). Arrive Fort MacMurray; accomadation at the MacKenzie Park Inn.

September 21, Saturday
AM - (1) Tour of the Syncrude minesite, where 25,000 m^3 (160 000 barrels) of synthetic crude are produced each day
PM - (1) Drive to the Viewpoint Section along the Mackay River, where coarse fluvial sediments of the lower McMurray, open estuarine sediments of the middle McMurray and small scale channel deposits of the upper McMurray Formation are exposed; and (3) stop at the Abasand Oil Company Ltd. site - time permiting.

September 22, Sunday
AM - (1) Geological presentation and examination of UTF Phase B core. (2) Tour of the Fort MacMurray Interpretive Centre. (3) Hangingstone River Section for detailed examination of the upper McMurray. At this locality, pelecypod and gastropod shells are abundant.

Regional Stratigraphy

The McMurray Formation is the lowest formation in the Lower Cretaceous Mannville Group and directly overlies a regional unconformity developed on Devonian carbonates in the Athabasca area (Figure 2). The McMurray Formation outcrops in the vicinity of Fort McMurray and reaches depths of about 500 m (subsurface) in the southern part of the deposit. It is mined at surface at the Syncrude and Suncor plants and pilot projects have produced bitumen at *in situ* depths ranging from 75 m to 500 m (including the UTF operation). The McMurray Formation was never buried to great depths (probably less than 1 km of overburden has been removed; Nurkowski, 1985; Moshier and Waples, 1985) and thus is a sequence of uncemented sands and shales.

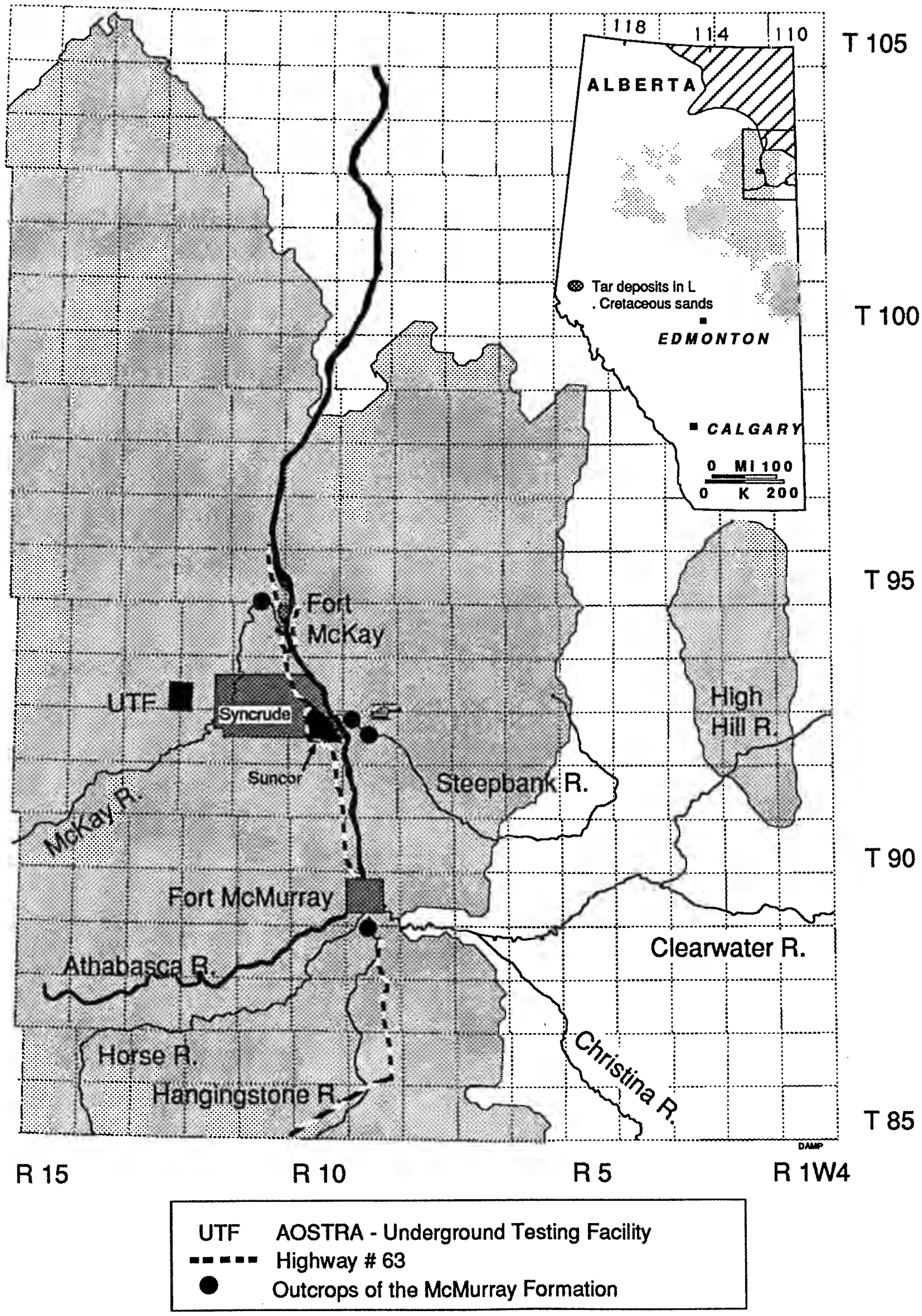


Figure 1. Map of the Athabasca Oil Sands Area and localities visited on this field trip (map compliments of Don McPhee).

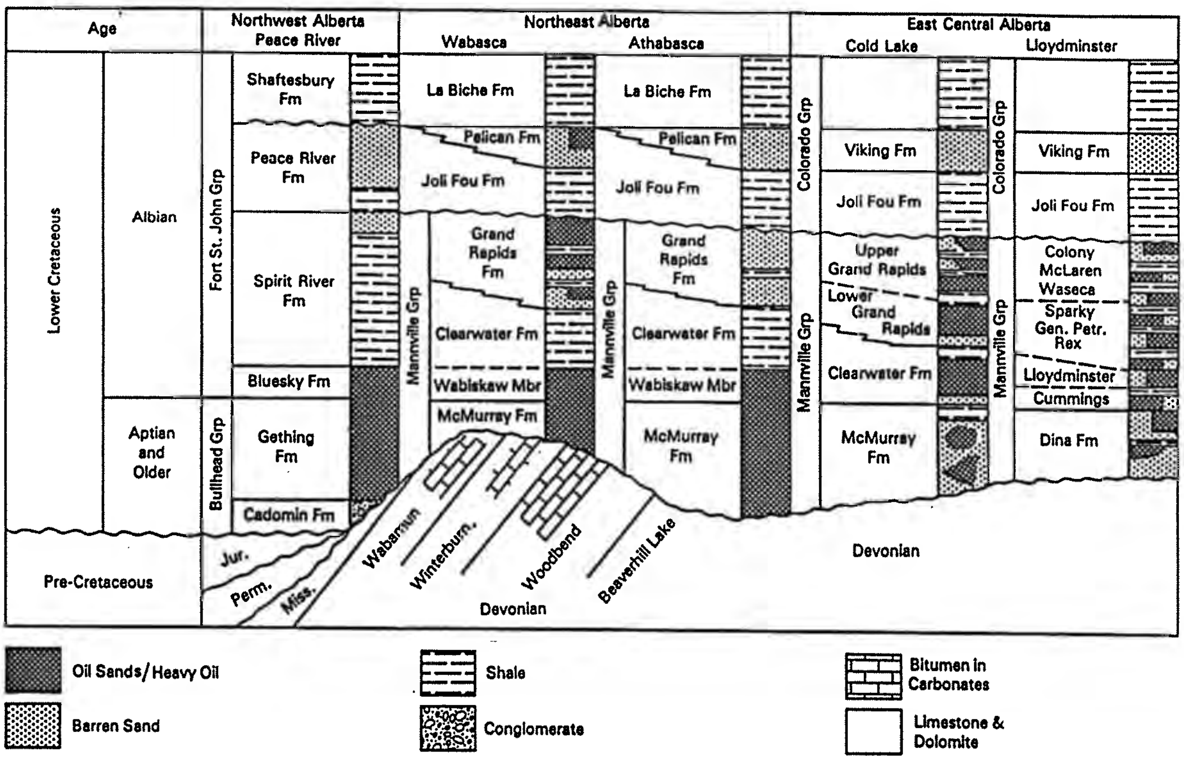


Figure 2. Table of formations illustrating the primary oil sands and heavy oil horizons in Alberta.

The McMurray Formation represents the initial sedimentation on the regional unconformity as a response to rising sea level to the north. McMurray sediments were deposited in a ridge and valley system develo ped on the Devonian carbonates and infilled the topographic lows on that surface. The lowest parts of the formation (lower McMurray, Figure 3) are the result of a poorly organized drainage system on an irregular carbonate surface and represent continental sedimentation (Flach, 1984). The middle to upper parts of the formation indicate an increasing marine influence and brackish water deposits are common. The degree of marine influence generally increases stratigraphically upwards and geographically to the north, which reflects the encroachment of the boreal sea (Jeletzky, 1971). A well developed northward paleoflow existed during middle to upper McMurray time, and the bulk of the McMurray Formation represents a channelized succession.

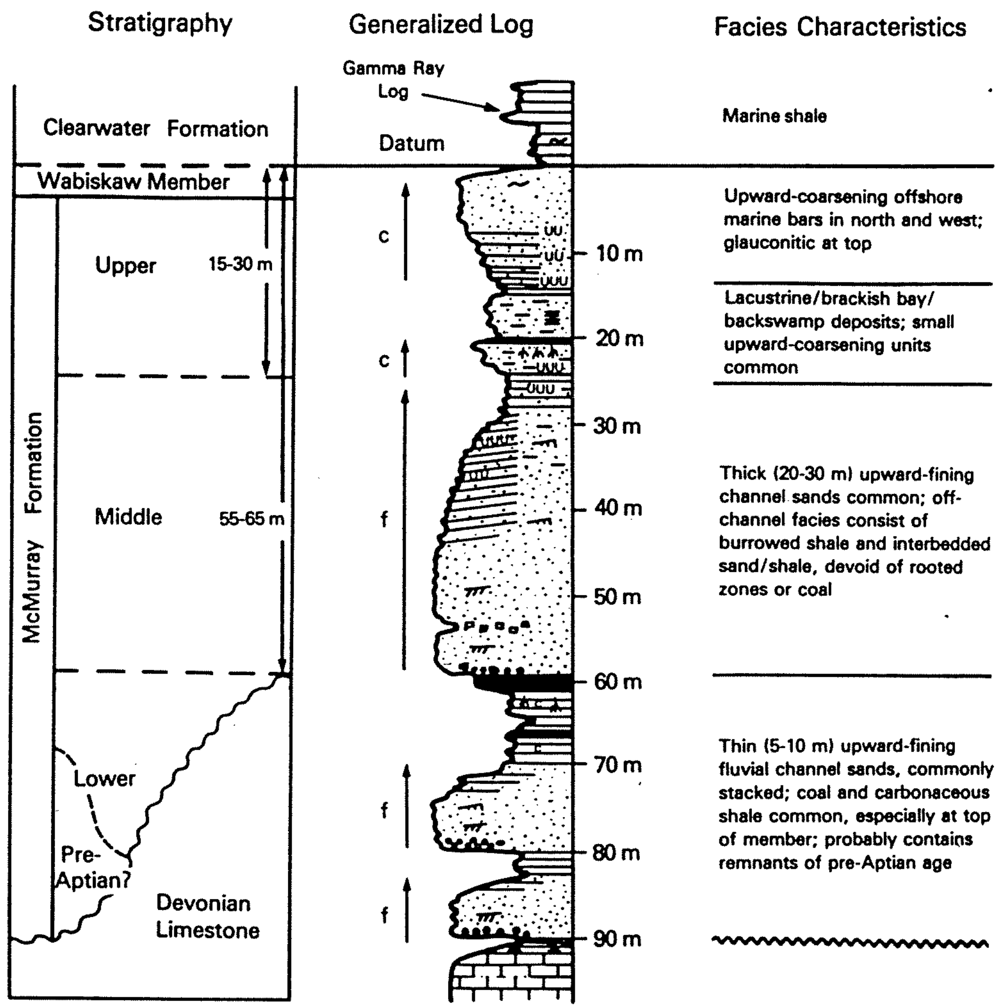


Figure 3. Type well for the Athabasca Oil Sands Area (modified after Flach, 1984).

At the end of McMurray time, all of the carbonate ridges in the Athabasca area were nearly or completely covered and the boreal sea transgressed southward over this relatively flat surface, creating a marine environment. The base of the Wabiskaw Member (Clearwater Formation) sands are defined on the first appearance of glauconite (Badgley, 1952) and the bulk of the Wabiskaw sediments were deposited in a marine, shelf-type environment.

Geological Setting

The McMurray Formation attains thicknesses of over 100 m on the east side of the Athabasca area where it occupies a large valley on the unconformity surface (Figure 4). Keith *et al.* (1990) termed this feature the 'main valley', which is a part of a larger system that has been mapped by Christopher (1975). The formation thins to less than 10 m to the west where a prominent ridge, the Grosmont High (Keith *et al.*, 1990), is developed on the unconformity surface.

The thickness of sands in the McMurray Formation is also strongly controlled by the topography on the unconformity surface. Sands attain thicknesses of greater than 80 m in the main valley and thin to less than 10 m to the west over the Grosmont High. The bulk of the reservoir quality sands in the valley are comprised of channel deposits of the main northward flowing river system. Sands to the west of that (isopach values from 20 to 40 m) include channel deposits of smaller systems, probably tributaries to the main river. Farther to the west, the sands thin onto the flank and crest of the Grosmont High where channel deposits are thin or absent. Comparison of the McMurray Formation sands to the Prairie Evaporite salt scarp shows that the thickest sands occur above or to the east of the scarp (Figure 5). Thus, salt dissolution appears to have controlled both the deepest part of the valley and the location of the main river within the valley. Salt dissolution occurred prior to, during and after the deposition of the McMurray Formation (McPhee and Wightman, 1991).

Trapping Mechanism

The trapping mechanism in the Athabasca deposit is not fully understood, but both stratigraphic and structural elements are likely involved. The regional dip to the west, combined with salt collapse in the east, resulted in some degree of structural closure (Vigrass, 1968; Jardine, 1974); a significant portion of oil sands reserves in the deposit, however, lie east of this anticlinal feature; therefore, structure is only a partial control on bitumen trapping. (Flach, 1984; Wightman *et al.*, 1991)

The bitumen is thought to have originated as lighter liquid hydrocarbons in deeper parts of the basin during the early Tertiary, migrating eastward to updip areas of northeast Alberta (Masters, 1984; Moshier and Waples,1985). The Clearwater Formation shales act as a cap rock for the deposit and the final termination of bitumen migration appears to have occurred when these liquids were biodegraded to the point of immobility (Mossop, 1980; Masters, 1984).

Recent studies by Underschultz and Bachu (1992) on regional ground water flow in the Athabasca North area, indicate that a strong density and salinity contrast is observed associated with salt dissolution, in the vicinity of the Prairie Evaporite salt scarp. The salinity contrast was likely present during hydrocarbon migration, since dissolution was active during the late Cretaceous and early Tertiary. It is possible that fresher formation waters to the east of the scarp enhanced the biodegradation process.

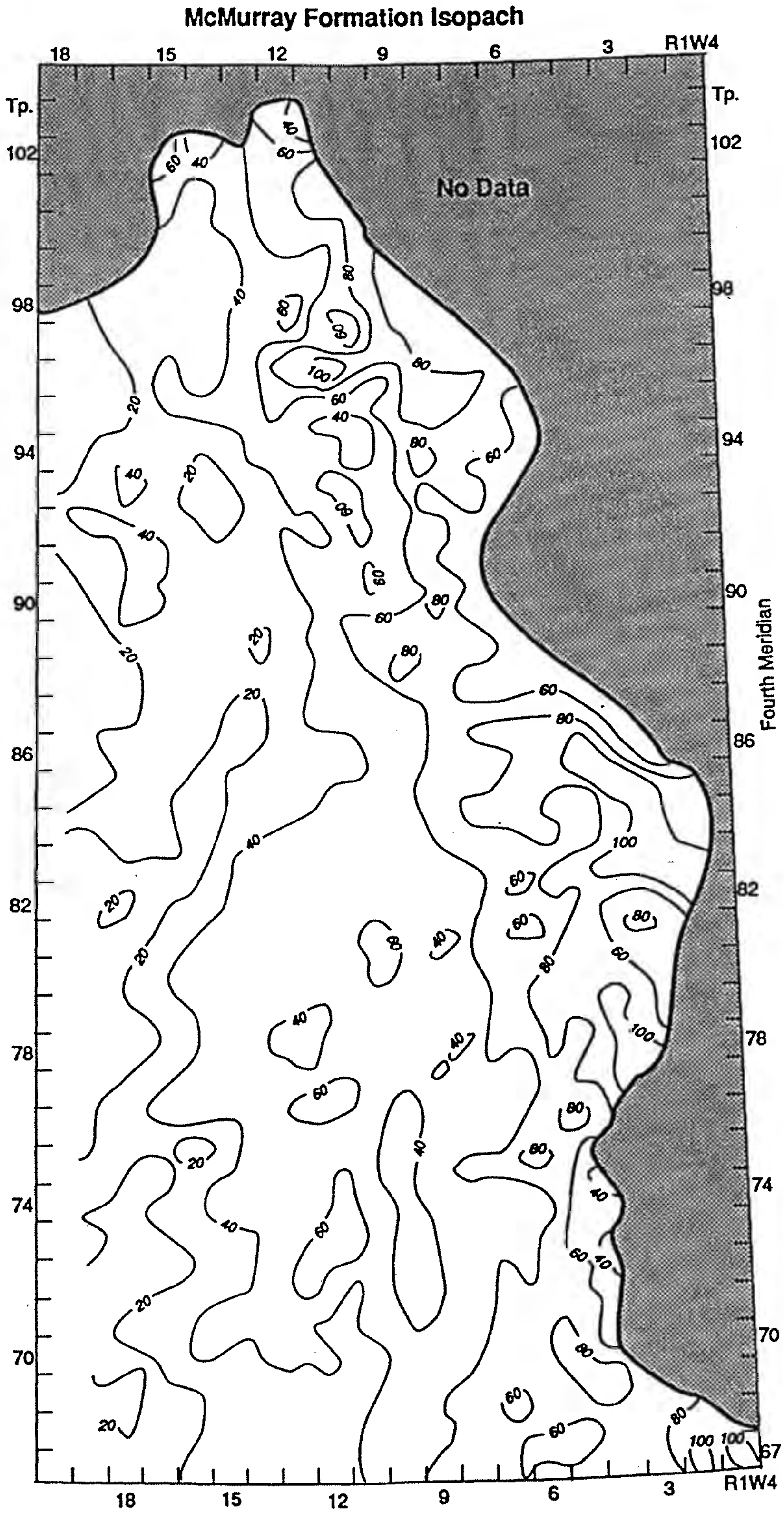


Figure 4. McMurray Formation isopach, Athabasca Oil Sands Area. Note the thickening along the eastern side of the map area (from Wightman *et al.*, 1991).

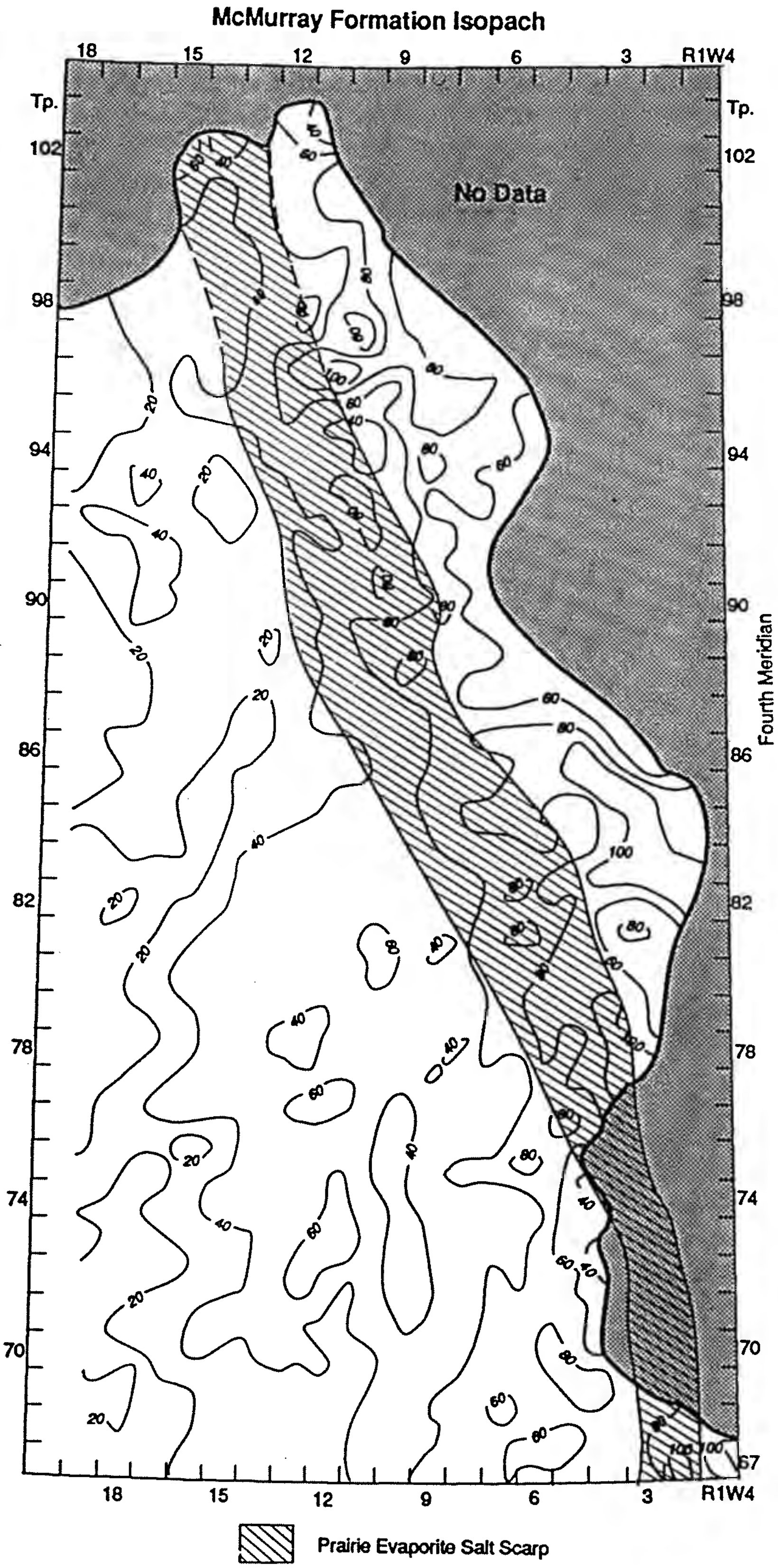


Figure 5. McMurray Formation isopach showing the correlation between the location of the Prairie Evaporite salt scarp and the main valley (from Wightman *et al.*, 1991).

In addition to the bitumen resources, thick gas sand accumulations are prevalent in the upper part of the McMurray Formation, commonly trapped along the salt dissolution anticline. Smaller gas deposits scattered elsewhere in the Athabasca region also occur in the upper part of the formation and are probably trapped by local structural features related to topography on the sub-Cretaceous unconformity.

In situ Recovery

To date, the only commercial scale bitumen recovery operation in the Athabasca deposit, is open pit mining. Ninety percent of the reserves in the deposit, however are buried too deeply for surface mining and require *in situ* methods.

Flach (1984) outlines how most problems associated with *in situ* recovery are due to the following reservoir characteristics: (1) an oil viscosity so high that the bitumen is essentially immobile at reservoir temperature; (2) a lack of formation energy, such that a drive mechanism is required; (3) an extremely heterogeneous reservoir.

During this field trip, participants will view these reservoirs at surface, to develop a better understanding for some of the challenges facing reservoir geologists and engineers. A tour of AOSTRA's Underground Test Facility provides the opportunity to see a pre-commercial *in situ* pilot, using a steam assisted gravity drainage (SAGD) technique. It is estimated that a commercial project using this technique could produce bitumen for $11 to $13 per barrel, including capital and operating costs (O'Rourke *et al.*, 1991) This is comparable to current production costs of the Syncrude mining operation.

Wettability

Perhaps the single most characteristic feature of the oil sands is that the grains are dominantly water wet or hydrophilic. The oil in the pores are not in direct contact with the mineral grains; rather, each grain is surrounded by a thin film of water, beyond which, in the centre of the pore is the oil (Figure 6). The relatively inexpensive hot water extraction process could not work if the grains were other than water wet.

McMurray Formation (Steepbank) Units

Three distinct units which characterize the McMurray succession along the Steepbank River outcrops are described by Flach and Mossop (1985) and Flach (1984). These units vary in thickness and outcrop expression from exposure to exposure, but they are invariably present in the same vertical order. A thick bedded sand, 20 to 40 m thick, characterizes the lower unit. Gradationally overlying this and interfingering with it, is a large scale inclined heterolithic stratification unit (interpreted as lateral accretion beds) up to 25 m thick. The uppermost unit consists of horizontally bedded argillaceous sands and silts. The contact between the argillaceous unit and the underlying inclined heterolithic unit (epsilon cross beds of Flach, 1984) is commonly sharp and erosional (Figure 7).

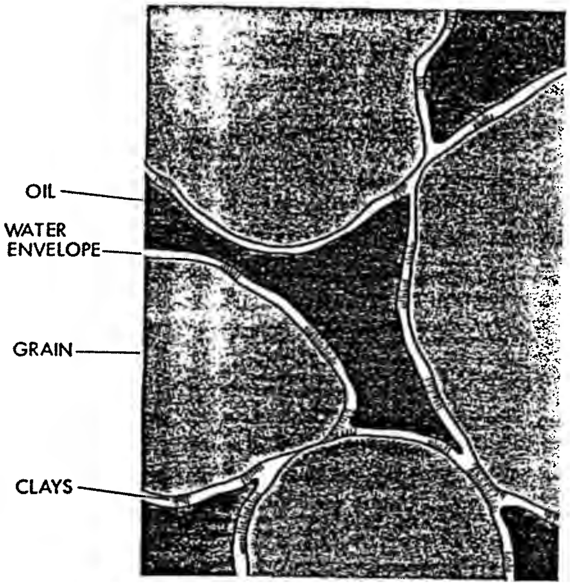


Figure 6. Distribution of bitumen and water in the pore systems (from Mossop *et al.*, 1981).

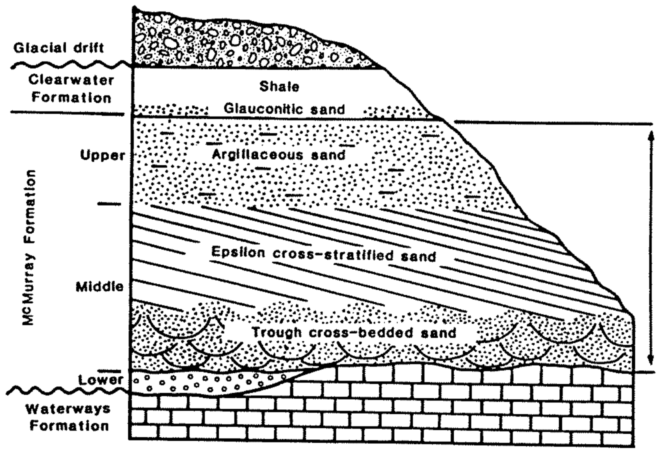


Figure 7. Schematic representation of the units that characteristically make up the McMurray Formation at the Steepbank outcrops (from Flach, 1984).

Thick bedded sand unit

The thick bedded sand unit consists of well sorted, fine grained quartz sand, with only minor shale beds and/or shale clast breccias. Estimated porosities for the interval are in the order of 35%, with bitumen contents up to 16 mass% (33% by volume). This is the richest portion of the reservoir with the most favourable primary porosity and permeability.

The base is erosional and is characterized by large-scale trough cross sets averaging 0.5 to 1 m in thickness (Figure 8), with some sets up to 6 m across. In the upper portions of this unit, trough cross beds grade into smaller scale current structures and climbing ripples. Indicated paleocurrent transport in any given exposure is unidirectional.

Heterogeneities which may affect fluid flow in this unit include shales which drape cross bed sets, shale clast breccias and argillaceous sands associated with toe sets. The lateral extent of these types of heterogeneities appear to be controlled by adjacent and overlying cross bed sets, which remove upper portions of previously deposited beds. Breccias consist of angular clasts of laminated silt and clay, set in a matrix of fine grained sand. Clasts are usually 2 to 20 cm in diameter and a few centimetres thick, but blocks up to 1.5 m thick are present locally. These data suggest that in the thick sand facies, these heterogeneities when present, are commonly thin and discontinuous.

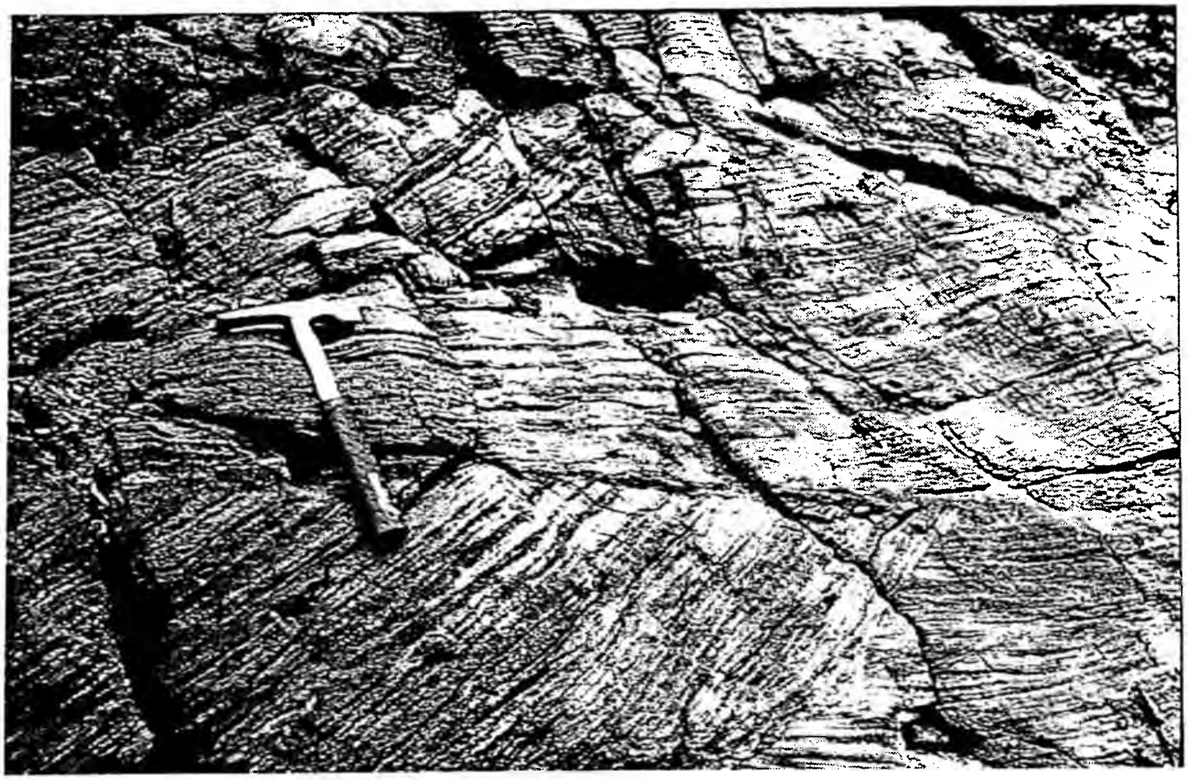


Figure 8. Trough cross stratification consisting of high porosity sands with only minor shales (photo courtesy of Grant Mossop).

Inclined heterolithic stratification unit

The uppermost portion of the thick bedded sand unit transitionally grades into and interfingers with the inclined heterolithic beds (epsilon cross strata of Mossop and Flach, 1983). Along the outcrop, this relationship can be documented by tracing groups of heterolithic beds through a transition zone, where the mudstones die out and the sand beds grade into ripple laminated sands and small scale trough cross bedded sands.

Sets of inclined heterolithic stratification average 15 m in thickness (range 8-25 m) with surfaces dipping at an average of 8°-12° (range 4°-22°). The depositional strike and dip is normally consistent in any given exposure. The sloping strata consist of decimetre to metre thick beds of fine to very fine grained sand, normally current rippled, separated by mudstones, normally 2 to 5 cm thick which increase in abundance towards the top of the set (Figure 9). Trace fossils, which include *Cylindrichnus* and *Skolithos*, are relatively abundant in the mudstone beds and the vertical burrows penetrate down into the underlying sand (Pemberton *et al.*, 1982).

Directional data derived from measurements of rippled foresets of the heterolithic beds and trough axes of the underlying thickly bedded sand facies indicate unidirectional flow towards the northwest (Figure 10).

Figure 9. Inclined heterolithic stratification (photo courtesy of Grant Mossop).

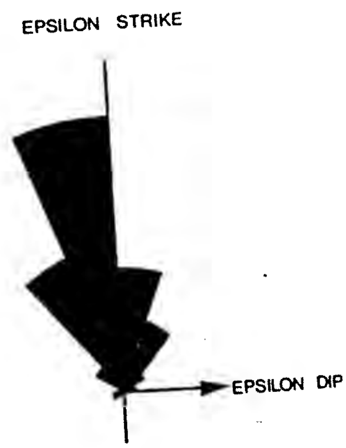


Figure 10. Rose diagram showing paleocurrent directions relative to the strike of the epsilon cross strata (from Mossop and Flach, 1983).

Argillaceous unit

The upper member of the McMurray Formation consists dominantly of horizontally bedded sands and muds. The sands are argillaceous and very fine grained commonly exhibiting current ripple cross stratification. The sand and mud beds average about 5 cm in thickness and can be intensely bioturbated. The trace fossil suite is similar to that of the underlying inclined heterolithic strata but includes additional forms such as *Dolopichnus* and *Bergaueria* (Pemberton *et al.*, 1982). Localized coals up to 10 cm thick with underlying root structures are rare and thin sideritic cemented beds are scattered throughout the unit.

Interpretation

The thick bedded and inclined heterolithic units of the McMurray Formation in the outcrops of the Steepbank River are believed to have originated from the lateral migration of very deep (20-45 m) channels (Mossop and Flach, 1983). The inclined heterolithic stratification is interpreted as deposition on the point bar of channels while contemporaneous trough cross bedded sands were deposited at the channel bottoms (Figure 11). The trace fossil suite of the inclined heterolithic strata is brackish and indicates that the channels were estuarine. The argillaceous unit is interpreted as overbank or off channel deposition in a brackish water setting (Pemberton *et al.*, 1982).

The presence of trough cross bedding, resulting from downstream migration of sinuous crested dunes up to 1.5 m in height is consistent with the flow regime one might expect at the base of such a large channel. The shale clast breccias are interpreted to have originated largely through bank caving on the cutbank side, while smaller clasts, particularly those near the top of the thick bedded unit, probably represent eroded portions of the inclined heterolithic strata. The angularity of the intraclasts indicates limited transport. Smaller scale cross stratification and ripple lamination of the heterolithic beds are a result of the lower flow regime of the middle to upper point bar. Deposition of the large scale trough cross bedded sands occurred in association with flood stage flow at the channel base.

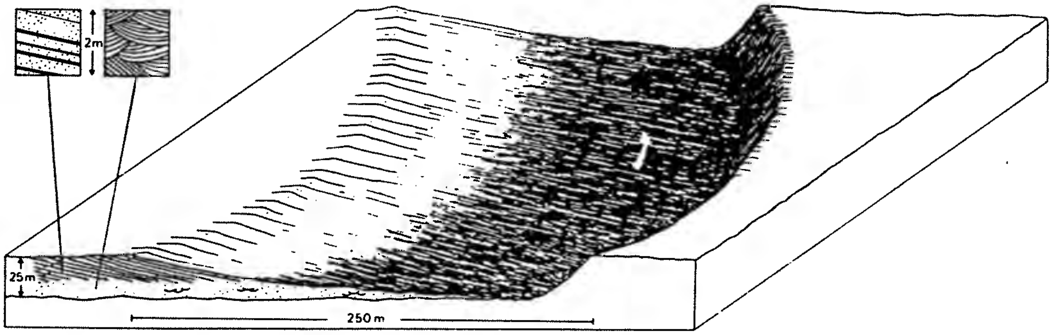


Figure 11. Schematic diagram of the deep estuarine channel setting proposed for the McMurray (Steepbank) succession (from Mossop and Flach, 1983).

Field Trip Day 1: September 21, Saturday

08:00 hrs	Depart from MacKenzie Park Inn
09:00 hrs	Arrive at Syncrude minesite for geological presentation and tour of the minesite
12:00 hrs	Lunch on route to next stop
13:30 hrs	Fort MacKay River section
16:30 hrs	Abasand site (time permitting)
17:00 hrs	Return to MacKenzie Park Inn

Syncrude Tour

Syncrude is one of the largest open pit mines in the world. The company commenced large scale operations in June 1977 and in 1992 is mining an average of 340,000 tonnes of oil sands per day. The daily output of approximately 160,000 bbls/day represents about 11% of Canada's 1992 domestic crude oil production.

The base mine is 4.5 km long and is split into four quadrants with highwall depths of up to 60 m. The mining method utilizes 4 electric draglines equipped with 70 cubic metre buckets. Feed grade oil sands (greater than 6 mass%) are mined by the draglines and windrowed parallel to the highwall crest (Figure 12). Lower grade oil sands (less than 6 mass%) are considered waste and are cast back into the mined out pit or placed on the bench and hauled away by truck. The windrowed feed is delivered to the extraction plant by a bucketwheel reclaimer and conveyor system. The conveyors are 1.8 m wide, running parallel to the windrows, carrying the oil sands to the extraction facilities. The conveyor belt systems are relocated 4 to 5 times per year.

The bitumen is extracted from the sand using a hot water process. Enhancement of the bitumen includes carbon reduction and hydrogen addition resulting in a "synthetic crude oil", a product which can replace or supplement conventional crude oil as a refinery feed stock (Price, 1991).

Mine Geology

Core analysis provides the basis for predicting grades and volume of material for the plant. Within the 5 year mine area, detailed highwall stability studies are also performed. A full suite of geophysical logs (including dip meter) are run for every drill hole. The spacing of the drill holes is dependent upon the complexity of the geology; however, drill hole spacing is a maximum of 130 m. In selected areas spacings of 40 to 50 m are common.

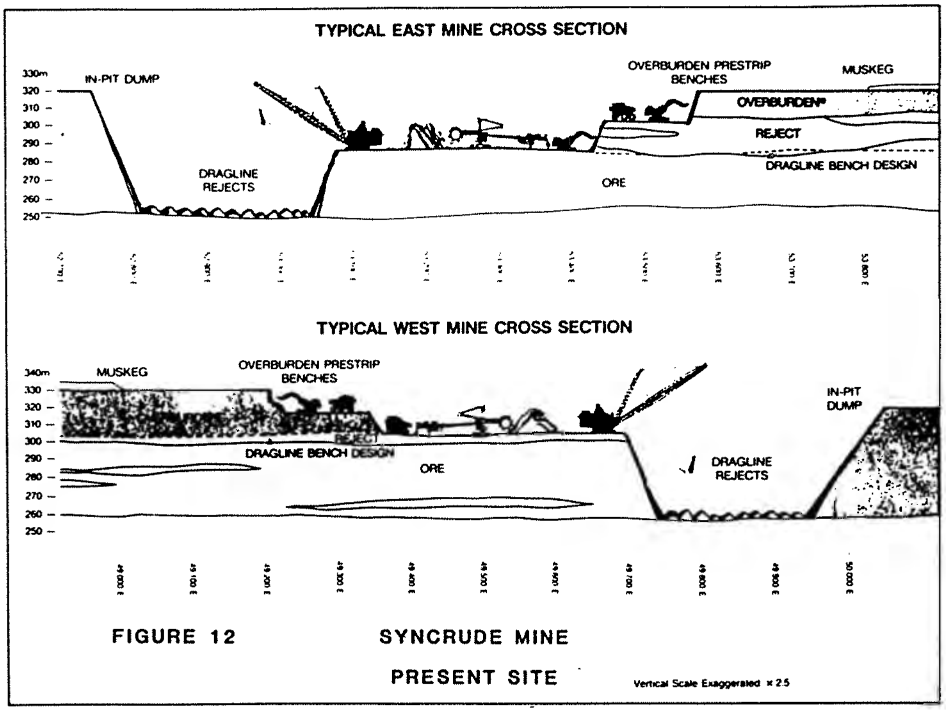


Figure 12. Oil sands mining operation, Syncrude Canada Limited (from O' Donnell and Jodrey, 1985).

Geologists use a comprehensive and detailed facies scheme to describe the cored intervals. Samples collected from a v-notch cut from the core are analyzed for mass% bitumen, water and solids and an estimate of the fines content (-44 microns) are provided. In addition, interpreted east-west structural cross sections are constructed. Interpretations are verified from highwall mapping and core studies. These data are the basis for detailed mine planning.

FORT MACKAY SECTIONS

Two outcrops, Viewpoint and Amphitheatre, will be visited along the MacKay River near Fort MacKay. The outcrops display features which contrast with those of the large channel successions exposed along the Steepbank River. In general, the trace fossils indicate a strong marine influence and many of the sedimentary structures can be interpreted as tidal in origin. Although detailed sections have not yet been measured at these outcrops, schematic sections are presented. In the afternoon, an outcrop along the Hangingstone River will be visited for an opportunity to collect some shells.

Fort MacKay

Viewpoint Outcrop

Approximately 20 m of the upper part of the McMurray Formation is exposed at the Viewpoint outcrop (Figures 29 and 30). At the base of the section, approximately 5 m of ripple cross stratified sands are overlain by a 2 m covered interval. Above this, about 4 m of cross stratified sands display a variety of interesting sedimentary structures. The cross stratified sands at the base contain convoluted bedding and possible double clay drapes which are overlain by climbing ripples and another set of cross beds with convoluted bedding. A set of cross beds in the upper part contains normal cross stratification that passes laterally into cross beds composed of ripples that climbed up the slip face of the bedform. Many of the small shale clasts scattered throughout this cross stratified unit are eroded trace fossils.

A 1 to 2 m interval of flat bedded, bioturbated sands and shales overlies the cross stratified unit and this in turn is overlain by a thin (2 m), fining upward succession. The cross bedded sand at the base of the fining upward unit contains small shale clasts of eroded trace fossils. The section is capped by 1 to 2 m of flat bedded, bioturbated sands and shales. Trace fossils are particularly well developed and include *Gyrolithes* (Figure 31), *Chondrites*, *Palaeophycus*, *Planolites*, *Skolithos*, *Cylindrichnus* and *Teichichnus*.

The two sand units at the base of the section (0-5 m; 7-11 m, Figure 30) are interpreted as deposits of an open estuarine setting where tidal currents produce complex bedforms. Double clay drapes are diagnostic of this environment as they result from the dominant and subordinate flows in a tidal setting. The cross beds that change laterally into rippled sands oriented up the slip face could be the result of a bedform moving under a unidirectional current that then became influenced by an opposing secondary current. Again, an open estuarine, tidal setting is ideal for the development of such complex bedforms. The two interbedded sand/shale units in the upper part of the section are interpreted as brackish bay deposits, particularly with the presence of *Gyrolithes*. The thin fining upward succession probably represents a tidal channel deposit.

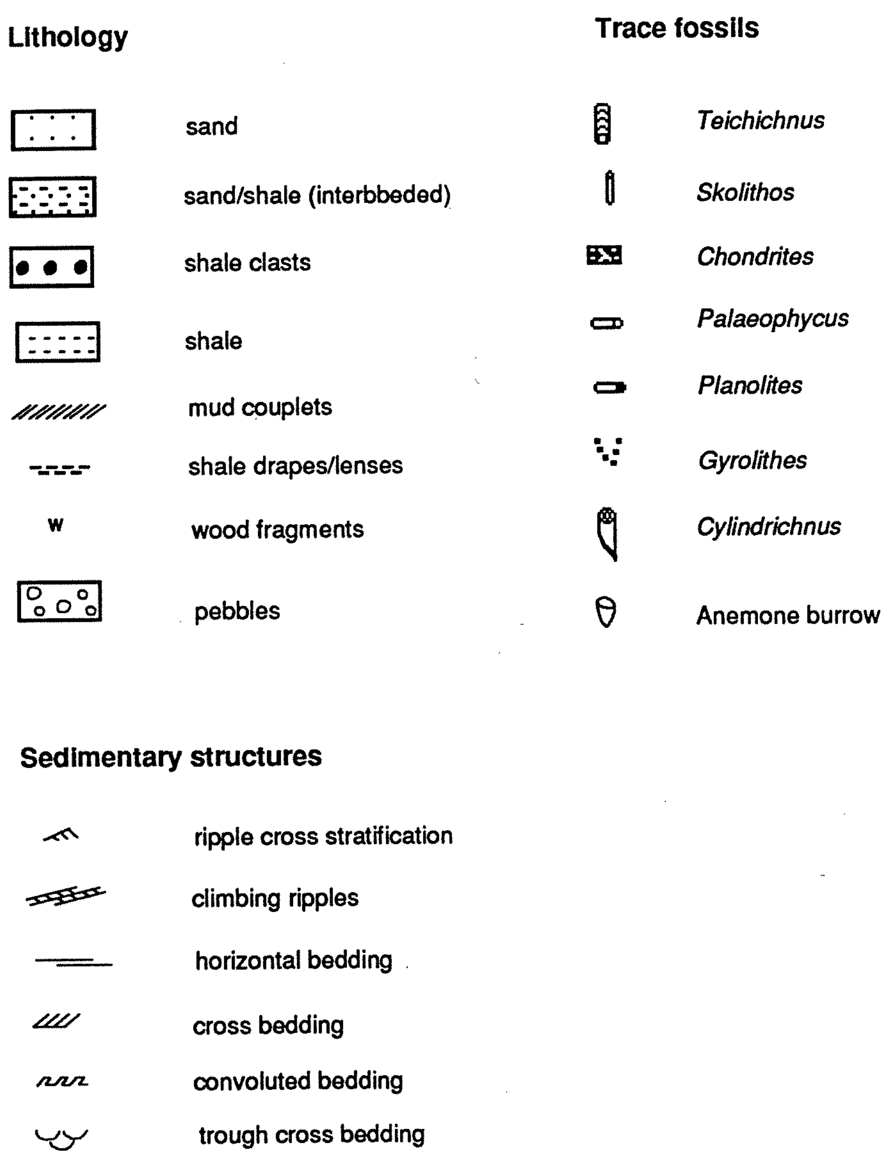


Figure 29. Legend for figures 30 and 31.

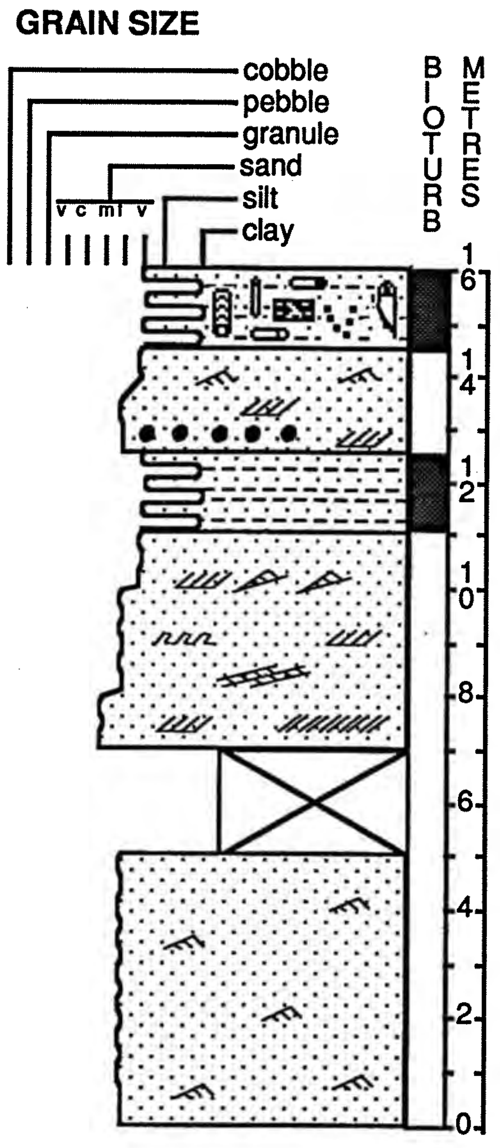


Figure 30. Schematic representation of the Viewpoint outcrop on the MacKay River.

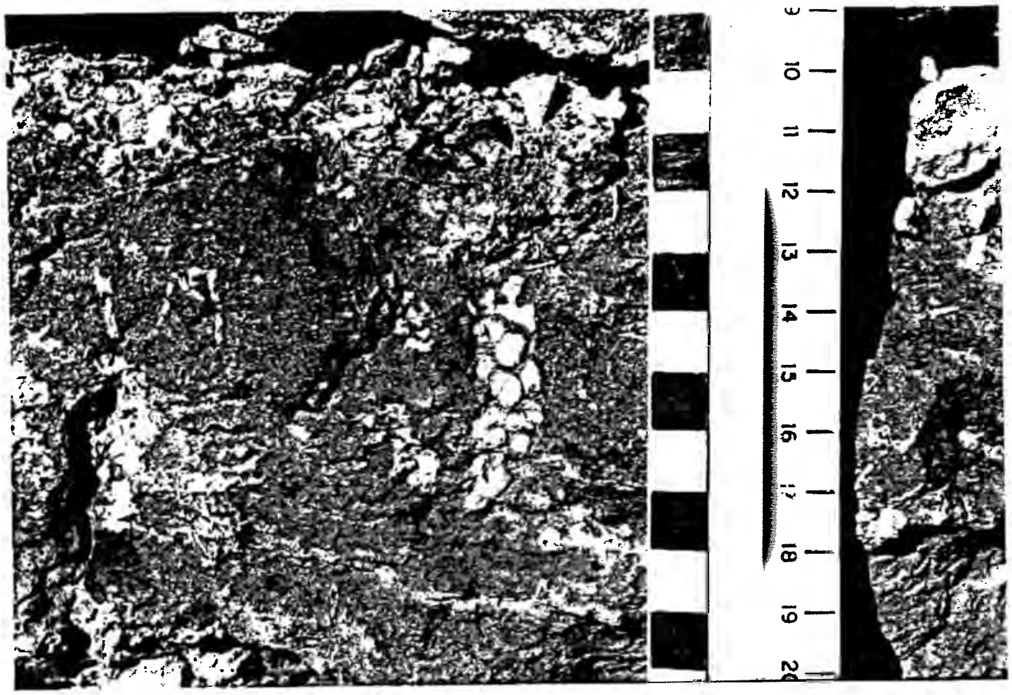


Figure 31. *Gyrolithes* in the interbedded sands and shales near the top of the Viewpoint outcrop.

Amphitheatre Outcrop

All of the informal members of the McMurray Formation (lower, middle and upper) are exposed at the Amphitheatre section (Figure 32). The lower McMurray Formation is present at the base of the outcrop and consists of coarse, poorly sorted sand and pebbles (0-2 m, Figure 32). Overlying the lower McMurray Formation is a thick section (~15 m) of highly bitumen saturated oil sands of the middle McMurray Formation that forms the bulk of the outcrop. The oil sands are predominantly cross stratified with trough cross beds (generally less than 1 m thick) and units (up to 2 m) of ripple cross strata. Some of the cross stratified sands contain double clay drapes (Figure 33) and convoluted bedding is common. Thin (less than 10 cm) shale beds, with limited lateral extent (less than 10 m), are scattered throughout the sands. The shales are bioturbated and trace fossils, including *Skolithos* and Anemone burrows, are also present in the sands.

In the central part of the outcrop it appears that an erosional contact, which is probably the base of a channel deposit, cuts down into the middle McMurray Formation. The nature of the channel infill is uncertain as the interval is partially covered and too steep for easy access. The upper McMurray Formation is well developed (approximately 4 m thick) and appears to be comprised of horizontally bedded, bioturbated sands and shales. However on close inspection, at least 2 units of low angle dipping sand/shale interbeds are discernible. Each of these units is fining up and is shalier at the top. The sand beds are up to 20 cm thick at the base of the units and thin upwards while the shale beds are 5 to 10 cm thick and thicken slightly upwards. The sands are ripple

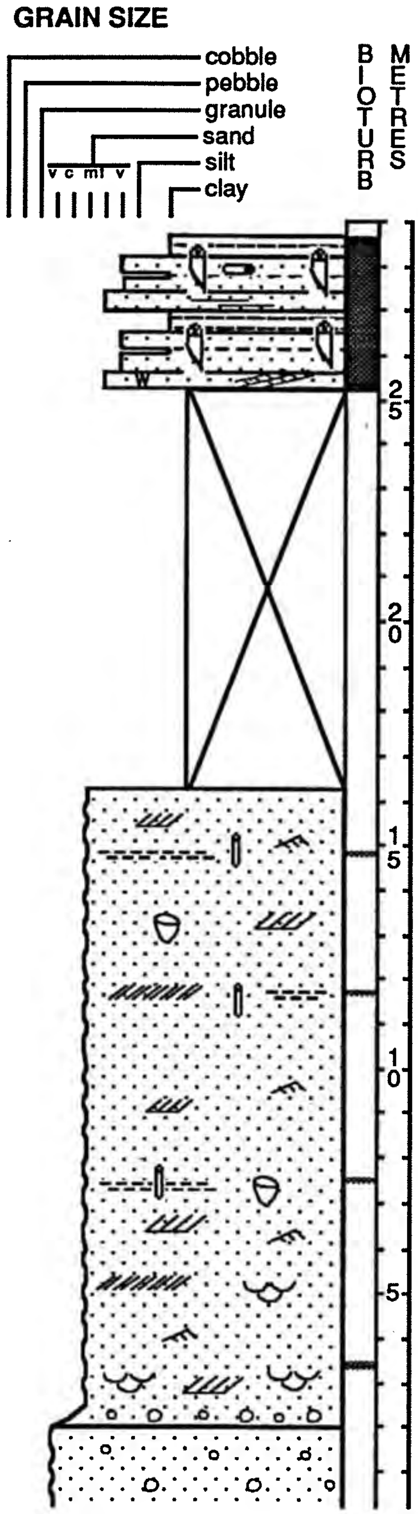


Figure 32. Schematic representation of the Amphitheatre outcrop on the MacKay River.

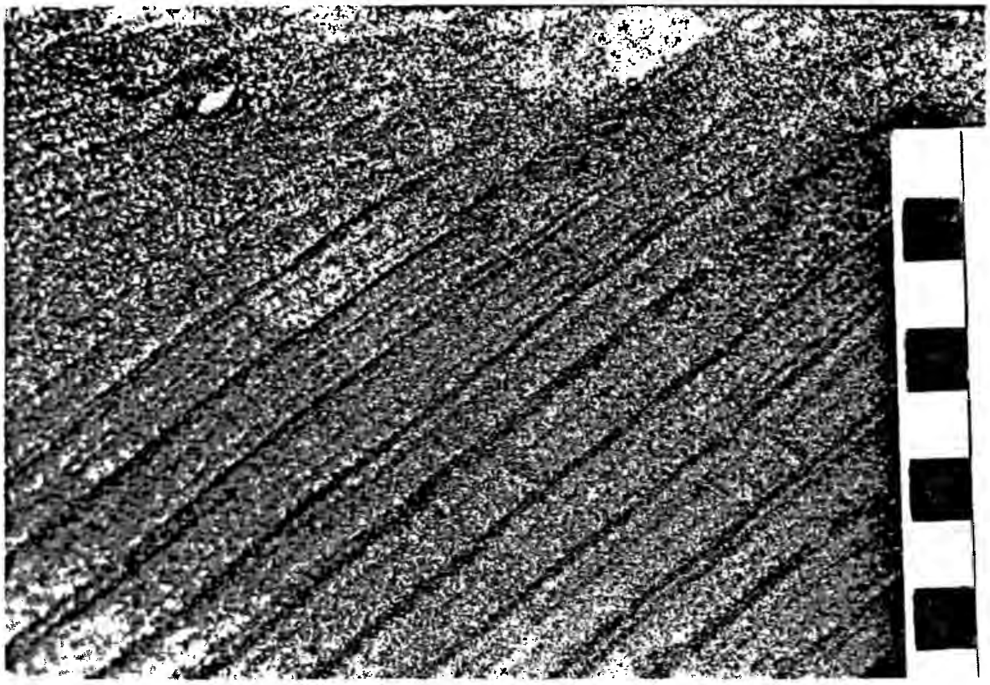


Figure 33. Possible double clay drapes in the cross stratified sands of the open estuarine unit, Amphitheatre outcrop.

cross stratified (with climbing ripples) and clasts, including coalified wood fragments, are present at the base of the units. Both the sands and shales are heavily bioturbated; trace fossils include abundant *Cylindrichnus* (Figure 34), *Skolithos* (abundant), *Planolites* and *Palaeophycus*. A thin (1-2 m) unit of Pleistocene sand and gravel, which includes some ice thrusted Cretaceous material, caps the section.

The tidal sedimentary structures and marine nature of the trace fossils indicate that the thick sand unit in the middle McMurray Formation was deposited in an open estuarine depositional environment. The fining upward units in the upper McMurray Formation are interpreted as tidal channel deposits, comprised almost entirely of inclined heterolithic strata; the low angle of the dipping beds is due to the section being strike oriented.

The thickness, high bitumen saturation, low volume of shale and absence of laterally continuous shale beds make the open estuarine sands a very attractive unit for oil sands development, whether it be for mining or *in situ* projects. The lateral continuity of the unit would be determined by the size of the estuary, which should create widths measured in hundreds of metres to kilometres. Overall exploitation potential of the tidal channel and brackish bay deposits is low due to the significant volume of shale and lower bitumen saturation of the sands.

Figure 34. *Cylindrichnus* in the inclined heterolithic strata near the top of the Amphitheatre outcrop.

Points to Remember:

1. Open estuarine sands.
   - thick (up to 10's of m)
   - well sorted (high bitumen saturation)
   - cross stratified, double clay drapes
   - thin, laterally discontinuous shale beds
   - shales and sands are bioturbated

2. Brackish bay deposits.
   - horizontally stratified sands and shales
   - extensively bioturbated, including Gyrolithes

3. Tidal channel deposits.
   - inclined heterolithic strata
   - extensively bioturbated, abundant Cylindrichnus and Skolithos

Abasand Site

Time permitting the field trip will stop at the original site of the Abasand Oil Company Ltd. The Abasand site began production in 1936 with a 400 ton/day plant on the Horse River site. The plant was burnt to the ground in 1941 and re-built a year later only to be destroyed by a second fire in 1945.

Field Trip Day 2: September 22, Sunday

08:00 hrs	UTF Phase B core presentation
09:30 hrs	Tour Interpretive Centre
11:30 hrs	Hangingstone Section (time permitting)
12:30 hrs	Lunch and depart for Edmonton

UTF Phase B Cores

Two cores from the UTF Phase B reservoir will be displayed in Room 126 of the MacKenzie Park Inn. The core viewing will be accompanied by geological interpretation discussing the reservoir variability.

AOSTRA's Underground Test Facility (UTF)

Thermal *in situ* recovery processes in the McMurray Formation have been ongoing without commercial success for close to 30 years. To date, most pilots have used conventional oil well completions (usually vertical injection and production wells) coupled with experimental steam based methods to mobilize the bitumen. A combination of mining with *in situ* recovery methods, like those tested at the UTF, may provide the breakthrough needed for commercial production. At the UTF, horizontal wells are drilled into the oil sands from tunnels in the underlying limestone (Figure 13).

The Underground Test Facility is owned and operated by AOSTRA (Alberta Oil Sands Technology and Research Authority). Industry participants include Amoco, Chevron, Conoco, Esso, Mobil, Petro-Canada, Shell and most recently (in 1992) a Japanese company. The UTF process appears to be capable of producing bitumen at costs competitive with surface mining and may be in line with current production costs of heavy oil reservoirs (O'Rourke *et al.*, 1991).

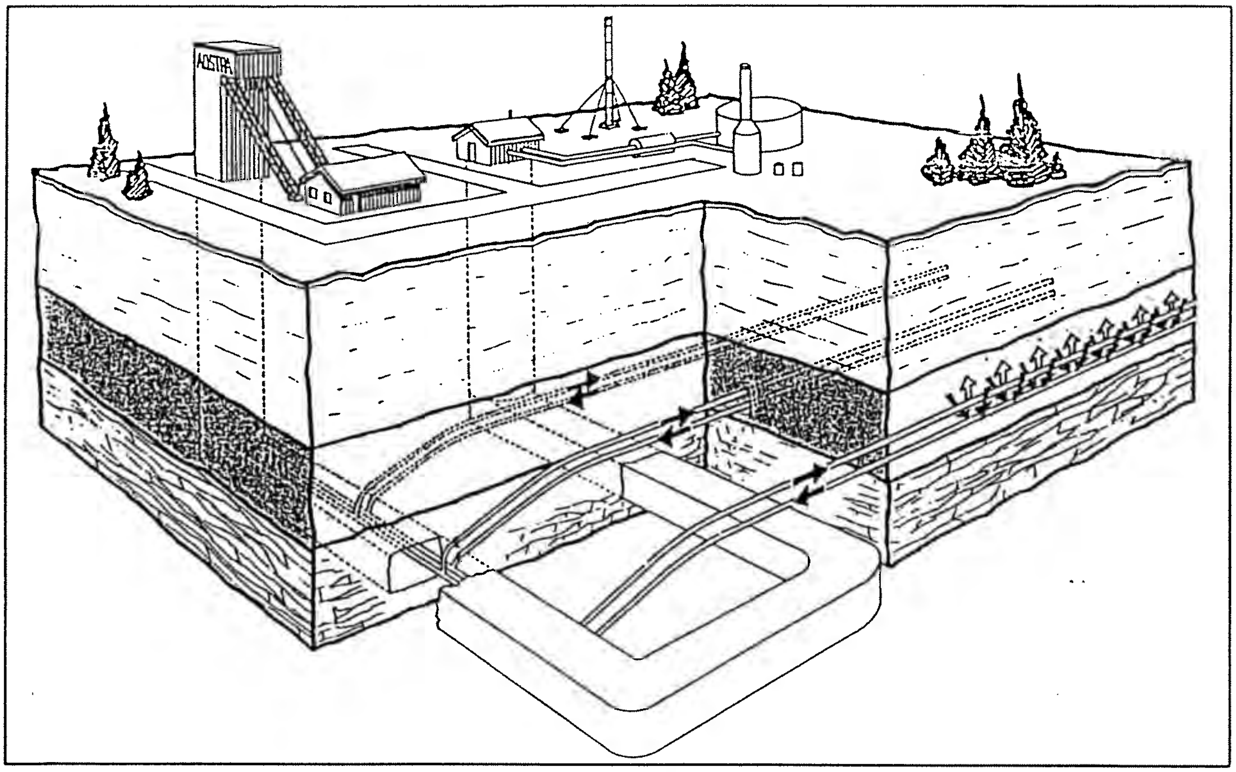
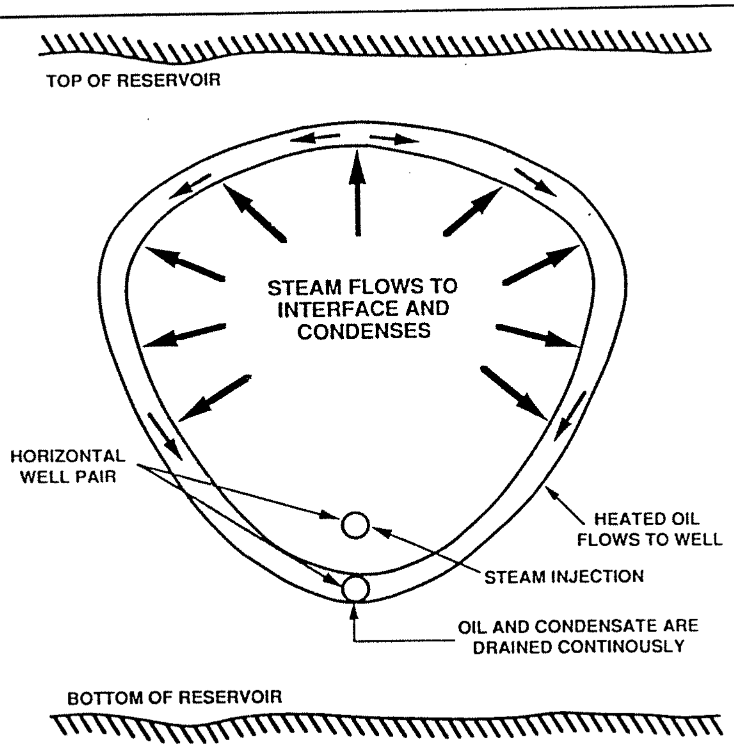


Figure 13. AOSTRA's Underground Test Facility (from O'Rourke *et al.*, 1991).



Start up process:

1. Steam circulates through upper and lower wells heating the bitumen so it flows between wells.
2. Steam breaks through to lower well after about 60 days.
3. Steam Chamber grows as bitumen is produced by continuous steam injection in upper well and production from lower well. Lower well is controlled automatically so outlet temperature is slightly below steam temperature so steam is produced.

Figure 14. Steam assisted gravity drainage (SAGD) process (from O'Rourke *et al.*, 1991).

UTF Process

A production unit consists of 2 parallel horizontal wells, vertically spaced 5 m apart at the bottom of the pay zone (Figure 14). Steam is injected below formation fracture pressure into the upper well with production from the lower well. The bitumen flows by gravity; hence the name "Steam Assisted Gravity Drainage" or SAGD (Butler and Stephens, 1980; Edmunds *et al.*, 1989).

Each well pair was designed to produce bitumen independently from the other well pairs. Well pairs in Phase A were 160 m long and 25 m apart. Bitumen recovery was estimated at 60% to the end of 1990 and tests from Phase A (1987 to 1990) have now been released from 3 well pairs (Figure 15). Bitumen production begins early in the process, the steam/oil ratio (SOR) is consistent throughout and virtually all of the injected steam is recovered as produced water.

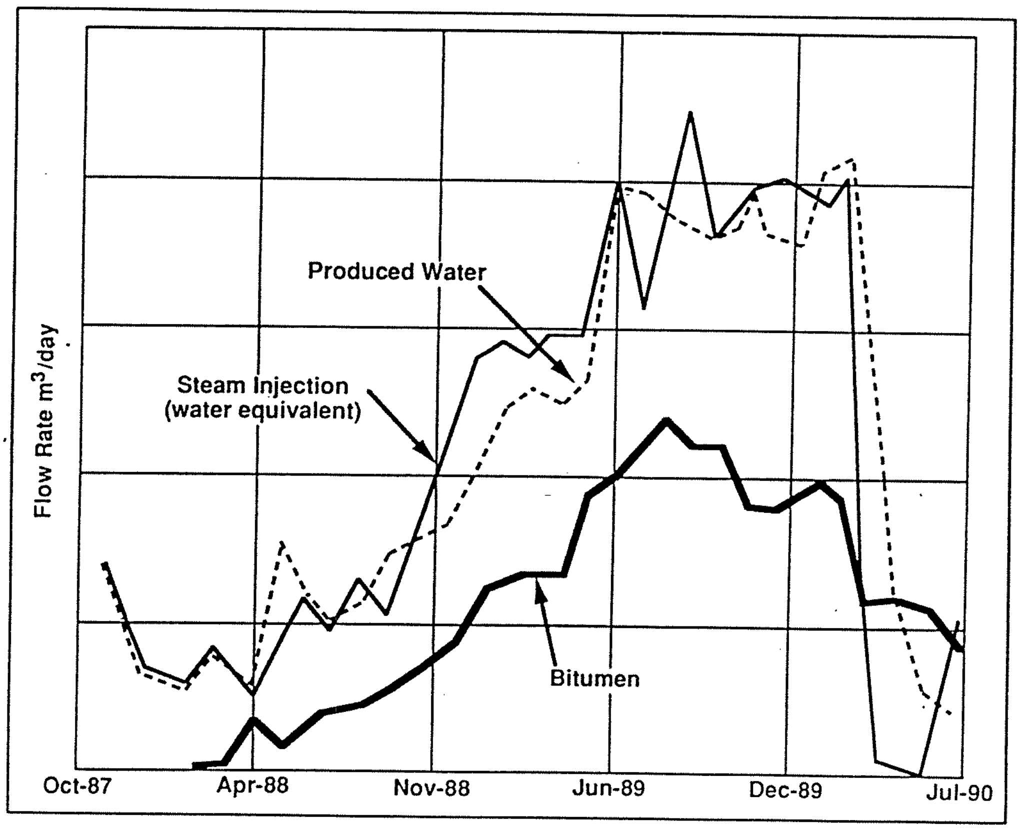


Figure 15. Phase A combined production rates from 60 m of the 160 m total length of the well pairs (from O'Rourke *et al.*, 1991).

Phase B Expansion

The technical success of Phase A and favourable production costs led to the development of the pre-commercial pilot project (Phase B). The objective is to see if the SAGD process is technically and economically feasible on commercial length wells (Figure 16). Phase B consists of 3 horizontal well pairs 600 m long spaced 70 m apart. Before the end of 1992, 550 m of new tunnels will have been excavated and a surface process facility constructed. The project is estimated to proceed through to March 31, 1994.

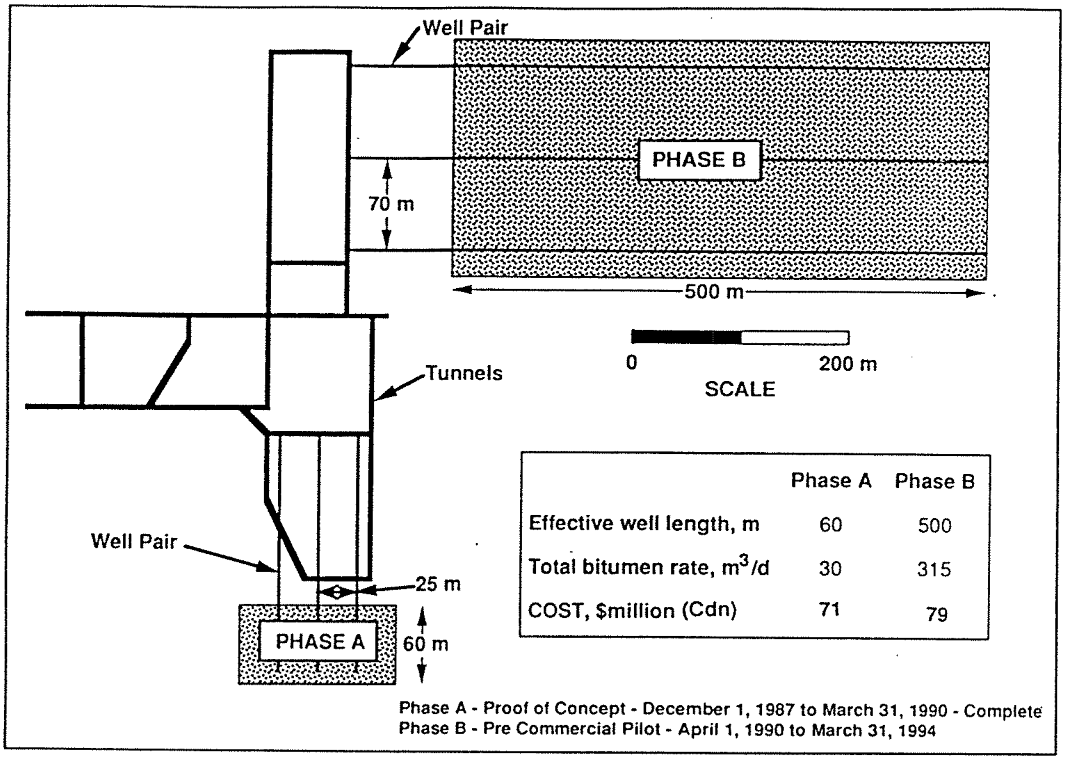


Figure 16. Phases A and B size comparison (from O'Rourke *et al.*, 1991).

The Fort McMurray Oil Sands Interpretive Centre

The Interpretive Centre features colourful, hands-on exhibits that bring you into the world of oil sands mining and technology. Highlights of the tour include:

- Quest for Energy - big-screen presentation
- Perform experiments that the oil sands pioneers used to pave the way
- See how bitumen is extracted and changed into synthetic crude
- Walk beside a seven storey high bucketwheeler excavator
- Operate a monstrous 150 ton heavy hauler

Hangingstone outcrop

An outcrop along the Hangingstone River displays bitumen saturated middle and upper McMurray Formation as well as the overlying Wabiskaw Member of the Clearwater Formation (Figure 35). The upper McMurray Formation at this locality contains shell beds which are uncommon at other outcrops (Figure 36). The shells are a mixture of fresh, brackish and marine forms although brackish species predominate.

Gastropod shells (*Viviparus*) are especially abundant and the shelly fauna corroborates the ichnological and sedimentological data that indicate that the upper McMurray Formation was deposited in a brackish water (marine shoreline) setting.

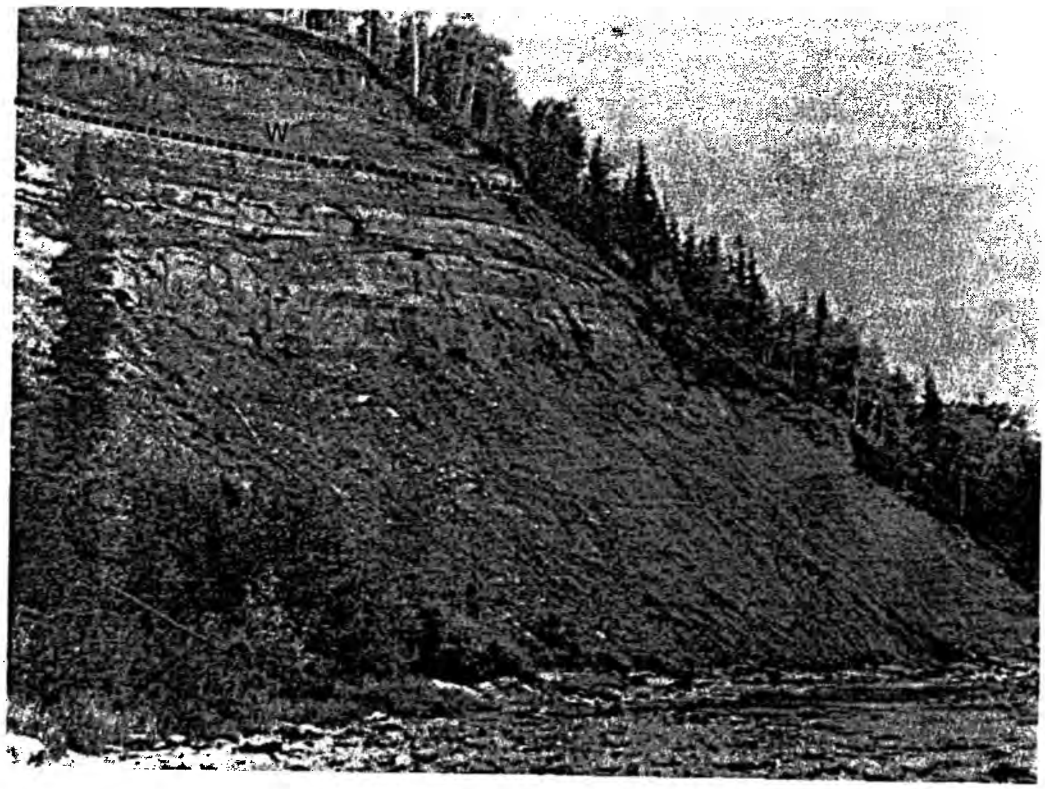


Figure 35. Outcrop, along the Hangingstone River, that contains shell beds in the upper part of the McMurray Formation (re-photographed from Carrigy and Kramers, 1973). S marks the shell bed in figure 36 and the heavy dashed line delineates the contact between the McMurray Formation and the Wabiskaw Member (W).

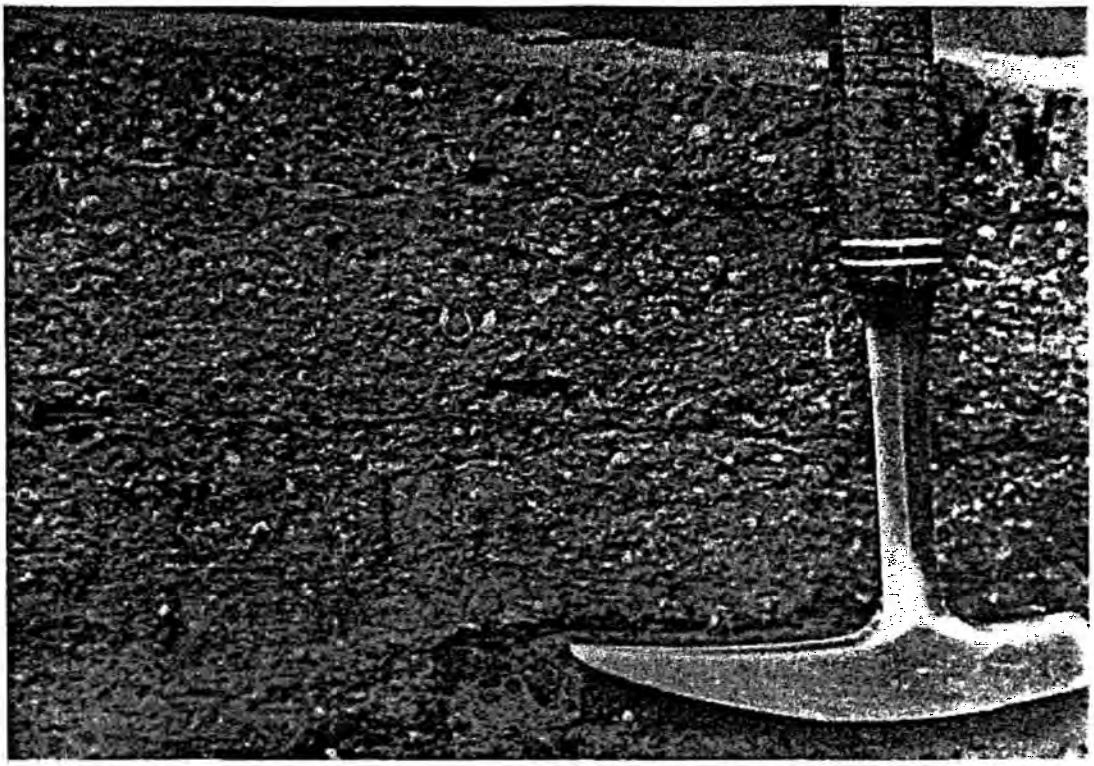


Figure 36. Shell bed in the upper McMurray Formation, Hangingstone River outcrop (re-photographed from Carrigy and Kramers, 1973).

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APPENDIX 1

HISTORICAL HIGHLIGHTS

ATHABASCA OIL SANDS

1778 - 1992

(modified after Carrigy and Kramers, 1973)

HISTORICAL HIGHLIGHTS
LOG OF MAJOR EVENTS IN THE HISTORY OF THE ATHABASCA OIL SANDS

(Modified after Carrigy and Kramers, 1973)

Year		Event
1778	•	Peter Pond, a fur trader with the North-west Company, reaches the Athabasca River by way of Methy Portage and becomes the first European to see the tar sands outcrops.

Alexander Mackenzie
(Photograph courtesy of the Public Archives of Canada, Ottawa).

1792	•	Alexander Mackenzie enters the Clearwater-Athabasca River system via Methy Portage and describes the tar sands.
1799	•	David Thompson makes a track survey of the Athabasca River from the Clearwater forks to Lake Athabasca.
1819	•	Sir John Franklin examines the Athabasca River between Lake Athabasca and the mouth of the Clearwater River.

1848 • Sir John Richardson makes geological notes on a journey to the Arctic in search of Franklin. Correlates the tar sands with the Marcellus shales of the New York State Devonian sequence.

1882 • Dr. Robert Bell of the Geological & Natural History Survey of Canada examines the tar sands area in detail. Recognizes the Lower Cretaceous age of the tar sands strata proposes a Devonian origin for the bitumen, and reports that hot water extraction of the bitumen might be feasible. He also proposes building a pipeline from the east end of Lake Athabasca to Hudson's Bay to transport the oil to foreign markets.

Dr. Robert Bell
(Photograph courtesy of the Geological Survey of Canada, Ottawa).

1884 • William Ogilvie D.L.S. makes a new track survey of the Athabasca River.

1888 • Mr. R. G. McConnell of the Geological & Natural History Survey of Canada gives the first modern geological description of the tar sands, and correlates them with the Dakota sandstones of the U.S. western interior.

• Estimates the area underlain by tar sands to be in excess of 1,000 square miles and the reserves of bitumen at not less than 4.2 million long tons. Suggests that lighter oil might be found in the same strata down dip at Pelican Rapids.

R. G. McConnell
(Photograph courtesy of the Geological Survey of Canada, Ottawa).

Count Alfred von Hammerstein
(Photograph courtesy of the E. Brown collection, Provincial Museum and Archives of Alberta, Edmonton).

1906 • Count Alfred von Hammerstein follows up Robert Bell's suggestion and drills for oil in the Devonian limestones along the banks of the Athabasca River. He does not find oil but discovers salt in a well drilled at the mouth of the Horse River.

1911 • G. H. Blanchette completes a survey of the 23rd base line.

1913 • Mr. Sydney C. Ells, an engineer with the Mines Branch in Ottawa, begins a detailed survey of the tar sands exposures on the lower Athabasca River.

1915 • Mr. Ells lays a demonstration bituminous pavement in Edmonton using tar sands from near Fort McMurray.

Sydney Ells

(Photograph courtesy of the Public Archives of Canada, Ottawa).

1916 • Northern Alberta Railway track reaches the junction of the Christina and Clearwater Rivers, 12 miles southeast of Fort McMurray.

1917 • Dr. F. H. McLearn of the Geological Survey of Canada gives the name McMurray Formation to the strata containing the tar sands.

Dr. F. H. McLearn
(Photograph courtesy of the Public Archives of Canada, Ottawa).

1920 • Dr. Karl Adolf Clark joins the Alberta Scientific and Industrial Research Council in Edmonton to study the use of Athabasca tar sands as a road paving material.

• *Mr. D. Diver makes the first attempt at production of oil by an in situ* method. He tries to distill oil from the bituminous sands by lowering a heating unit to the bottom of a well drilled in Sec. 9, Tp. 89, R. 9, W.4th Mer. near Fort McMurray.

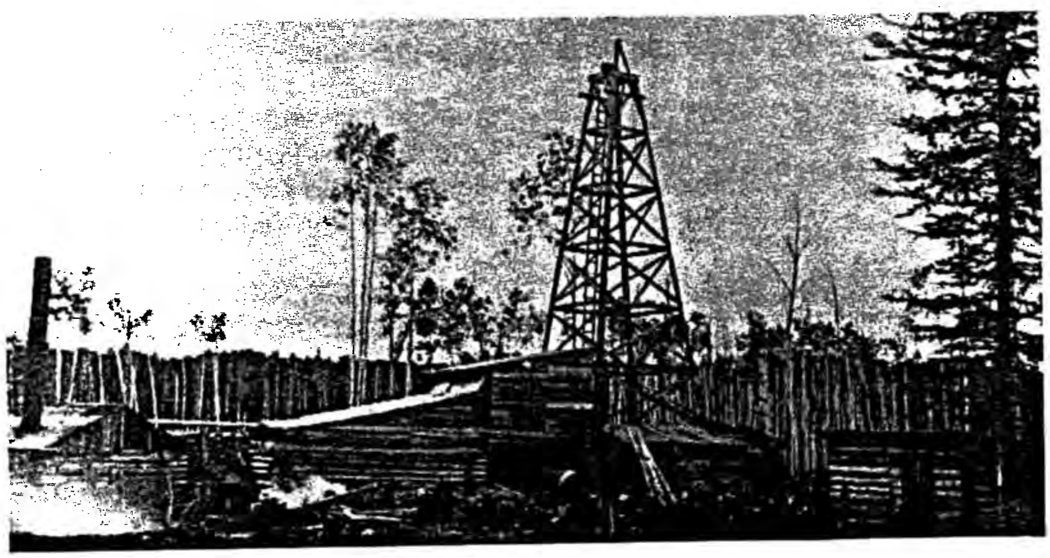
1922 • A group of New York city policemen form the Alcan Oil Company to drill for oil near the tar springs found along the Athabasca River in townships 96 and 97.

1923 • Dr. K. A. Clark and Mr. S. M. Blair build the first hot water extraction pilot plant at the University of Alberta.

1924 • Clark and Blair erect a larger hot water pilot plant at the Dunvegan Railway yards in northeast Edmonton.

1926 • Mr. S. C. Ells successfully drills and cores tar sands. Northern Alberta Railway completed to Waterways.

Dr. Karl Adolf Clark at Bitumount, 1948.
(Photograph courtesy of the Government of Alberta, Edmonton).



Diver's in situ operation, 1920.
(Photograph from J. A. Allan collection, courtesy of Alberta Research Council, Edmonton).

1927 • Mr. R. C. Fitzsimmons forms the International Bitumen Company for commercial development of the tar sands.

Mr. R. C. Fitzsimmons, ca. 1934.
(Photograph courtesy of the Provincial Museum and Archives of Alberta, Edmonton).

First commercial tar sands separation plant (Fitzsimmons' plant) at Bitumount.
(Photograph courtesy of the Provincial Museum and Archives of Alberta).

1927 (cont.) • Mr. S. C. Ells lays tar sands payment in Jasper National Park, from the CNR railway to Jasper Park Lodge.

1928 • Dr. K. A. Clark is awarded a Canadian Patent for his hot water process.

1929 • Mr. J. O. Absher attempts *in situ* distillation near Fort McMurray. Tries to ignite the tar sands at the bottom of a well to induce production.

• Mr. S. C. Ells conducts blasting experiments to soften the tar sands for easier digging.

1930 • The Research Council of Alberta hot water extraction plant is moved from the Dunvegan yards to the Clearwater River near Waterways, and uses tar sands mined by the Mines Branch of Canada.

Research Council of Alberta pilot plant, Waterways, ca. 1930.
(Photograph courtesy of the Public Archives of Canada, Ottawa).

• Mr. R. C. Fitzsimmons produces 8,400 gallons of bitumen at the Bitumount plant of the International Bitumen Company.

1930 (cont.) • Max Waite Ball forms Abasand Oil Company to extract oil commercially from the tar sands.

Max Waite Ball
(Photograph courtesy of Wallace E. Pratt and the American Association of Petroleum Geologists, Tulsa).

• Mr. B. F. Haanel of the Mines Branch in Ottawa begins hydrogenation experiments on Athabasca bitumen.

1936 • Dr. K. A. Clark awarded a U.S. patent for the hot water process and apparatus.

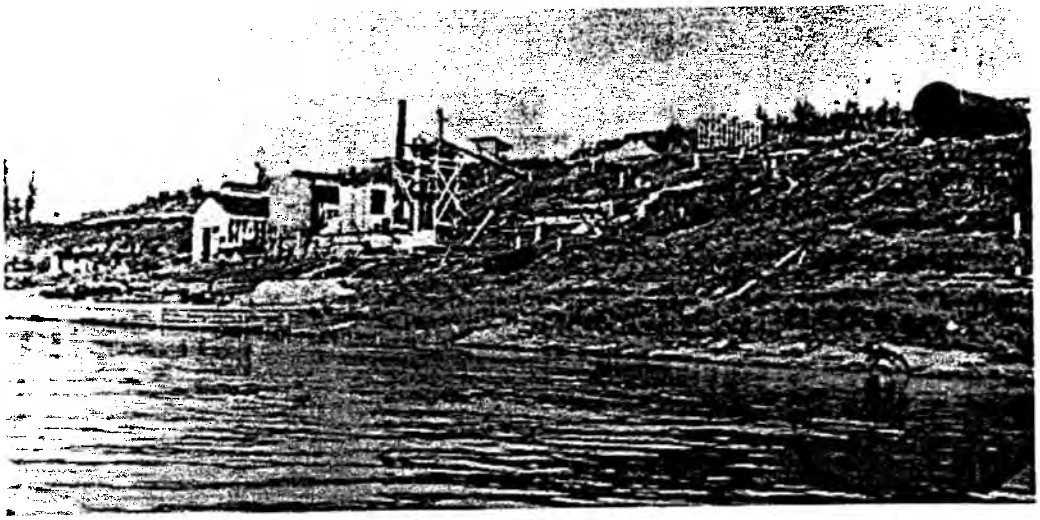
• Abasand Oil Company Ltd. completes construction of a 400 ton per day plant on the Horse River site.

• International Bitumen Company enlarges its plant at Bitumount to 350 barrels per day and adds a distillation unit.

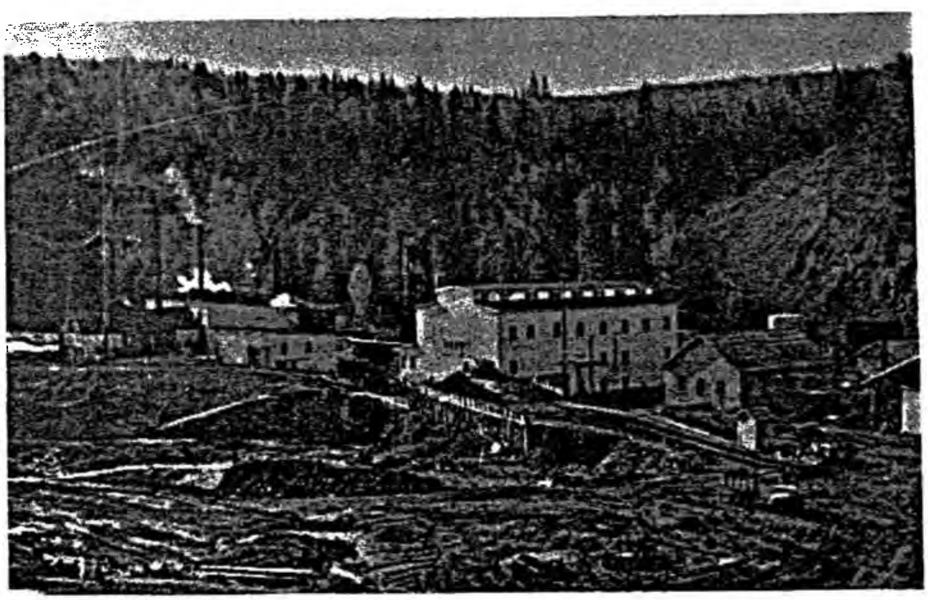
1938 • International Bitumen Company produces 4,500 drums of asphalt and 2,000 barrels of fuel oil at Bitumount.

1941 • Abasand Plant is destroyed by fire.

1942 • Mr. L. R. Champion acquires control of International Bitumen Company and renames it Oil Sands Limited. The Abasand plant is rebuilt.



International Bitumen Company plant at Bitumount, ca. 1930.
(Photograph courtesy of the Provincial Museum and Archives of Alberta, Edmonton).



Abasand plant
(Photograph courtesy of the Public Archives of Canada, Ottawa).

1942 (cont.) • Government of Canada begins an exploratory drilling and coring program to outline the tar sands reserves for war-time emergency use.

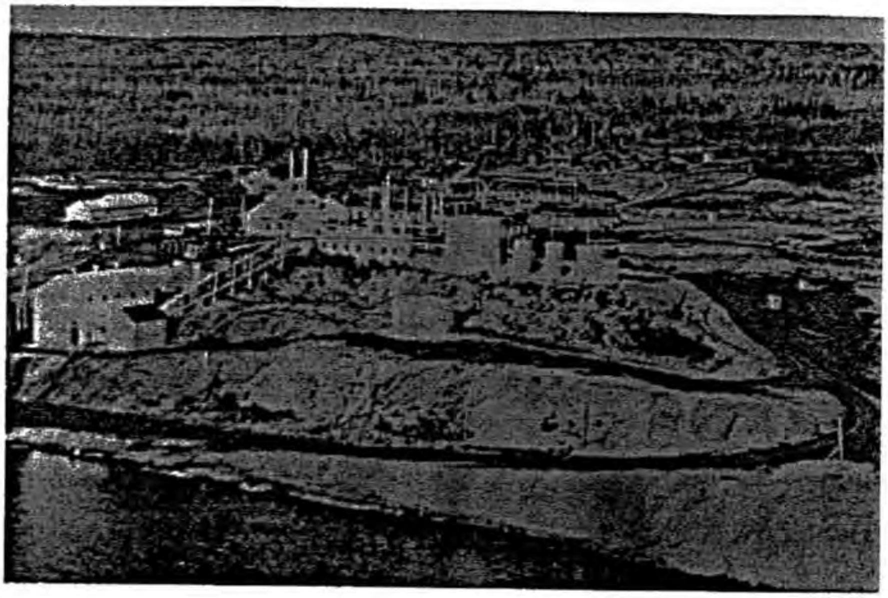
1943 • Mines Branch takes over the Abasand property and begins to redesign and reconstruct the plant.

1945 • Rebuilt Abasand plant is again destroyed by fire.

1947 • Dr. P. E. Gishler begins investigation of a fluidized solids process for bitumen recovery at the National Research Council of Canada.

• Canada Mines Branch drilling is completed after proving up reserves of 1.75 billion tons of commercial grade tar sand and discovering the rich deposit near Tar Island, now being exploited by Great Canadian Oil Sands Ltd.

1948 • Government of Alberta builds a 500 ton per day plant at Bitumount to demonstrate the commercial feasibility of the Clark hot water process.



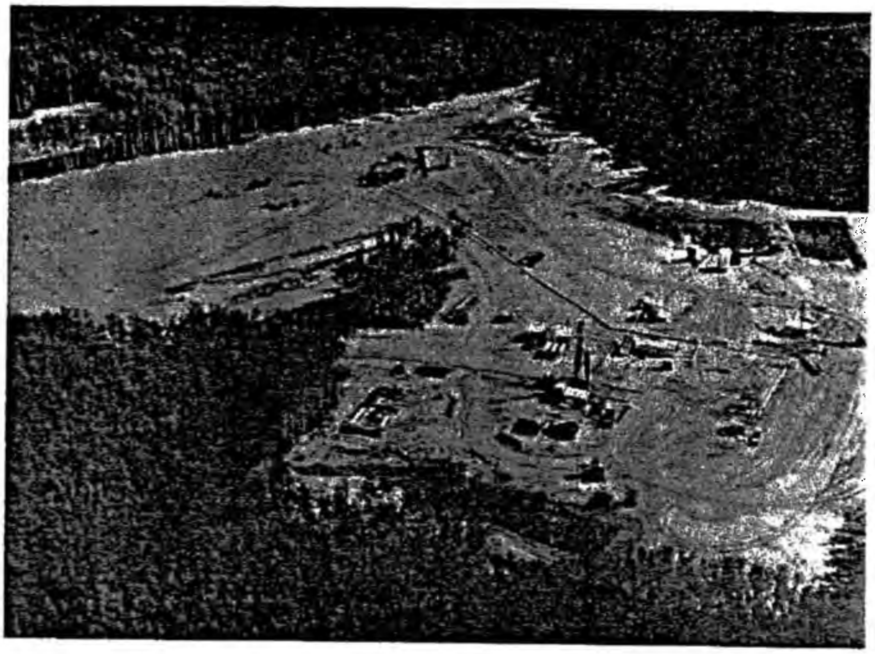
Government of Alberta demonstration plant at Bitumount.
(Photograph courtesy of Alberta Research Council, Edmonton).

1950 • Mr. S. M. Blair publishes a report indicating that large-scale economic development of the tar sands is now feasible. He estimates the cost of producing one barrel of synthetic oil and delivering it to Edmonton by pipeline at $2.36.

1951 • First Athabasca Oil Sands Conference is held in Edmonton. Alberta Government publishes its bituminous sands leasing policy and issues the first permits to oil companies.

1954	•	Great Canadian Oil Sands Ltd. is formed to take over the interests of Oil Sands Ltd.
1957	•	Shell Oil Company of Canada begins in situ steam drive experiments on lease 26.
1959	•	Cities Service Athabasca Inc. builds a pilot plant near Mildred Lake to test various separation methods.
	•	Pan American Petroleum Company begins in situ combustion experiments near Gregoire Lake.
	•	Atlantic Richfield and partners propose an experiment to release oil by exploding a nuclear device beneath the oil sands.
1960	•	Great Canadian Oil Sands Ltd. applies to the Alberta Oil and Gas Conservation Board for permission to produce 31,500 barrels per day from the oil sands.
1962	•	Great Canadian Oil Sands Ltd. receives permission from the Alberta Oil and Gas Conservation Board to build a 31,500 barrel per day plant at Tar Island.
	•	The Shell Oil Company of Canada applies to the Alberta Oil and Gas Conservation Board for permission to produce 130,000 barrels per day of bitumen by an in situ steam drive process.
1962	•	A consortium of companies consisting of Atlantic Richfield, Cities Service Athabasca Inc., Imperial Oil Ltd., and Royalite Oil Company apply to the Alberta Oil and Gas Conservation Board for a permit to produce 100,000 barrels per day of synthetic crude oil by a mining and hot water process.
1963	•	Second Athabasca Oil Sands Conference is held in Edmonton.
	•	The Alberta Oil and Gas Conservation Board publishes the first comprehensive estimate of bitumen reserves in the Athabasca deposit at 626 billion barrels of bitumen in place.
	•	Sun Oil Company of Philadelphia acquires a controlling interest in Great Canadian Oil Sands Ltd.
1964	•	The Alberta Oil and Gas Conservation Board increases Great Canadian Oil Sands Ltd. production allowable to 45,000 barrels per day. The Syncrude consortium (Atlantic Richfield, Cities Service, Imperial Oil and Gulf Oil) is incorporated to operate oil sands projects for member companies.
1967	•	Great Canadian Oil Sands Ltd. plant goes on stream.

1968 • Muskeg Oil Company (Amoco) applies to the Alberta Oil and Gas Conservation board for permission to produce 8,000 barrels per day of bitumen by a modified in situ combustion process.



Amoco in situ experimental site south of Gregoire Lake.
(Photograph courtesy of Amoco Canada Petroleum Company Ltd., Calgary).

1969 • Syncrude's application is amended to 80,000 barrels per day.

1972 • Great Canadian Oil Sands Ltd. applies for permission to increase production to the 50-60,000 barrels per day range.

1972 • Alberta Energy Resources Conservation Board gives conditional approval for Syncrude to build a 125,000 barrels per day plant at Mildred Lake.

1973 • Shell Canada Limited applies to the Alberta Energy Resources Conservation Board for approval of a mining operation to produce 100,000 barrels per day from the Athabasca oil sands.

• Texaco's Fort McMurray Pilot initiates steam-based recovery processes.

1974 • Alberta Oil Sands Technology and Research Authority (AOSTRA) established. Recognition of the need for focussed research on in situ bitumen recovery.

1977 • Amoco and Gulf/Numac pilots utilize hydraulic fractures to establish interwell communication.

1979	•	Petro-Canada with partners Cities Service, Esso and Japan Canada (PCEJ) test electrical preheating to establish horizontal communication.
1981	•	Canterra (Husky) pilot tests a process utilizing a central injector with surrounding steam stimulated production wells.
1984	•	Amoco-Gregoire Lake pilot uses foam to reduce the effects of steam over-ride.
	•	AOSTRA constructs the Underground Test Facility (UTF) to test horizontal wells and Steam Assisted Gravity Drainage (SAGD). Recovery of more than 60% achieved (by 1990).
1991	•	AOSTRA initiates pre-commercial testing at UTF Phase B.
1992	•	Chevron commences piloting of their patented HAS Drive technology (vertical injection wells and a horizontal recovery well).

APPENDIX 2

STEEPBANK RIVER SECTIONS

The prominent McMurray Formation outcrops examined on this field trip are Outcrops 7, 4, and 3 (Figure 17). Combined, all three exposures exhibit the units schematically illustrated in Figure 7.

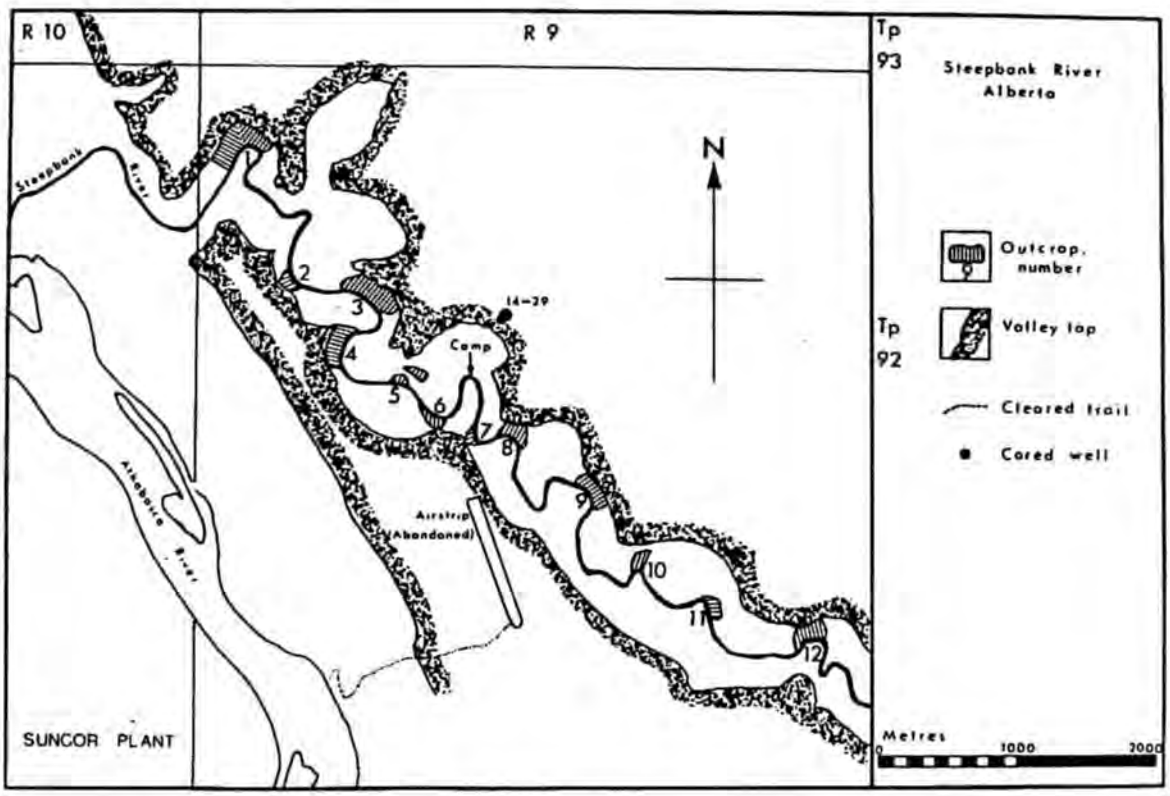


Figure 17. Map of the lower Steepbank River showing prominent McMurray Formation exposures (numbered consecutively upstream from the mouth). Sections encompassed in the field trip include Outcrop 3 (Figure 22), Outcrop 4 (Figure 21) and Outcrop 7 (Figure 19) (from Mossop *et al.*, 1982).

OUTCROP 7

The middle member of the McMurray Formation is well represented in Outcrop 7 (Figures 18 and 19). Nearly vertical relief and continuous exposure provides a superb opportunity to measure the continuity of individual facies and heterogeneities.

At the base of the outcrop on the downstream end, interlaminated sand and shale overlie Devonian limestone. This is a remnant which pre-dates the cutting of the estuarine channels through the area. Palynology indicates a continental environment. This unit was cut into by a middle McMurray estuarine channel over 40 m deep and possibly up to 250 m wide (Figures 18 and 19). The channel sands (Unit 4, Figure 20) are dominated by trough cross-beds. A transition zone (Units 6-8, Figure 20) is characterized by ripple cross laminated sand indicative of a lower flow regime. The epsilon cross strata (Unit 9, Figure 20) are ripple cross laminated and burrowed. The upper McMurray is absent in Outcrop 7.

Points to Remember:

1. Pre-estuarine channel remnant.
2. Large estuarine channel deposit.
   - inclined heterolithic stratification
   - trough cross beds at base
3. Outcrop ideal for interwell characterization of a large channel succession.

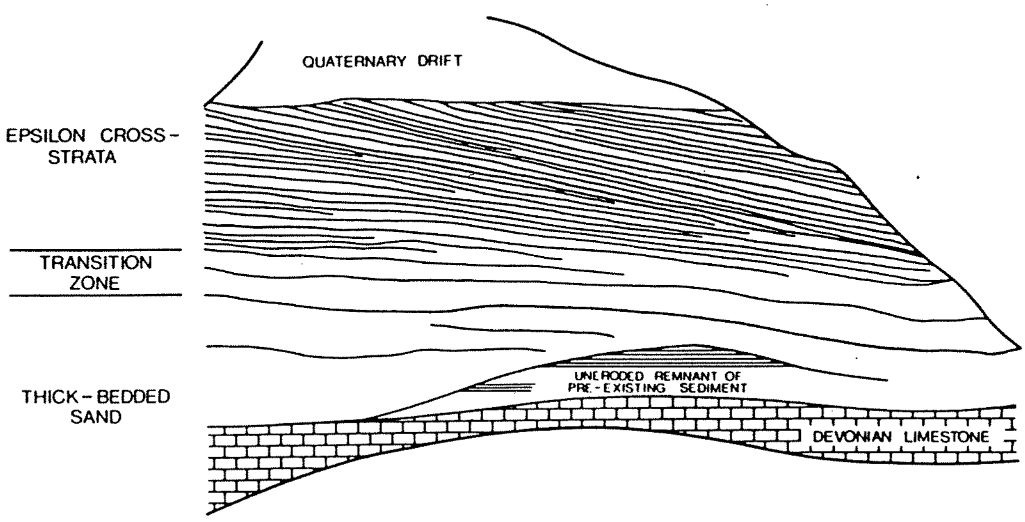


Figure 18. Schematic diagram showing the major units in Outcrop 7 (from Mossop and Flach, 1983).

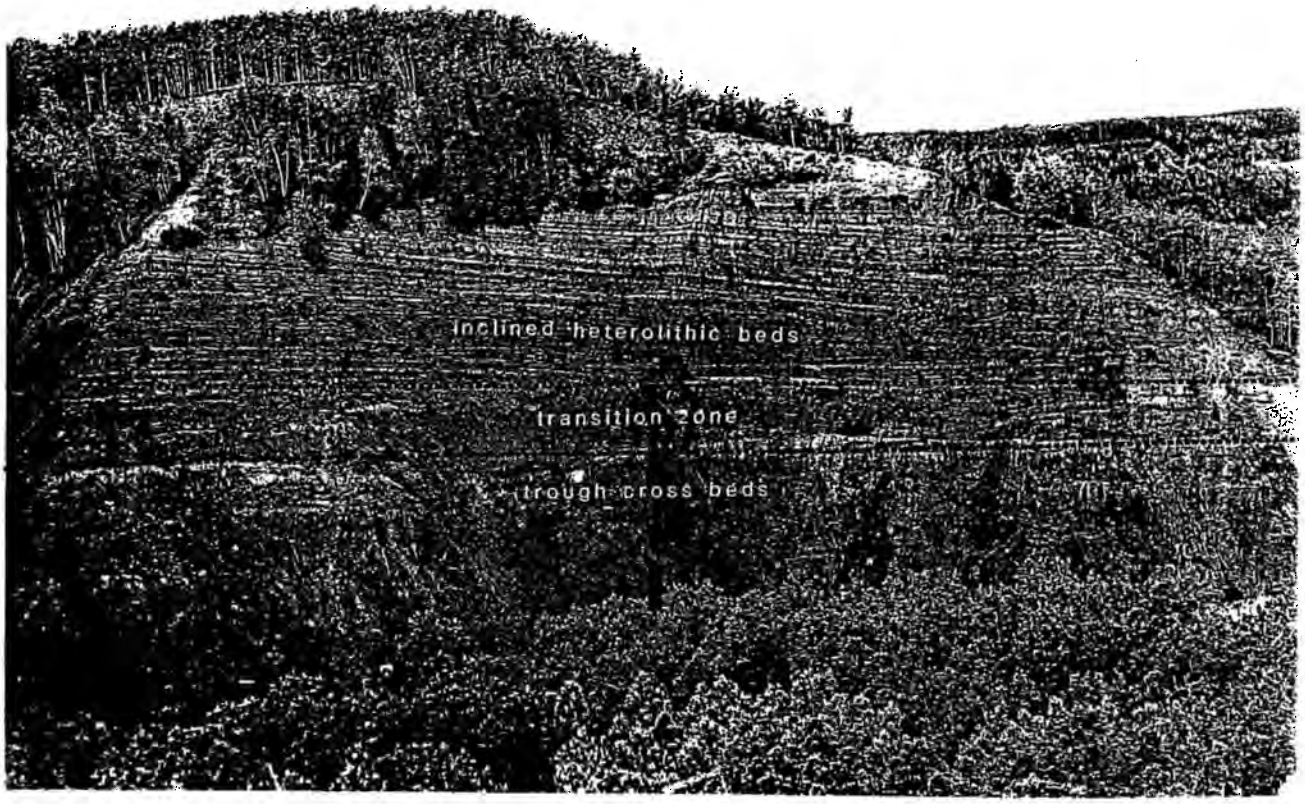


Figure 19. Steepbank Outcrop 7, illustrating the major units of a large scale estuarine channel deposit. The outcrop is approximately 45 m x 120 m.

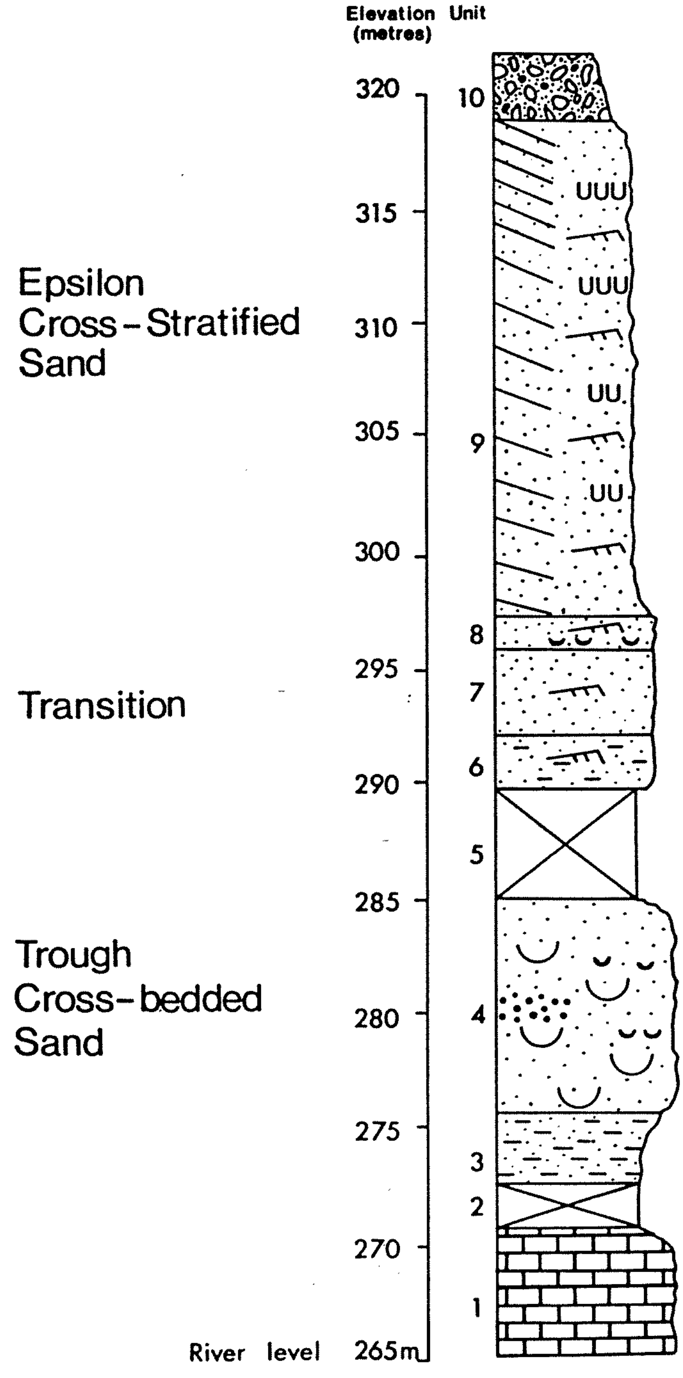


Figure 20. Generalized section of the Steepbank 7 outcrop (from Mossop *et al.*, 1982). Units on diagram are described on facing page.

Unit	Thickness (metres)	Description
10	2.8	Glacial drift
9	21.6	Oil sands, very fine to fine grained, w/thin interbeds of shale; sand beds 5 to 50 cm, shale beds 1 to 15 cm; sand beds generally rippled; burrowing increases with height in section, especially above 310 m; shale beds often intensely burrowed; above 302 m, bedding is thinner (5-15 cm), with higher percentage of shale.
8	1.2	Oil sands, very fine to fine grained; shale fragments at base, ripples through top 3/4 of unit; 8 cm shale bed at top.
7	3.7	Oil sands, very fine to fine grained; abundant ripples, also massive beds; 5-10 cm of shale at top.
6	2.4	Oil sands, very fine grained, argillaceous; bedding 2-30 cm; rippled throughout.
5	4.6	Covered.
4	9.1	Oil sands, fine grained; bedding on scale of 1 m; trough cross-bedded throughout, sets 15 cm to 2 m thick; shale rip - up clasts to 10 cm diameter present along bedding, often separating cross-bed sets; medium to coarse sand at the base of some sets.
3	3.4	Oil sands, very fine to fine grained, interbedded to interlaminated with shale, grey; bedding on scale of millimetres to 5 centimetres.
2	1.8	Covered.
1	5.5	Limestone, green-grey, rubbly oxidized zone at top is in places hard ironstone.

OUTCROP 4

Outcrop 4 affords excellent exposure of the lower McMurray Formation, cross cutting channel relationships of the middle McMurray and a full section of the upper McMurray.

The lower McMurray is very poorly sorted. It is representative of very rapid sedimentation in earliest McMurray time, the materials having been scavenged from the unconformity surface and adjacent source areas and subsequently dumped into depressions in the limestone topography. That the unconformity surface is dramatically depressed at Outcrop 4 is evidenced by the fact that, in the adjacent exposure (Outcrop 3), the limestone rises some 22 metres above river level.

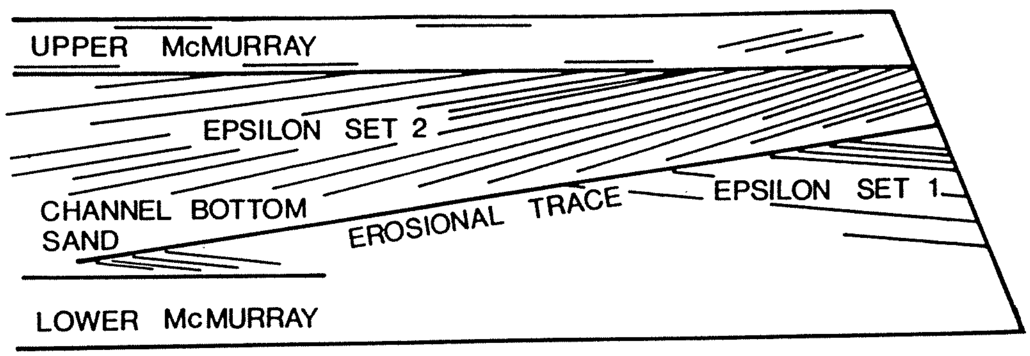


Figure 21. Schematic representation of the cross cutting channel relationships evident in Steepbank River Outcrop 4. Erosion of younger channel (Set 2) resulted in channel bottom sand being deposited above the epsilon beds of the older channel (Set 1) (from Mossop *et al.*, 1982).

The middle McMurray Formation in Outcrop 4 exhibits two separate sets of epsilon cross strata (Figure 21). The first channel succession (Set 1), with epsilon beds dipping towards the right, has been differentially eroded by a second channel succession (Set 2) with epsilon beds dipping toward the left. It is important to note that the channel bottom sands associated with Set 2 can be seen to overlie truncated epsilon beds of Set 1.

The upper McMurray Formation in Outcrop 4 consists dominantly of bioturbated sand. An ironstone band extending the length of the outcrop may have been a horizon of subaerial exposure. A small scale set of epsilon cross strata is present in the upper McMurray near the downstream end of the outcrop. It may have been produced as a result of lateral accretion in a small tidal channel complex. The exposure is capped by glauconitic sands of the Wabiskaw Member of the Clearwater Formation.

Points to Remember:

1. Coarse grained and poorly sorted lower McMurray Formation.

2. Several channel successions in the middle McMurray Formation.

3. Small channel succession in the upper McMurray Formation.

OUTCROP 3

Outcrop 3 (Figure 22) affords excellent exposure of the middle (Figure 23) and upper parts of the McMurray Formation. The lower member, which is characteristically confined to lows on the unconformity surface, is absent because the limestone is structurally higher at this point than anywhere else on the Steepbank River.

The middle McMurray is characterized by cross bedded and ripple cross laminated sands (Units 3-7, inclusive, Figure 24). Laterally accreting epsilon cross beds (Units 8 and 9, Figure 24) overlie these thick-bedded sands. Large scale erosional surfaces within the epsilon cross beds (Figure 23) show that the point bar was periodically eroded by high energy events. Paleocurrent measurements taken within the sands of the sand/mudstone couplets indicate unidirectional transport toward the northwest, at approximate right angles to the dip of the epsilon cross beds (northeast). Current direction was thus across the sloping beds, rather than down their dip.

The entire middle McMurray succession in Outcrop 3 (Units 3-9, Figure 24) is a single upward-fining cycle, with moderate but detectable upward decrease in mean sand size, and pronounced upward increase in the number and thickness of shale beds. Both the grain size profile and the paleocurrent data thus support a channel interpretation for the origin of the sequence.

The upper McMurray consists of a resistant bed grading from cross bedded, well saturated oil sands at the base to argillaceous, rippled, poorly saturated sands at the top (Unit 10, Figure 24). Burrowing intensity and clay percentage both increase upward. The indicated paleocurrent direction is again strongly unidirectional toward the northeast. This unit is interpreted to be a shoreline deposit.

Three separate upward-coarsening cycles are present in the overlying parts of the upper McMurray. The first of these (Units 11 and 12, Figure 24) consists of interbedded sand and shale at the base, coarsening upward to a well sorted sand with cross-beds, ripples and scour-and-fill structures at the top. The next cycle (Units 13 and 14, Figure 24) comprises heavily bioturbated argillaceous sand which grades upward into well sorted, very fine sand. Parallel laminated sand typical of beach deposits, and symmetrical ripples indicative of wave action, are both represented. At the top of this cycle are large funnel-shaped burrows, *Bergaueria*, interpreted as anemone dwelling structures. The final upward-coarsening cycle (Unit 15, Figure 24) consists of silty and argillaceous sand, bioturbated throughout.

Unit 16 (Figure 24) is a bioturbated, highly argillaceous sand with trace amounts of glauconite, which is thought to represent the initial transgression of the Clearwater Sea from the north.

Unit 17 (Figure 24), poorly exposed, is the highly glauconitic sand of the Wabiskaw Member of the Clearwater Formation.

Figure 22. Photograph showing Outcrop 3, Steepbank River.

Figure 23. Inclined heterolithic strata (epsilon cross beds) displaying large scale erosional features at Outcrop 3. Field notebook for scale.

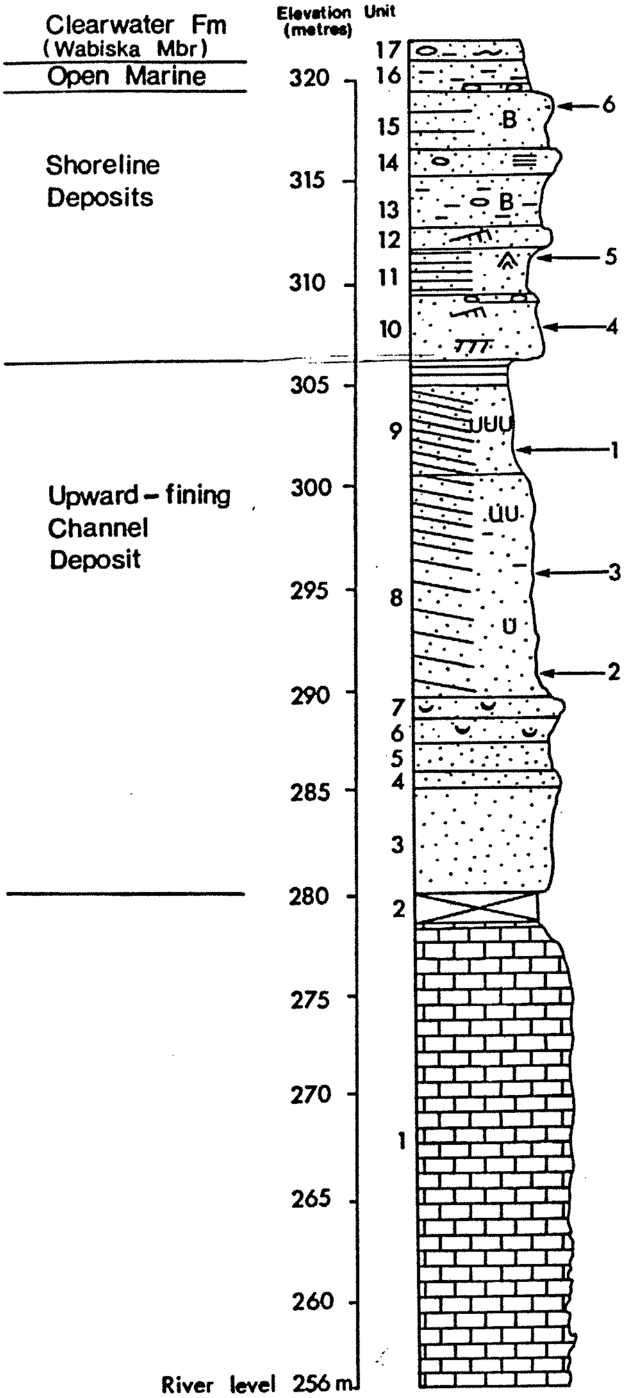


Figure 24. Generalized section of the Steepbank 3 outcrop (from Mossop *et al.*, 1982). Units on diagram are described on facing page.

Unit	Thickness (metres)	Description
17	0.6	Sandstone, very fine grained, very argillaceous, glauconitic; contains ironstone concretions.
16	1.8	Oil sands, very fine grained, very argillaceous; bioturbated; ironstone bed 30 cm from base.
15	3.7	Oil sands, very fine grained, very argillaceous; less argillaceous towards top; bioturbated throughout
14	1.2	Oil sands, very fine grained, laminated to rippled in part; large burrows at top, occasional concretions.
13	2.4	Oil sands, very fine grained to silty, very argillaceous; bioturbated.
12	1.2	Oil sands, very fine grained; trough ripples throughout; medium scale cross beds at top (5 cm sets).
11	2.4	Oil sands, very fine grained, very silty and shaly, interbedded w/shale; occasional wave ripples; fissile and recessive unit.
10	3.1	Oil sands, very fine grained, poorly defined bedding; burrows abundant along bedding planes; ripples present, medium scale cross-bedding (5-10 cm) at base.
9	5.8	Oil sands, very fine grained, very argillaceous, to shale and interlaminated oil sands/shale at top.
8	10.7	Oil sands, very fine grained, interbedded w/shale and siltstone; sand generally rippled; bedding very distinct, w/clean sand beds (10-30 cm) separated by beds of shale (1-10 cm); individual sand beds often grade from massive at bottom to rippled at top.
7	1.2	Oil sands, very fine grained, top half rippled throughout; shale rip-up clasts in lower part.
6	1.2	Oil sands, fine grained, w/abundant shale rip-up clasts throughout, diameter generally a few millimetres, but up to 10 cm.
5	1.2	Oil sands, very fine to fine grained, trough ripples throughout; medium scale cross-beds (5 cm thick) at top.
4	0.9	Oil sands, very fine to fine grained, resistant; bedding not laterally continuous.
3	4.9	Oil sands, 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.

ICHNOLOGY - OUTCROP 3

Outcrop 3 affords an excellent opportunity to examine the prolific ichnofossil suite (Figure 25) contained in the middle and upper McMurray Formation. Present are representatives of at least 9 ichnogenera (*Skolithos*, *Cylindrichnus*, *Monocraterion*, *Planolites*, *Dolopichnus*, *Bergaueria*, *Palaeophycus*, *Teichichnus*, and *Lockeia*) as well as two types of vertical escape structures. The middle McMurray contains: (1) *Skolithos*, representing at least two different morpho-types; (2) rare to common *Monocraterion*; (3) rare to common *Cylindrichnus*; (4) rare to common *Planolites* and *Palaeophycus*; (5) rare to common escape structures; and (6) numerous fine grained units which are characterized by a bioturbate texture in which individual forms are difficult to discern. The upper McMurray (argillaceous sand unit) contains a much more diverse suite of ichnofossils, including; *Bergaueria*, *Dolopichnus*, *Monocraterion*, *Cylindrichnus*, *Planolites*, *Palaeophycus*, *Skolithos* (2 types), *Lockeia* and *Teichichnus*, as well as numerous bioturbated units in which distinct forms are difficult to discern.

Description of Ichnofossils

A) *Skolithos* Sp. A: The most prolific burrow present in the section is *Skolithos* Sp. A, which consists of vertical to inclined to arcuate, clay-lined shafts with diameters ranging from 1.5 to 4 mm and lengths up to 20 cm; preserved in endogenic full - relief. Interpreted as the dwelling burrows (domichnia) of filter-feeding organisms.

B) *Skolithos* Sp. B: Commonly associated with *Skolithos* Sp. A, is another type of simple vertical shaft which differs in having smaller dimensions and does not possess distinct clay linings.

C) *Cylindrichnus*: Subconical form, weakly curved, circular to oval in cross-section with diameters of 2 to 6 mm; irregular outline with exterior wall composed of faint concentric laminations, central core 0.5 to 2 mm in diameter; preserved in endogenic full relief. Interpreted as the dwelling burrows (domichnia) of filter - feeding organisms.

D) *Monocraterion*: Vertical, funnel-shaped burrows up to 30 mm long, upper funnel structure (5-8 mm wide and 6-9 mm deep) is penetrated by a central tube (1-3 mm wide); preserved in endogenic full relief. Interpreted as a dwelling burrow (domichnia) of a filter feeding organism or more likely as a dwelling/feeding burrow (domichnia/fodinichnia) of a deposit feeding organism.

E) *Planolites*: Predominantly cylindrical, smooth walled, rarely to irregularly branched or unbranched burrows; typically oriented more or less parallel with the bedding. Burrow infills are characteristically different from the host rock, which is indicative of active infilling of the burrow; preserved as endichnia, hypichnial ridges, and epichnial grooves. Interpreted as feeding burrows (fodinichnia) of deposit-feeding organisms.

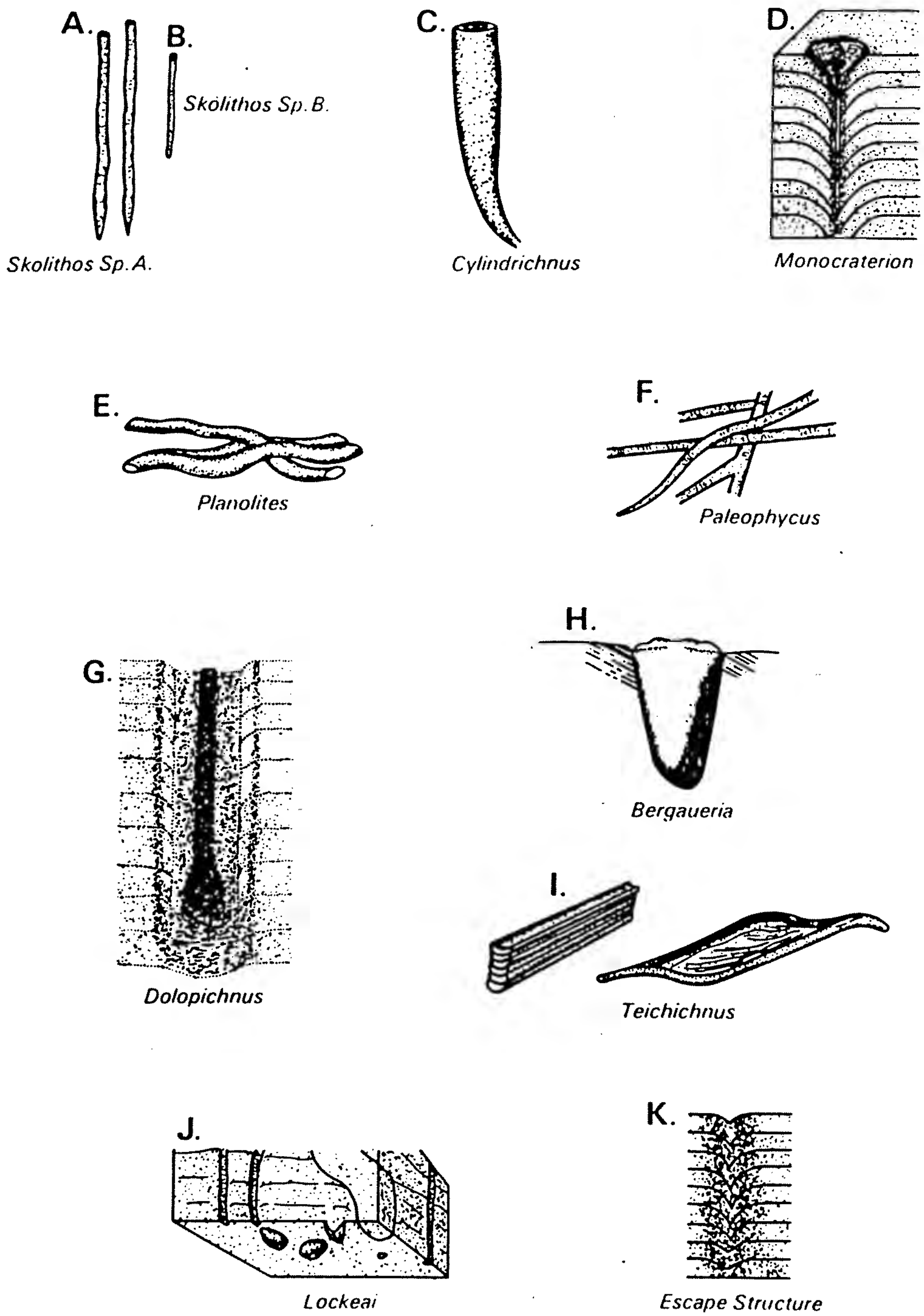


Figure 25. Prominent ichnofossils from the McMurray Formation (modified from Mossop *et al.*, 1982).

F) *Palaeophycus*: Smooth, unornamented, more or less horizontal burrows of variable dimensions, thinly but distinctly lined. True branching is relatively rare and irregular; crossovers, interpenetrations, and collapse features can be observed. Burrow infills are characteristically similar to the matrix of the host rock, which is indicative of passive infilling of the burrow; preserved as endichnia or, more commonly as hypichnial ridges or epichnial grooves. Interpreted as dwelling or foraging burrows of a predaceous veriform organism.

G) *Dolopichnus*: Large, vertical, cylindrical burrows with circular cross-sections 20-25 mm in diameter. Laminae in the sands bend downward around the burrows which terminate in flattened hemispheres with concentric impressions. A vague, central cylinder about 10 mm in diameter occurs within the burrow; preserved in endogenic full relief and interpreted as dwelling burrows (domichnia) of sea anemones.

H) *Bergaueria*: Vertical, cylindrical, sac-like burrows with smooth walls and rounded lower terminations; diameters up to 40 mm, length characteristically one-half the width; preserved in endogenic full relief. Interpreted as dwelling burrows (domichnia) of suspension-feeding actinian anemones.

I) *Teichichnus*: Long, wall-like burrows formed by the vertical displacement of horizontal or oblique tubes. The tube diameters of the McMurray specimens range from 3 to 10 mm and the final tube is rarely preserved; the associated spreiten structures are concave downward and represent a retrusive pattern; preserved in endogenic full relief. Interpreted as feeding burrows (fodinichnia) of worm-like organisms.

J) Lockeia: Small, almond-shaped, oblong structures which taper to sharp or obtuse points at both ends; dimensions variable (2-4 mm wide and 3-6 mm long); preserved in convex hyporelief. Interpreted as resting traces (cubichnia) of small, burrowing bivalves or conchostracan branchiopods.

K) Escape structures: Two distinct types of escape structures are present: (1) the most common type is represented by asymmetric subtriangular notches defined by closely spaced laminae which are commonly distorted and occasionally broken (Figure 25); such structures are commonly associated with the upward movement of bivalves in response to sudden influxes of sediment; and (2) the other type of escape structure represents a vertical repetition of a distinct trace which relocates in response to increased sedimentation.

Trace Fossils of the Epsilon Cross Stratified Unit

The McMurray Formation epsilon cross strata consist of single sand/mudstone couplets. Although the unit appears somewhat monotonous, detailed stratigraphic analysis reveals significant variations, many of which are delineated by the distribution, density and nature of the ichnofossils.

A typical epsilon set is characterized by a relatively consistent association of: vertical shafts (*Skolithos* and *Cylindrichnus*), representing the dwelling burrows of suspension - feeding organisms, in the main sand body; and a bioturbate texture, possibly the result of deposit-feeding and foraging veriform organisms (represented by *Planolites* and *Palaeophycus*, as well as a general burrow mottling) in the ensuing silty partings (Figure 26). Dwelling burrows of filter-feeding organisms often attain very high densities and develop in response to a variety of environment conditions which include: high energy and oxygen levels, and sand substrates with low detritus levels (Seilacher, 1967; Frey, 1971; Howard, 1972). As a result, filter-feeders dominate the biota and deposit-feeding and mobile carnivorous forms are selectively excluded. The ichnocoenose of the silty partings consists predominantly of horizontal deposit-feeding structures. Howard (1972) suggests that such an assemblage is indicative of low energy levels, slow continuous sedimentation rates, sediments rich in organics, and an overlying water column either too turbid or too slow moving to support abundant filter-feeding organisms. Such a scenario is consistent with the falling flow regime interpretation postulated here for the epsilon cross-beds in which sand deposition may have taken place only during flood stage, with fines accumulating as clay drapes during the remainder of the cycle.

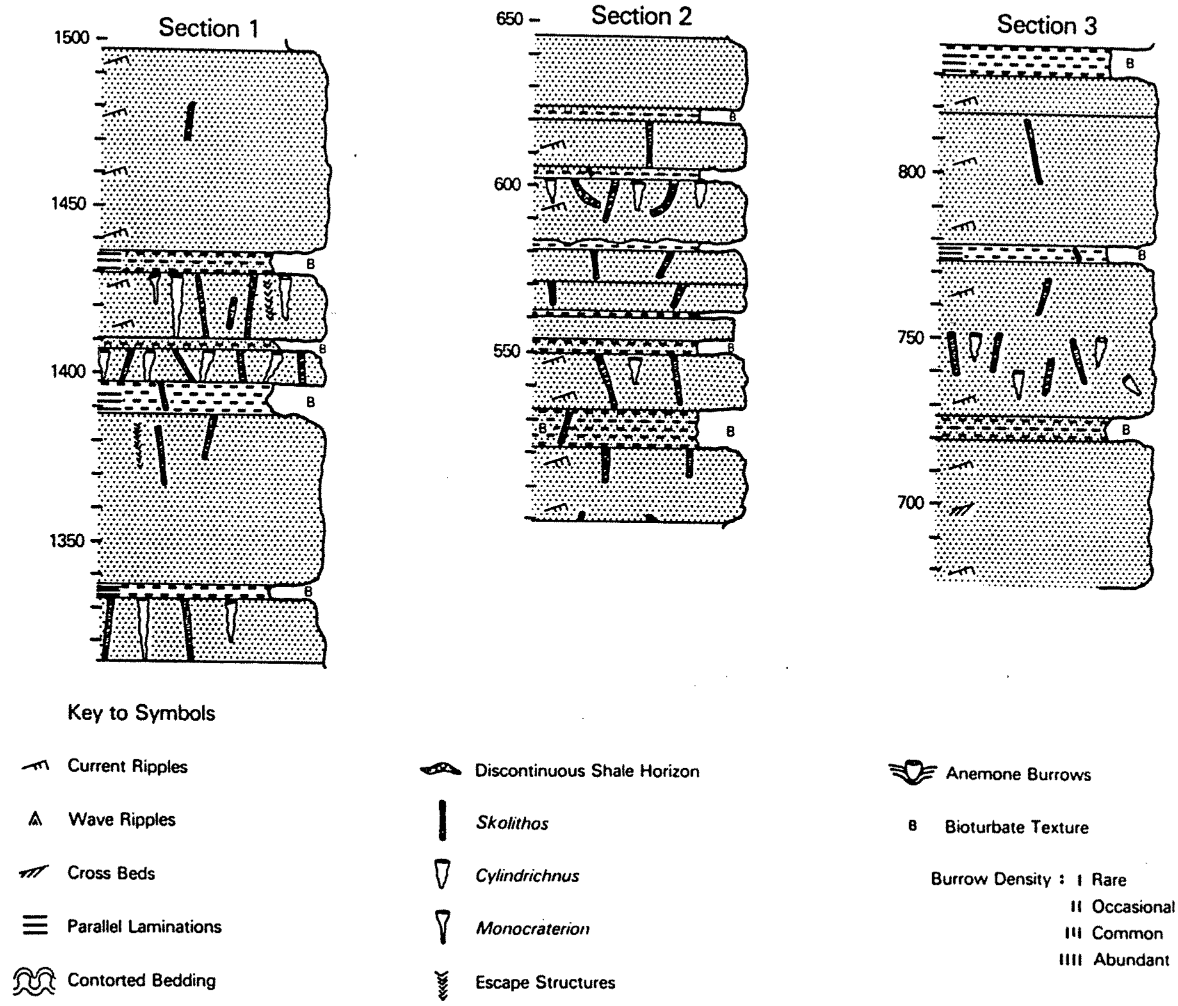


Figure 26. Diagram illustrating the distribution and density of prominent ichnofossils from the middle McMurray in Outcrop 3 (from Mossop *et al.*, 1982).

Although this basic pattern persists throughout the middle McMurray, certain generalizations and deviations have been noted.

Generally the ichnocoenose of the sandy beds are much more diverse and abundant in the thinner units (Figure 26) which increase in number upsection. In sandy substrates, which are characterized by high water contents, infaunal organisms must construct burrows with distinct wall linings. This is generally accomplished by gleaning fine grained material from the substrate during the excavation of the burrow and incorporating it along the burrow margin. Thin epsilon beds generally display higher clay contents and the sand contact with the overlying silty unit is often gradational. The silt partings are characterized by profuse numbers of clay-lined *Skolithos* and multi-lined *Cylindrichnus* burrows and rare funnel-shaped *Monocraterion* burrows which persist throughout the bed. Thicker units, on the other hand, are generally cleaner, the upper contact with the overlying silty unit is often sharp, and they are characterized by much lower densities of *Skolithos* and *Cylindrichnus* burrows (which are generally restricted to the upper portion of the bed) and rare to common escape structures. This dichotomy in the ichnofossil assemblages may reflect fundamental differences in the magnitude of the processes responsible for the deposition of the epsilons.

Although each sand/mudstone couplet superficially resembles a single genetic event, the distribution of the ichnofossils indicates that in some instances this is not the case. A number of units have been recognized that indicate that perhaps some amalgamation of the sandy units has occurred (Figure 26). In such beds, distinct horizons, characterized by a concentration of ichnofossils, indicate that a pause in sedimentation must have taken place since all infaunal organisms must maintain contact with the sediment-water interface. Additionally, the presence of *Cylindrichnus*, with its multilayered wall lining (indicative of relatively slow depositional rates), is also suggestive of a depositional break. In some cases the only other clue to the recognition of this horizon is a subtle change in colour.

Trace Fossils of the Argillaceous unit

The ichnofossil suite in the upper McMurray (Figure 27) is essentially similar to the one described for the middle McMurray. Amalgamated sand beds (similar to the amalgamated epsilon beds) have been recognized mainly on the basis of ichnological criteria. Upsection, the beds are characterized more by a bioturbate texture in which individual burrow forms are indistinct, and primary sedimentary structures are indistinct (Figure 27).

Further upsection is a distinct sand horizon (approximately 120 cm thick) characterized by parallel laminations, wave ripples, contorted bedding and ball and pillow structures. This horizon contains a different ichnofossil suite consisting of *Dolopichnus* (Figure 28), *Bergaueria*, and vertical escape structures (a single specimen of a possible *Rosselia* burrow has also been found). *Dolopichnus* and *Bergaueria* have been interpreted as dwelling burrows of sea anemones (see Hantzschel, 1975 and Alpert and Moore, 1975 for details). Finally at the top of the upper McMurray are profuse numbers of the wall-like feeding burrow *Teichichnus*, which is generally considered to be a marine form indicative of slow sedimentation rate.

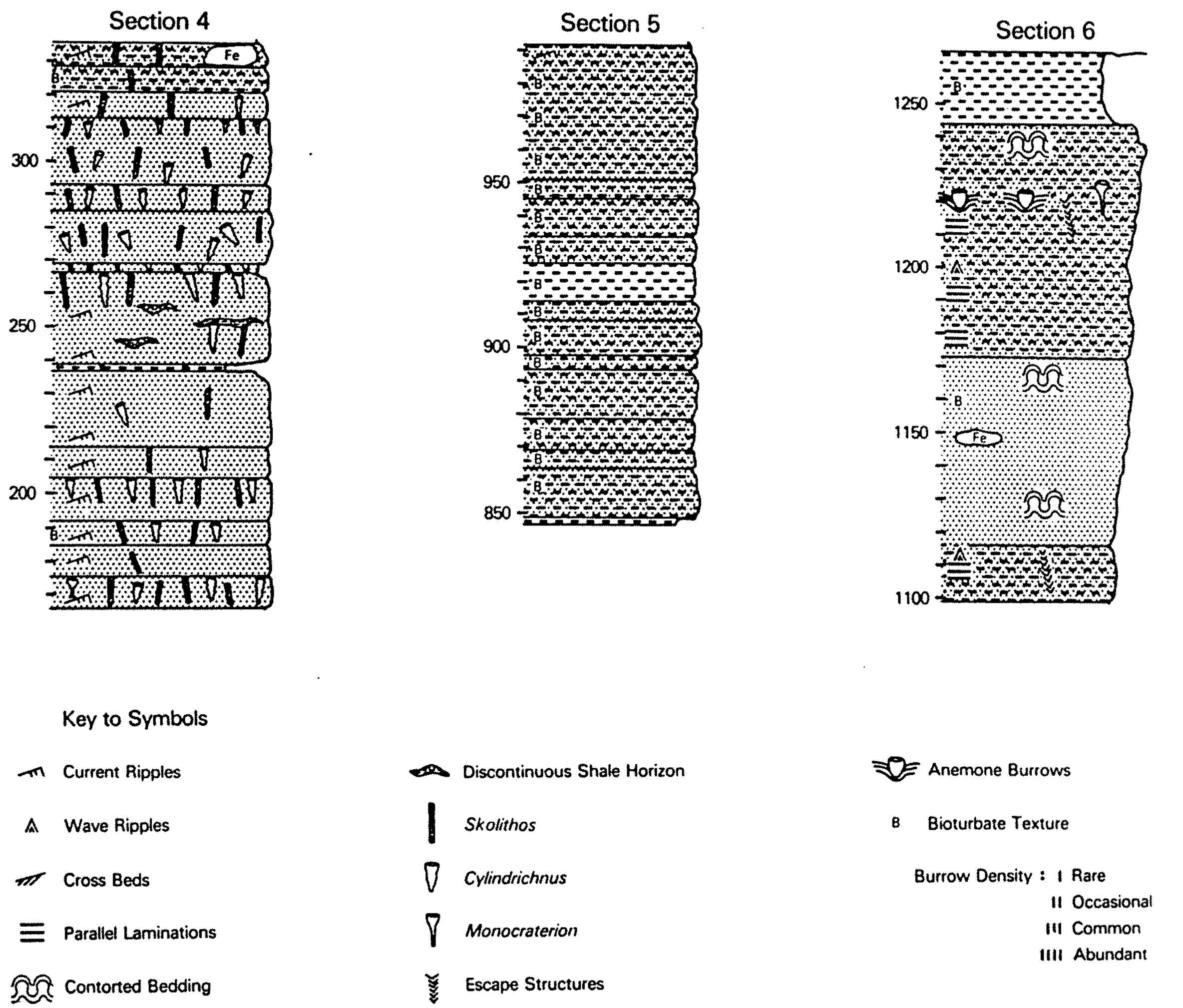


Figure 27. Diagram illustrating the distribution and density of prominent ichnofossils from the upper McMurray in Outcrop 3 (from Mossop *et al.*, 1982).

Points to Remember:

1. Devonian limestone exposed at base of section.
2. Channel succession in middle McMurray Formation.
   - well exposed trace fossils in epsilon (inclined heterolithic) strata
3. Well developed argillaceous unit (upper McMurray Formation).
   - includes 3 coarsening upward successions
   - moderate to extreme bioturbation, including anemone burrows
4. McMurray Formation/Wabiskaw Member contact well exposed.

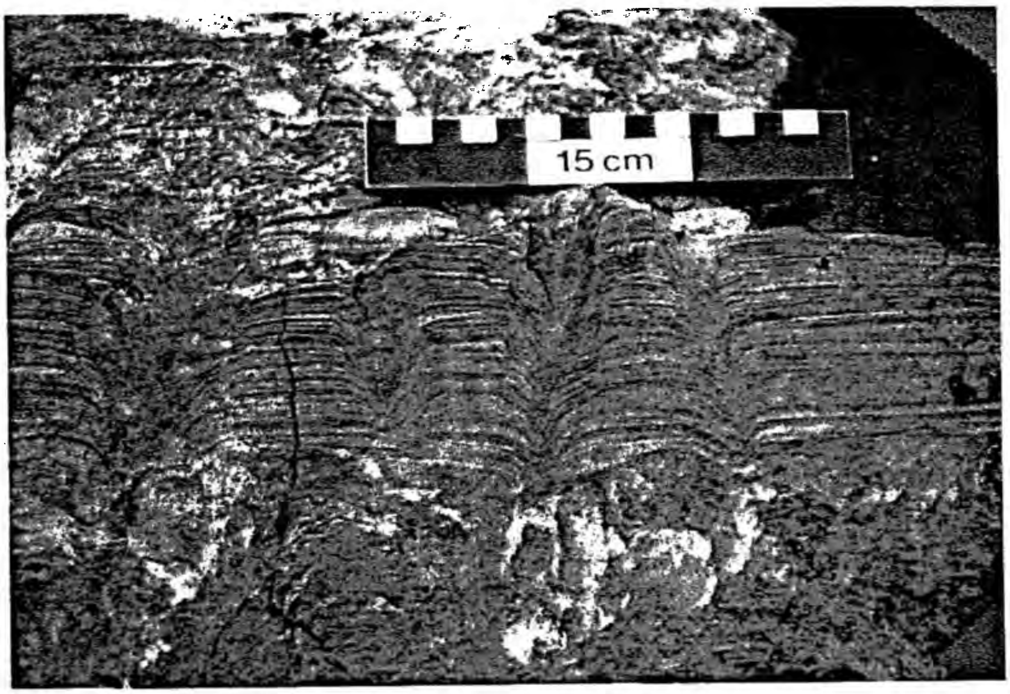


Figure 28. Anemone dwelling burrows, *Dolopichnus* (below 15 on the scale) and *Bergaueria* in the upper McMurray Formation, Outcrop 3, Steepbank River.