



Field Guide: Regional Sedimentology and Processes of Deposition of the Athabasca Oil Sands, Northeast Alberta



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F.J. Hein and D.K. Cotterill¹

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Author addresses

Darrell K. Cotterill
Consultant, Parallax Resources Ltd.
32-54030 Range Road 274
Spruce Grove, Alberta
T7X 3S9, Canada;
E-mail: parallax@primus.ca

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Alberta Energy and Utilities Board
Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, Alberta
T6B 2X3
Canada
Tel: (780) 422-3767 (Information Sales)
Fax: (780) 422-1918
E-mail: EUB.AGS-Infosales@gov.ab.ca
Website: www.ags.gov.ab.ca

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1 Introduction

Oil sands (also called ‘tar sands’) are found in about 70 countries, from Venezuela and Trinidad/Tobago in the Caribbean to as far north as Russia. By far, the main deposits are hosted within Cretaceous rocks of Venezuela and Canada, and among these the largest is the Athabasca Oil Sands of northeast Alberta (Figure 1). Oil sands consist of bitumen (soluble organic matter, solid at room temperature) and host sediment, with associated minerals, and excluding any related natural gas. The crude bitumen within the sands is a naturally occurring viscous mixture of hydrocarbons (generally heavier than pentane), often with sulphur compounds, that will not flow to a wellbore in its natural state. Upon heating, the bitumen will flow, and on a hot summer’s day bitumen oozes from the outcrops along the river valleys in northeast Alberta.

Since the 1990s, bitumen has evolved as a major source of energy in Canada (Lee, 2006), largely a result of three major factors:

- 1) in situ technologies, such as Steam Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulation (CSS) have become used in commercial field-scale operations;
- 2) in Alberta, crude bitumen production has exceeded conventional crude oil production; and
- 3) bitumen from Canada is considered an integral part of the world’s oil reserves (Lee, in press; U.S.G.S., 2000).

In Canada, the oil sands occur in Cretaceous fluvial-estuarine deposits of northeastern Alberta, covering an area >140,000 km² (Figure 1B). Bitumen is also found in Devonian carbonates (most notably within the Grosmont Formation) but, this bitumen has not been commercially produced (Harrison, 1987; Theriault, 1988; Dembicki and Machel, 1996; Rice et al., 2003; Buschkuehle, 2003; Buschkuehle and Grobe, 2004).

In 2003, Alberta’s reserves estimates of remaining established reserves was 174.5 billion barrels (Gb)¹, comparable with the oil reserves of Saudi Arabia. In 2001, Alberta’s production of raw bitumen and synthetic crude oil (SCO) exceeded conventional crude oil, accounting for 53% of Alberta’s oil production. This trend is expected to increase to about 80% of Alberta’s oil production by 2013¹ (Figure 2).

Development of the Canadian oil sands industry has a history of more than 90 years. In 1913, Sidney Ells organized the first field parties to work on the oil sands, hauling over 9 tons of oil sands by scows up the Athabasca River valley (see cover; Appendix 1). Today, near Fort McMurray, oil sands are recovered in open-pit mines by truck-and-shovel operations, in which the world’s largest Caterpillar 797 and 797B trucks have payloads of 380 tons. Oil sand is transported to processing plants, where hot or warm water separates the bitumen from the sand, followed by dilution with lighter hydrocarbons and upgrading to synthetic crude oil (SCO) — a mixture of pentanes and heavier hydrocarbons. About 20% of the oil sands reserves in Alberta are recoverable by surface mining; in situ technologies need to be used for the remaining 80% of the oil sands that are buried at depth (> 75 m).

¹ Alberta Energy and Utilities Board, Alberta’s Reserves 2003 and Supply/Demand Outlook 2004-2013, Statistical Series (ST) 2004-98.

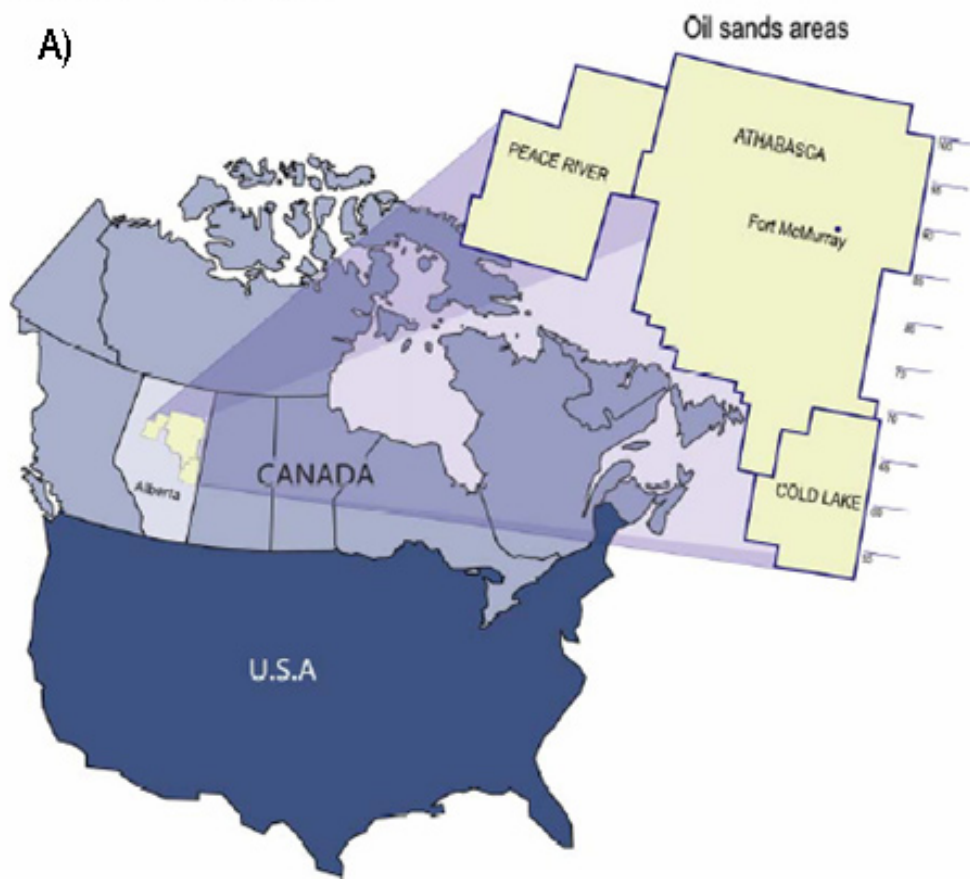


Figure 1. Location of the Athabasca, Cold Lake and Peace River oil sands in Alberta with A) regulatory boundaries and B) surficial expression of the deposit boundaries.

Alberta's Total Oil Supply

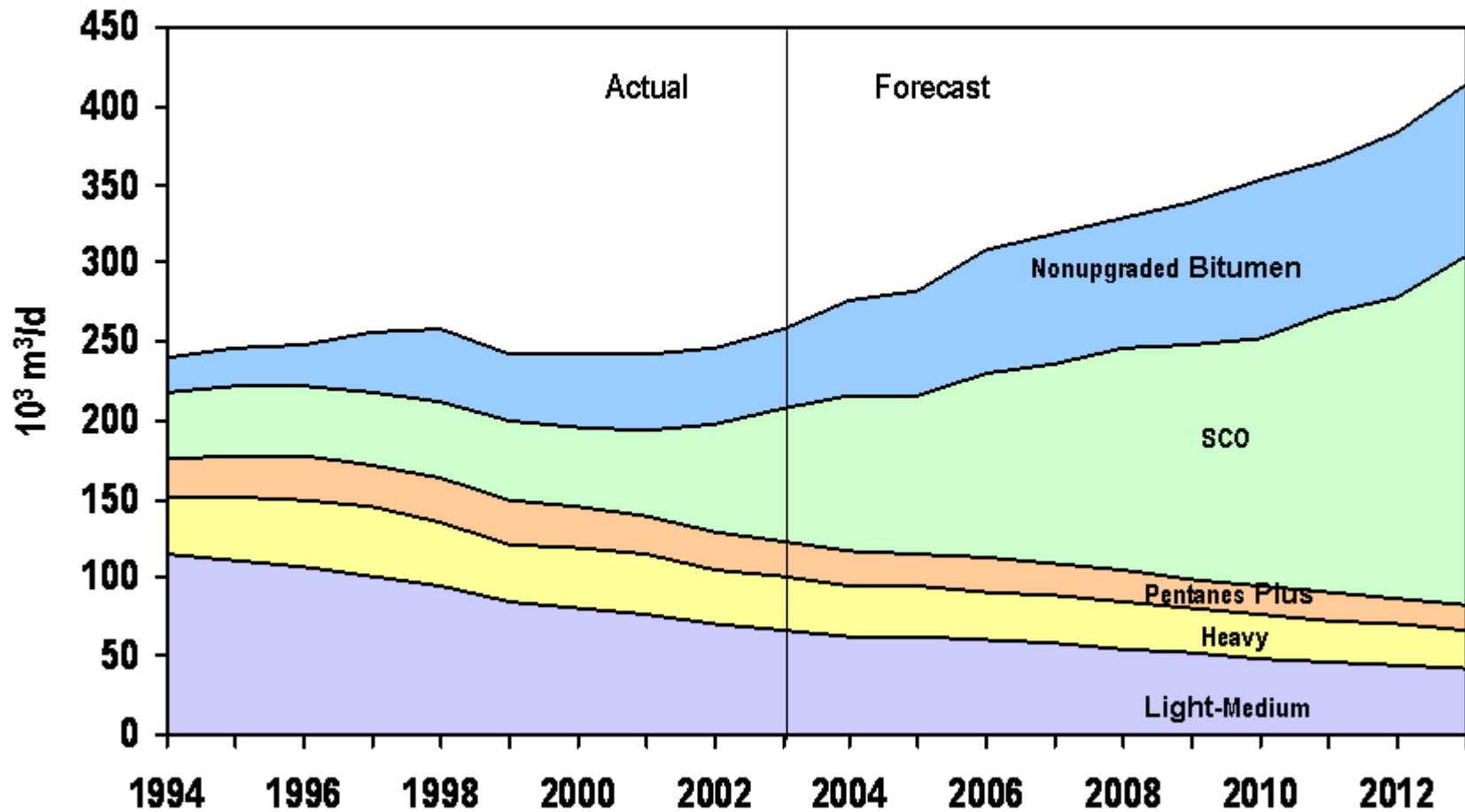


Figure 2. Alberta's total oil supply, projected and forecast from 1994 to 2013, showing relative amounts derived from conventional oil (light-medium), heavy oil (heavy), extra-heavy oil (Pentanes Plus), synthetic crude oil (SCO) and nonupgraded bitumen (from Alberta Energy and Utilities Board, 2004).

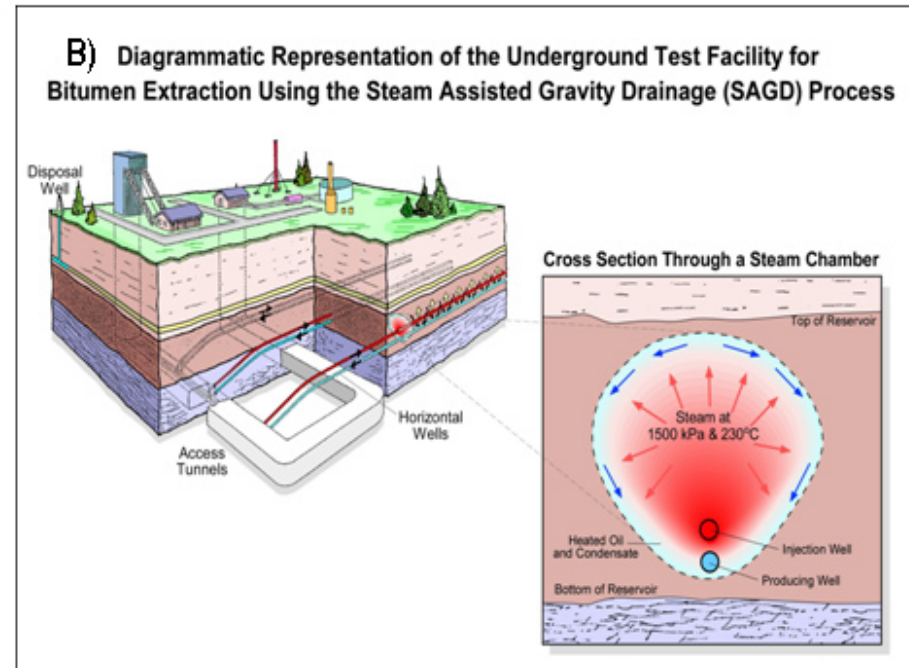
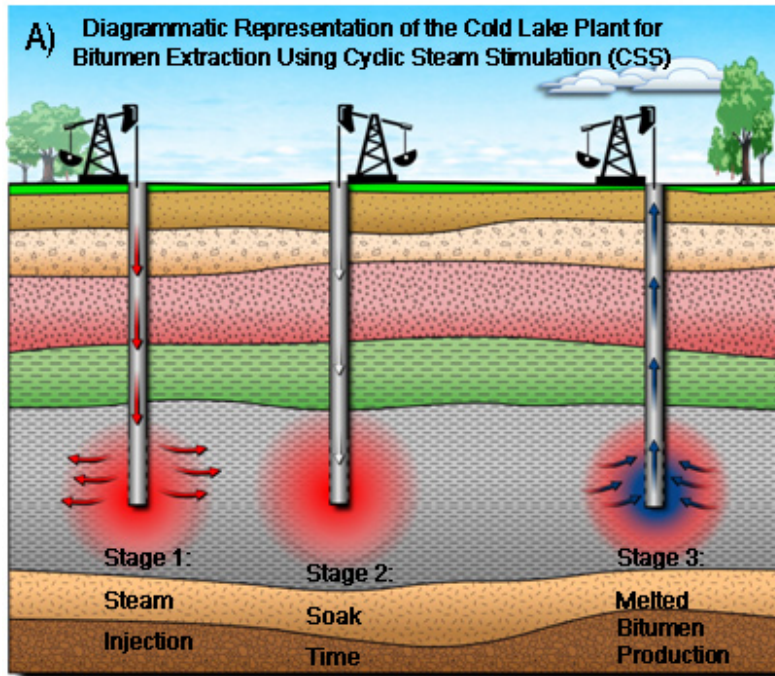


Figure 3. Diagrammatic representation of bitumen extraction using: A) Cyclic Steam Stimulation (CSS) at the Cold Lake plant; B) Steam Assisted Gravity Drainage (SAGD) at the Dover Underground Test Facility (UTF).

The oil sands of Alberta are unconsolidated, held together by the pore-filling bitumen. The bitumen is a natural, tar-like mixture of hydrocarbons, that when heated has a consistency of molasses. In its natural state, bitumen (density range of 8° to 12° API; at room temperature viscosity > 50 000 centipoises) will not flow to a wellbore. In Alberta, other heavy oil in sand is also considered 'oil sands' if within the oil-sand application areas (Figure 1A). However, because the pore-fluid is heavy oil and will flow to a well, these deposits are referred to as 'primary in situ crude bitumen.' The major challenge of recovering bitumen from depth is to overcome its high viscosity to allow it to flow to the wellbore. To do this, thermal (or other non-primary) in situ methods are used, most commonly Cyclic Steam Stimulation (CSS) and Steam Assisted Gravity Drainage (SAGD) (Figure 3).

Canada's largest in situ bitumen recovery project uses CSS at Cold Lake. Steam injected down the wellbore into the reservoir heats the bitumen, followed by a soak time, and then the same wellbore is used to pump up fluids (Figure 3A). At Cold Lake, about 3200 wells are currently operating from multiple pads, with two above ground pipelines, one to deliver steam and the other to transport fluids back to the processing plant. At Athabasca, the SAGD technology is used. Horizontal well pairs (700 m long with 5 m vertical separation) are drilled from surface pads to intersect bitumen pay (Figure 3B). Steam from the upper injector well expands, reducing the viscosity of the bitumen, allowing the bitumen to flow. A shell forms at the cold interface with the unheated reservoir, along which heated bitumen/condensate drain by gravity to the lower producing well (Figure 3B). Locally, electrical submersible pumps (ESPs) may assist in lift.

Continuing challenges for economic in situ bitumen recovery involve water and gas requirements for steam generation, reclamation and emission controls of greenhouse gases. Generally, it takes 28 m³ (1000 ft³) of natural gas and from 2.5 to 4 barrels of water to produce one barrel of bitumen. Reclamation of mining sites is done to a standard of at least the equivalent of their previous biological productivity. Beginning in the mid 1970s, the North American energy crises have made the Canadian oil sands a more strategic resource for North American energy needs, accelerating industry's interest and efforts to tap these vast bitumen reserves (Houlihan and Evans, 1988; Sadler and Houlihan, 1998; Polikar et al., 1998; Newell, 1999; Meyer and Attanasi, 2003; Dunbar and Chan, 2004; Dunbar et al., 2004; Oommachan, 2004).

2 General Geological Setting

Most of the bitumen resources in the Athabasca Oil Sands area are within fluvial-estuarine channel/point-bar deposits of the Lower Cretaceous McMurray Formation. Locally, especially in the more northern outcrops along the Athabasca River, barrier-island, back-bay lagoon and coastal plain sediments occur. The McMurray Formation is the lowest part of the Mannville Group in Alberta, where it unconformably overlies Devonian carbonates. In the eastern outcrop part of the Athabasca deposit, the underlying carbonates are the Christina and Moberly limestones of the Beaverhill Lake Group. The Wabiskaw Member of the Clearwater Formation, in turn, unconformably overlies the McMurray Formation (Figure 4).

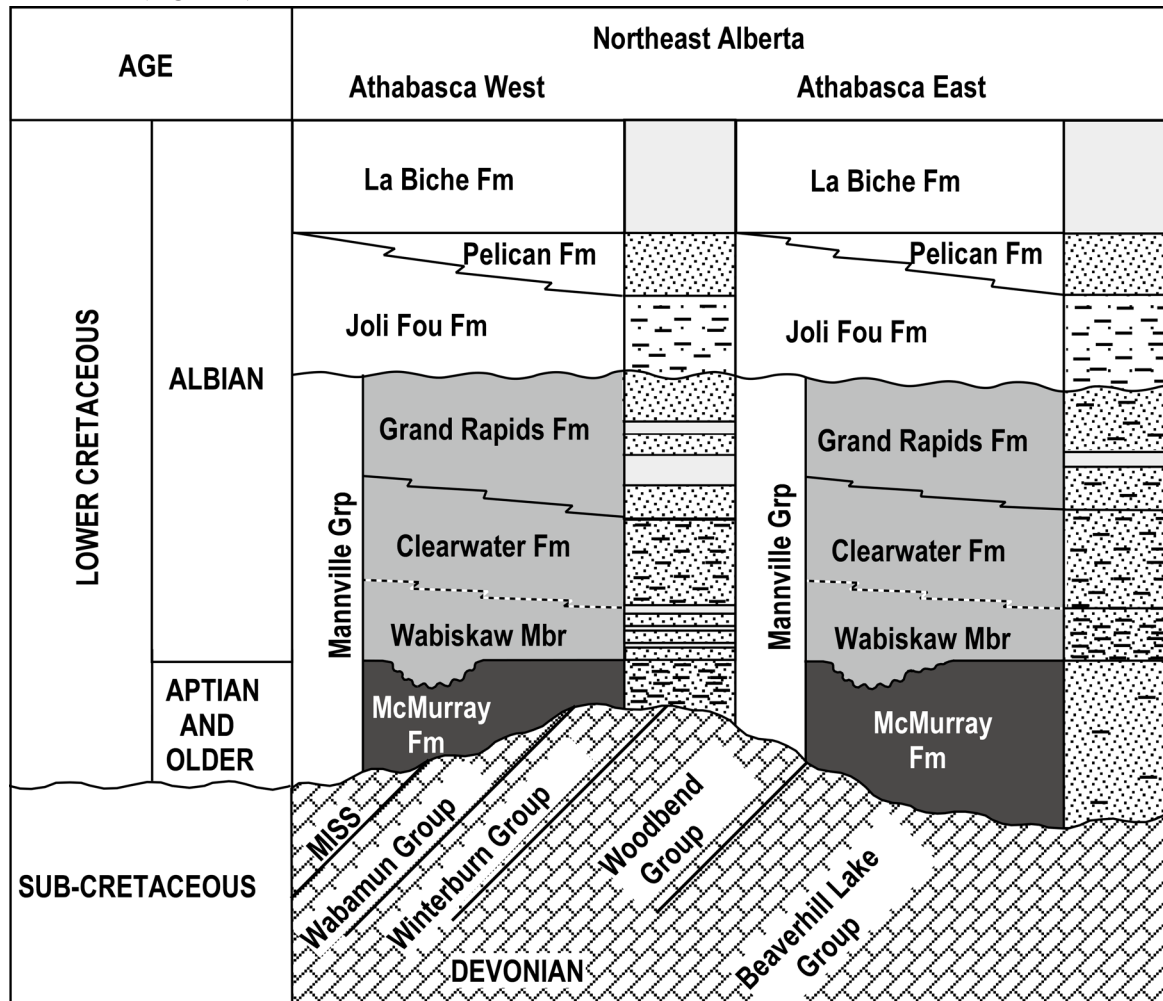


Figure 4. Stratigraphic nomenclature for the Lower Cretaceous Athabasca deposit.

The McMurray Formation was deposited on an exposed karstic landscape of ridges and valleys with local paleosols, and varies in thickness from being absent on some Devonian carbonate paleohighs to over 130 m thick in the Bitumont Basin, at the northern end of the outcrop belt (Figure 5). Bitumen reservoirs occur in stratigraphic and/or structural traps, in areas susceptible to salt-dissolution tectonics associated with removal of salts from the underlying Prairie Evaporite successions. The north trend in the McMurray thickness generally correlates with the salt dissolution front (Figure 5, shaded part).

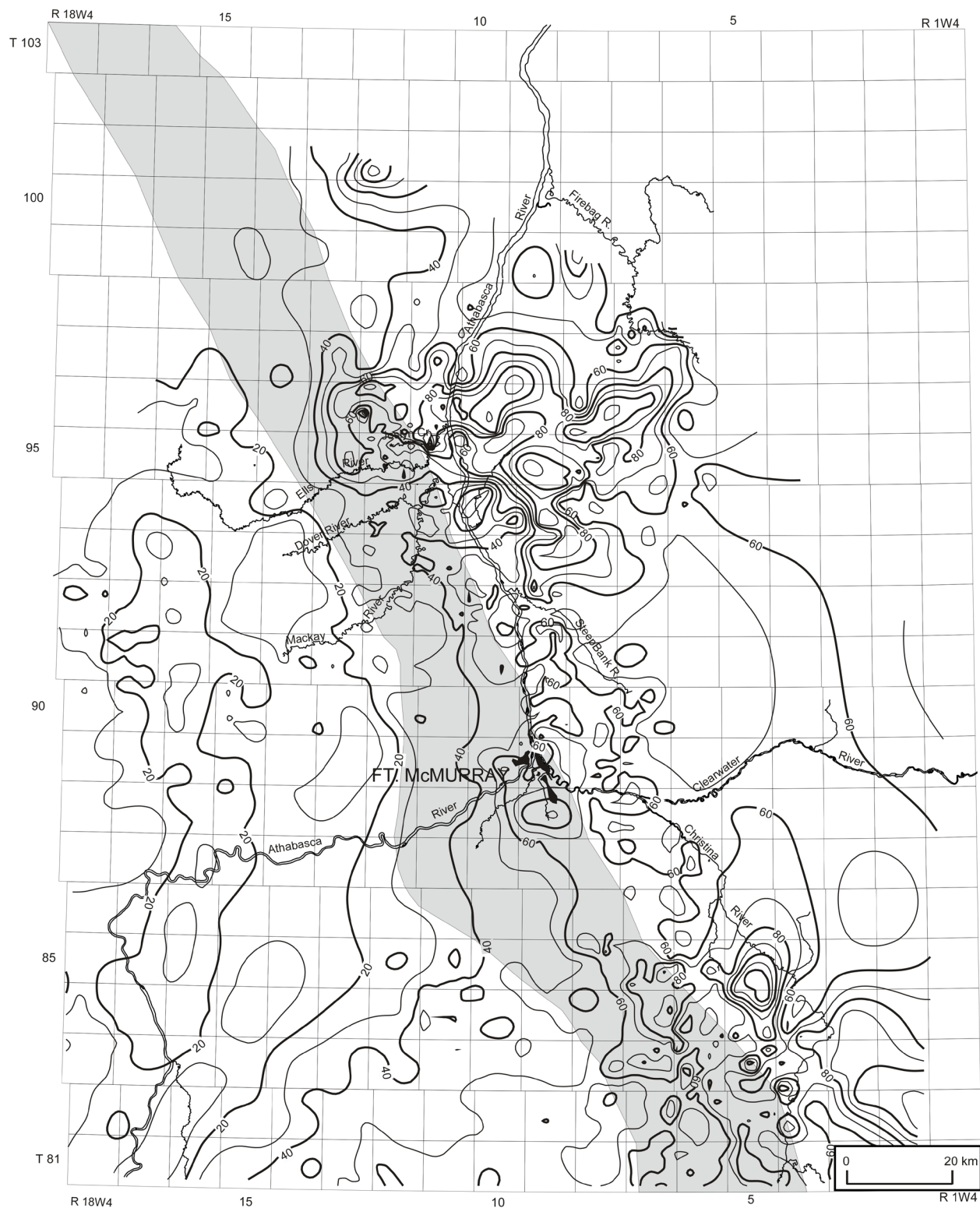


Figure 5. Isopach map of the McMurray Formation with the Prairie Evaporite Salt Scarp (shaded), from Township 81 to 103 and Range 1 West of the 4th Meridian to Range 18 West of the 4th Meridian, contour interval is 10 metres. Horizontal scale bar is 20 kilometres (modified from Hein et al., 2000).

North of Fort MacKay, the thickening trend of the Wabiskaw-McMurray succession has an east orientation, corresponding to an axial trend of the Bitumont Basin (Figure 5). The Bitumont Basin is also largely a salt-withdrawal feature formed prior to and during deposition of the Wabiskaw-McMurray succession. In the Wabiskaw-McMurray, bitumen reservoirs occur mainly within fluvial or fluvial-estuarine channel and bar complexes. Local water sands occur along the basal sub-Cretaceous unconformity, or higher upsection, offlapping Devonian paleohighs or as perched reservoirs within the Wabiskaw-McMurray. In the upper parts of the Wabiskaw-McMurray succession, gas and water reservoirs may be associated with the bitumen (Alberta Energy and Utilities Board, 1998, 2003).

A bedrock map of the Fort McMurray area shows that the oil sands outcrops are confined to the Athabasca-Clearwater drainage system (Figures 6 and 7). This outcrop distribution is related to the Pleistocene geomorphological history of northeastern Alberta and northwestern Saskatchewan (Teller and Clayton, 1983; Teller and Thorleifson, 1983; Teller, 1987; Smith and Fisher, 1993; Fisher and Smith, 1994; Fisher et al., 1995; Leverington and Teller, 2003).

Glacial Lake Agassiz formed by ice damming at the end of the last ice age, as meltwaters from the Laurentide ice sheet formed a large interior glacial sea. At its maximum extent (~ 9.9 ka BP) the lake was about 440 000 km², covering most of Manitoba and Saskatchewan, extending eastwards into Ontario, with the southern limit in Minnesota and North Dakota. Glacial Lake Agassiz drained to the south through the present Minnesota River valley to the Mississippi, eventually to the Gulf of Mexico, to the east to the Great Lakes, and to the west-northwest through northwestern Saskatchewan and northeastern Alberta (Figure 8). By 10.8 ka BP, the southern outlet of glacial Lake Agassiz was disrupted and by 9.4 ka B.P. this spillway was abandoned (Fisher, 1993). At ~ 9.9 ka BP, glacial Lake Agassiz broke through its margins to the northwest, spilling into the headwaters of the Clearwater River near present Methys Portage. Catastrophic floods originated at the head of the Clearwater River, flowed westward downriver to the confluence with the Athabasca River. Paleoflood flows then went to the north down the Athabasca River. Along the way, the paleoflood meltwater greatly enlarged the river valleys, creating major spillways and depositing flood boulder-gravels at Fort McMurray (Fisher, 1993). About 40 km to the north, near Fort MacKay, an exceptionally large braid-delta and aeolian sand complex formed, called the 'Athabasca Delta,' as floodwaters debouched into glacial Lake McConnell. Paleoflood flows eventually drained northward to the Arctic Ocean via glacial Lake McConnell and the Mackenzie River system (Rhine, 1984; Rhine and Smith, 1988; Smith and Fisher, 1993; Lemmen et al., 1994). A number of other smaller meltwater channels formed as precursors or tributaries to the main spillways, although these are mainly buried today (Andriashek, 2000). These buried meltwater channels incise up to 300 m down into bedrock in the subsurface, emplacing Quaternary sands in direct contact with Cretaceous Clearwater and underlying McMurray oil sand reservoirs. One of these, the Birch Channel, lies directly south of the Underground Test Facility (UTF) site, and the other, Willow Channel, lies between the Dover and Ells River, north of the UTF site.

Many of the buried Quaternary sand channel-fills are modern aquifers to the potable groundwater in the region. Additionally, Quaternary sand and gravel serve as local sources of aggregate in the Fort McMurray area. Although the Quaternary section is not the focus of this field guide, there are many outcrops that show a variety of glacial features at the top of the bedrock sections, including glacially thrust oil sand bedrock (Amphitheatre Outcrop near Fort MacKay), aeolian loess (Saline Creek and Hangingstone outcrops), glaciofluvial outwash sands and gravels, some with clasts of resedimented oil sands (Horse River and Dover River), locally convoluted ice-load features (Horse River), and glaciolacustrine units (Ells River). Remnants of beach ridges are common around the Thickwood Hills in Fort McMurray, and local moraines are preserved north of Fort McMurray near Clarke Creek (Twp 90-91, Rge. 8-9 W 4th Meridian) and northeast of the Steepbank River, Twp 91-95, Rge 7-9 W 4th Meridian) (Carrigy and Kramers, 1973).

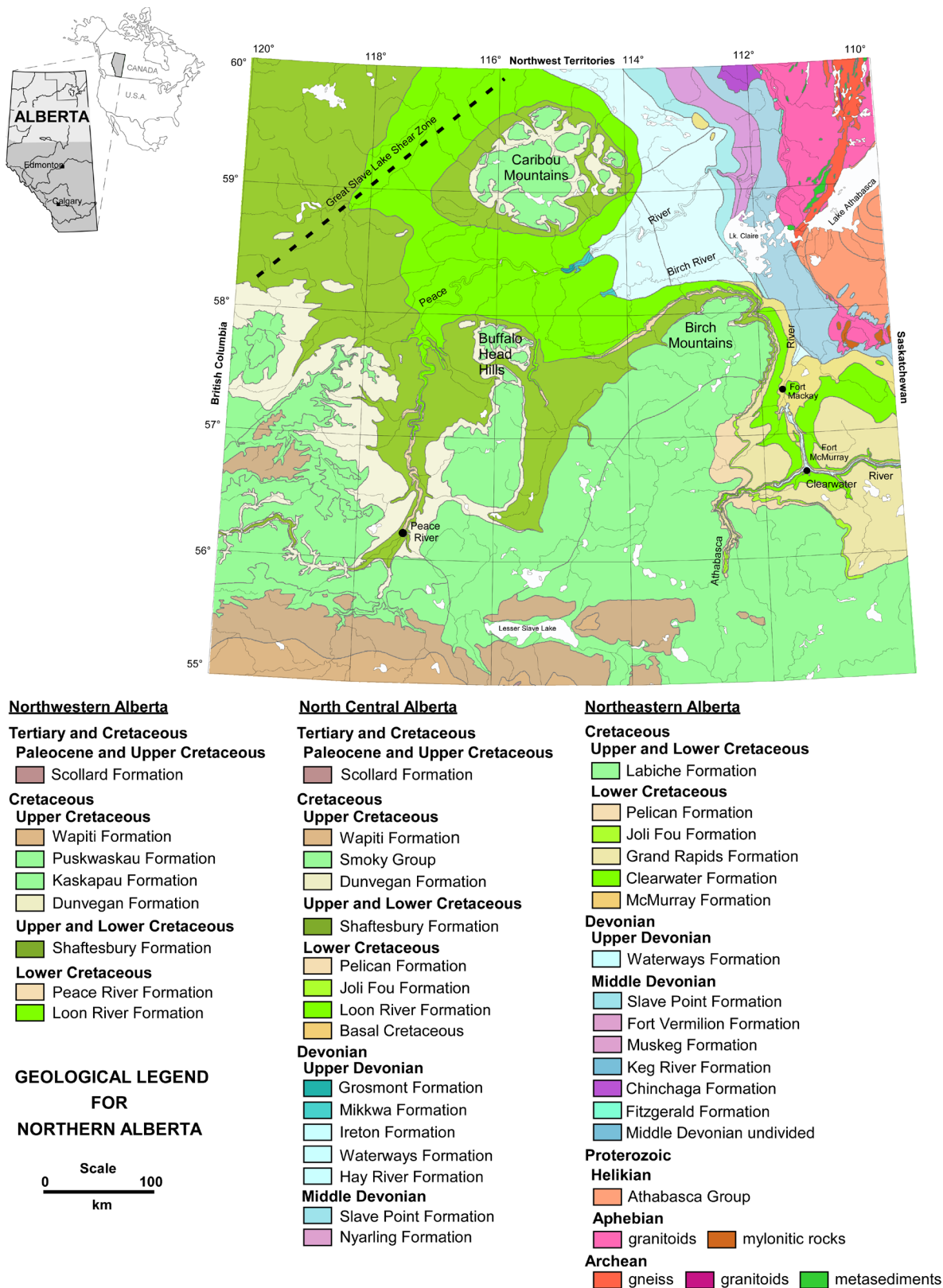


Figure 6. Bedrock map of northeastern Alberta (from Rice and Lonnee, 2004).

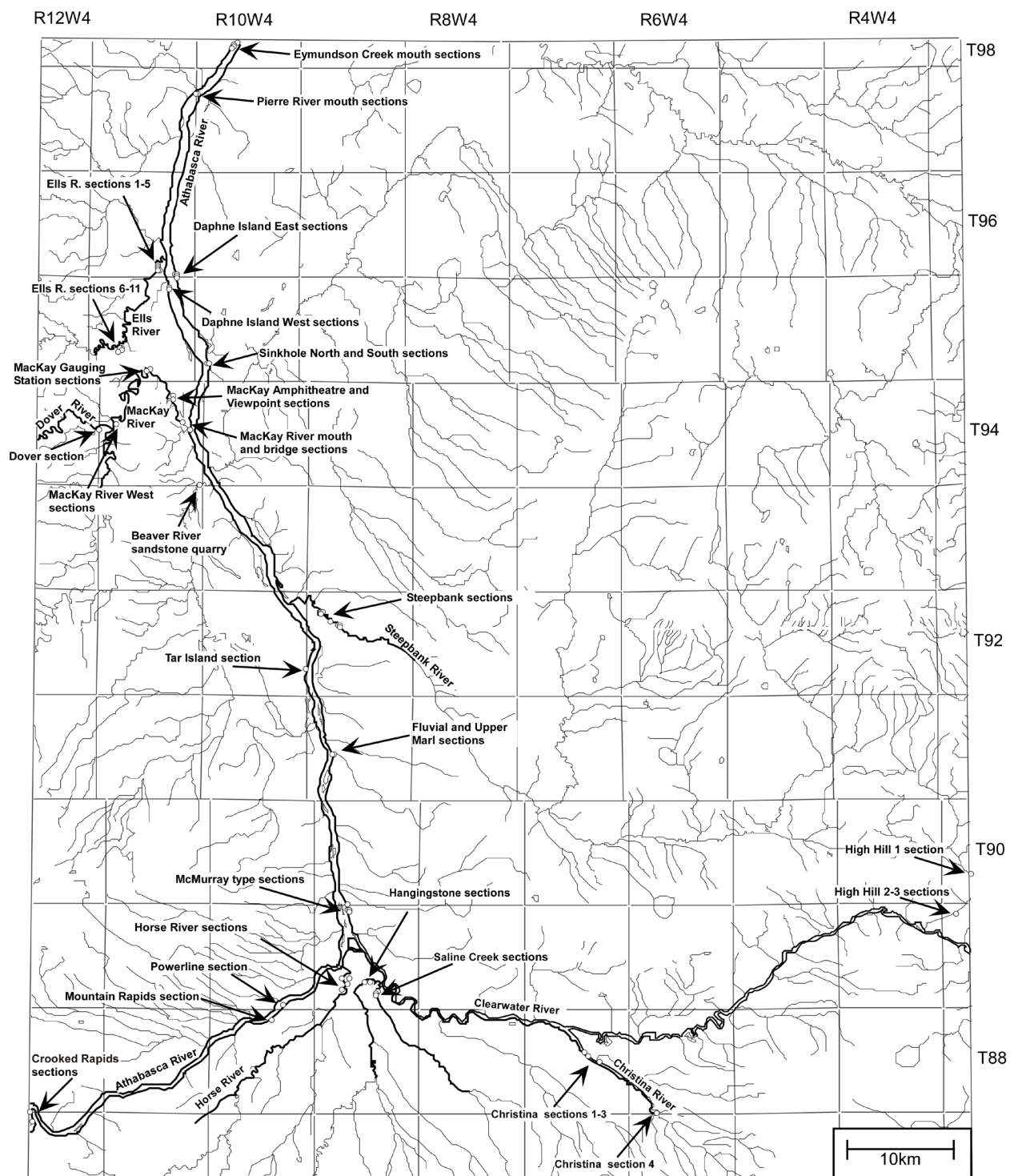


Figure 7. Map showing distribution of major outcrop sections of the McMurray Formation along the drainage system of the Athabasca and Clearwater rivers, from Township 87 to 98 and Range 3 West of the 4th Meridian to Range 12 West of the 4th Meridian. Horizontal scale bar is 10 kilometres (from Hein et al., 2000).

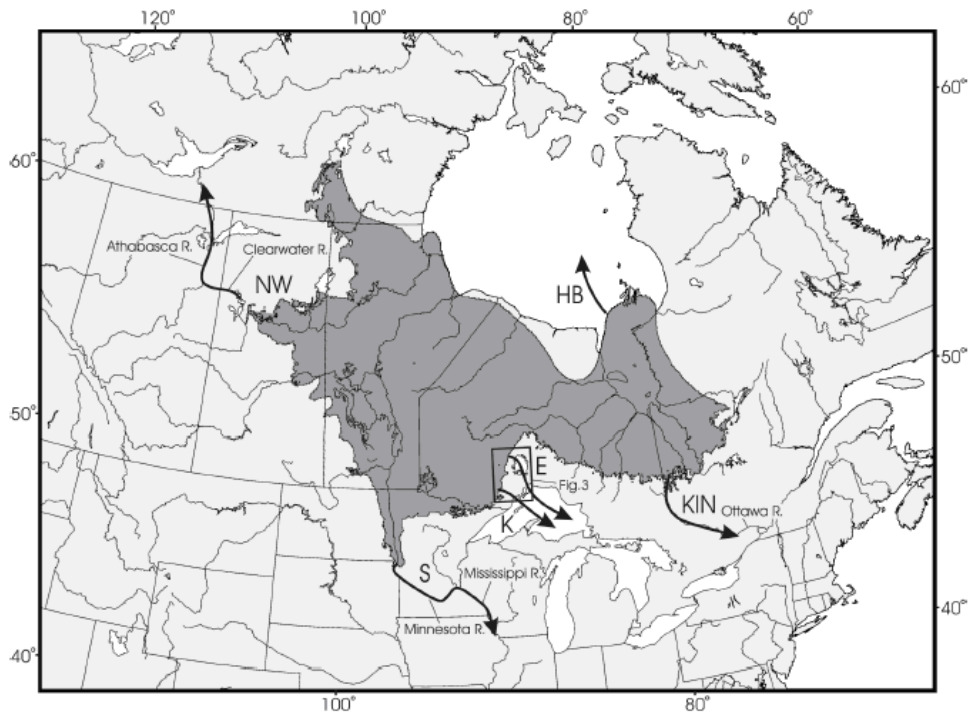


Figure 8. Map showing the 1.5 million km² total area that glacial Lake Agassiz occupied over its 5000-year history (shaded). The lake gradually shifted from south to north, following the retreating southern margin of the Laurentian Ice Sheet, with the earliest lake stages confined to the southernmost portion of the indicated area and the final stages occupying the lowlands south of modern Hudson Bay (HB). Primary routes of general overflow are labelled as follows: E, region of eastern outlet systems to the Superior basin; HB: general outburst direction of the final release of Lake Agassiz waters into the Tyrrell Sea (modern Hudson Bay); K: Kaministiquia route to the Superior basin; KIN: Angliers and Kinojevis outlets to the St. Lawrence River valley via the Ottawa River; NW: northwestern outlet to the Arctic Ocean via the Clearwater, Athabasca and Mackenzie river valleys; S: Southern outlet to the Gulf of Mexico via the Minnesota and Mississippi river valleys (from Leverington and Teller, 2003).

3 Previous Work

An historical overview of the study and development of the oil sands in northeastern Alberta is in Appendix 1. Detailed sedimentological and stratigraphic analysis of more than 80 outcrops, ~300 cores and over 7000 well logs by the Alberta Energy and Utilities Board/Alberta Geological Survey over the previous 7 years allow for a better understanding of the Athabasca Oil Sands deposit. Much of this work has relied on facies mapping on a regional scale, facilitated through a multidisciplinary approach involving palynological and facies analysis of outcrops and cores, well log analysis, seismic modeling, as well as comparisons with modern analogues (Hein et al., 2000, 2001; Hein and Dolby, 2001; Flach and Hein, 2001; Langenberg et al., 2002, 2003; Hein and Langenberg, 2003).

A number of field guides have been written about the geology of the Fort McMurray area, emphasizing the oil sands, with the most recent by Hein et al. (2001), Ranger and Gingras (2002) and Paulen et al. (2004). Selected applications of outcrop analogues to detailed subsurface reservoir characterization have been done at various locations, including the Dover River Project UTF site by Strobl et al. (1997a, b); the MacKay–Ells River area by Flach and Hein (2001); and in the Steepbank area by Flach (1977, 1984), Hein and Langenberg (2003) and Langenberg et al. (2002, 2003). The present field guide represents an updated and condensed version of the Hein et al. (2001) comprehensive field guide that incorporates a revised stratigraphy of the McMurray Formation and a unified lithofacies scheme for the oil sands.

4 Stratigraphy

The McMurray type section, as originally defined by McLearn (1917), is about 5 km north of Fort McMurray along the east bank of the Athabasca River (01-05-090-09W4). In 1959, Carrigy further subdivided the McMurray into three units – Lower, Middle and Upper (Figure 9). Typically in the past, the McMurray succession has been interpreted as fluvial for the lower McMurray, estuarine channel and point-bar for the middle McMurray, and coastal plain for the upper McMurray. Although this tripartite terminology has been applied throughout the surface mineable area of the Athabasca deposit, the continued use of this stratigraphic subdivision remains controversial (cf. Hein et al., 2000, 2001; Hein and Langenberg, 2003; Ranger and Gingras, 2003).

The main problem with the tripartite nomenclature is that one person's 'lower, middle, upper' does not necessarily represent another person's 'lower, middle, upper.' On a regional scale, most workers can distinguish the top of the lower fluvial McMurray from the overlying fluvial-estuarine McMurray because of changes in lithology and facies. By contrast, there is no uniform distinction in mineralogy, lithology, facies or palynology between the middle and upper McMurray. There has been no regional work that demonstrates that what is mapped as lower-middle-upper McMurray in one area (i.e., Athabasca North) is actually either lithostratigraphically or chronostratigraphically equivalent to what has been mapped as lower-middle-upper McMurray in another area (i.e., Athabasca South). In many locations of both the surface mineable and subsurface areas, lower McMurray fluvial deposits have been reworked into overlying upper McMurray estuarine channel successions or completely removed, such that an unconformity is interpreted to be at the top of the lower McMurray (Hein et al., 2000; Appendix 2).

Within the Mannville Group, it is common for channels of various ages and from different stratigraphic levels to cut down and remove underlying broad scale sedimentary packages. Within the Wabiskaw-McMurray succession, channels cut down from different levels (compare Figures 9 and 10). This makes regional correlation impossible without detailed palynological or other chronostratigraphic work. As succinctly stated by Keith et al. (1988, p. 312): "Subdivision into the middle and upper McMurray members is especially difficult where channel sands are absent (off-channel facies in both members) or where channel sands extend to the top of the McMurray Formation (upper member absent). Therefore ...only the lower portion of the McMurray Formation is differentiated." This inherent complexity of multiple incision and infill events, coupled with the dramatic north to south reduction in accommodation space for the Wabiskaw-McMurray succession (Figure 11), indicates that what is called 'middle' McMurray to the north may not, in fact, be correlatable with what is called 'middle' McMurray to the south. More likely, there is an upward clinoforming of stratigraphic units from north to south, making strict 'layer cake' correlation impossible. The schematic section in Figure 11 clearly shows interfingering of various fluvial, estuarine and fluvio-lacustrine sediments to the north, along the southern margin of the Bitumont Basin. Such interfingering suggests that what may be mapped as separate units to the south are actually parts of the same systems tracts and that it is impossible on any grounds to separate the middle and upper McMurray successions.

Although a type section is not designated for the Clearwater Formation, it is clear that where sandy, the lower Wabiskaw Member is glauconitic, salt-and-pepper, lithic sand that unconformably overlies the McMurray Formation (Badgley, 1952). In the area where the Wabiskaw Member was first named, Badgley also notes the occurrence of 'soft black' and 'greenish grey shales,' with interbedded green/grey sands and ironstone (siderite) concretions and cemented horizons, particularly toward the base of the member.

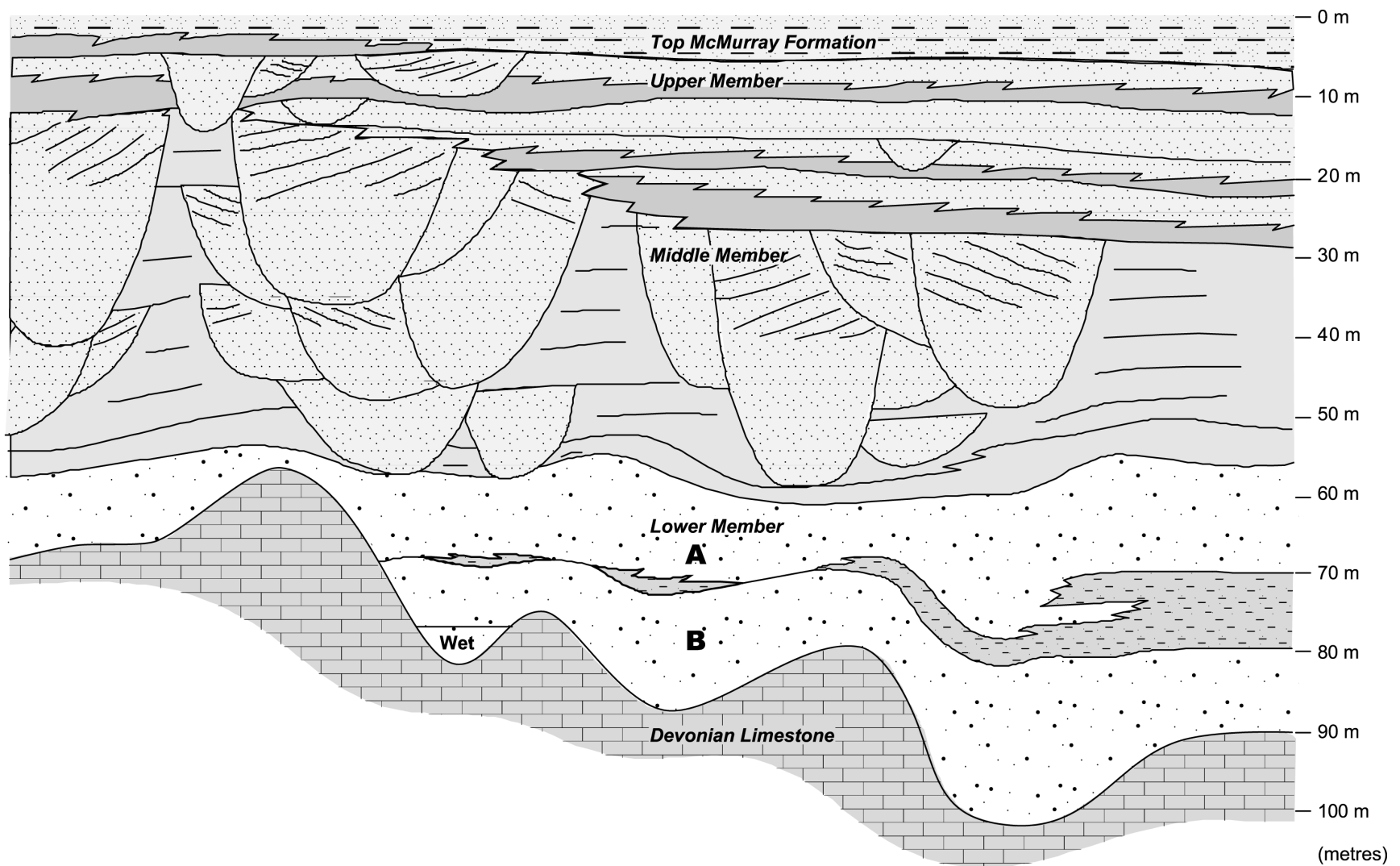


Figure 9. McMurray Formation schematic stratigraphy, Lease 24, in the Ells River—Joslyn Creek area, north of Fort MacKay (from Flach and Hein, 2001, published in Hein and Langenberg, 2003).

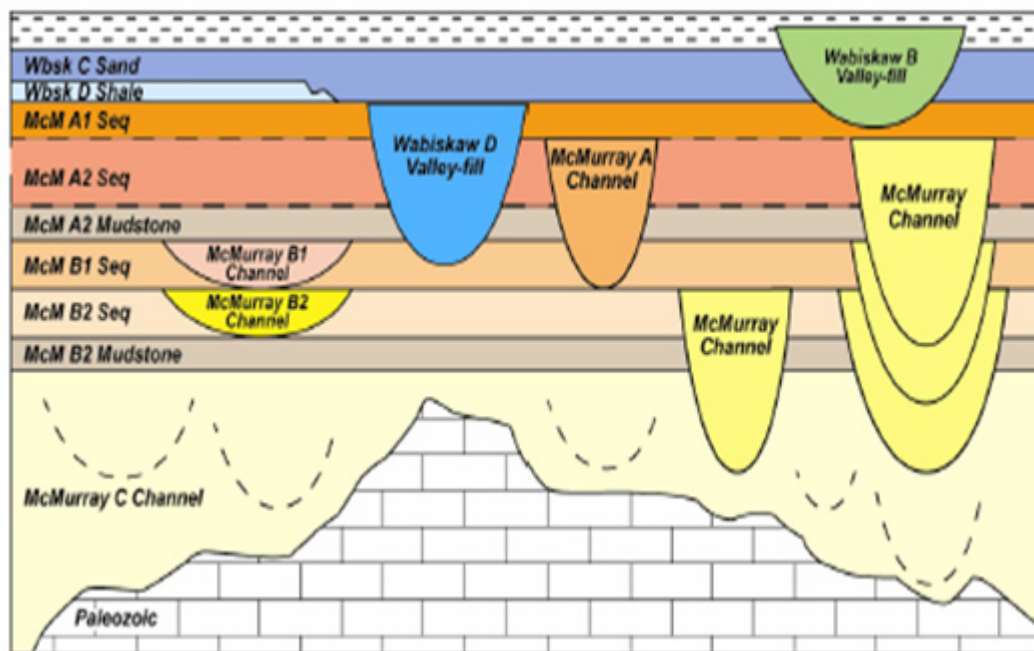


Figure 10. Stratigraphic model for the Athabasca Wabiskaw–McMurray deposit (from Alberta Energy and Utilities Board, 2003).

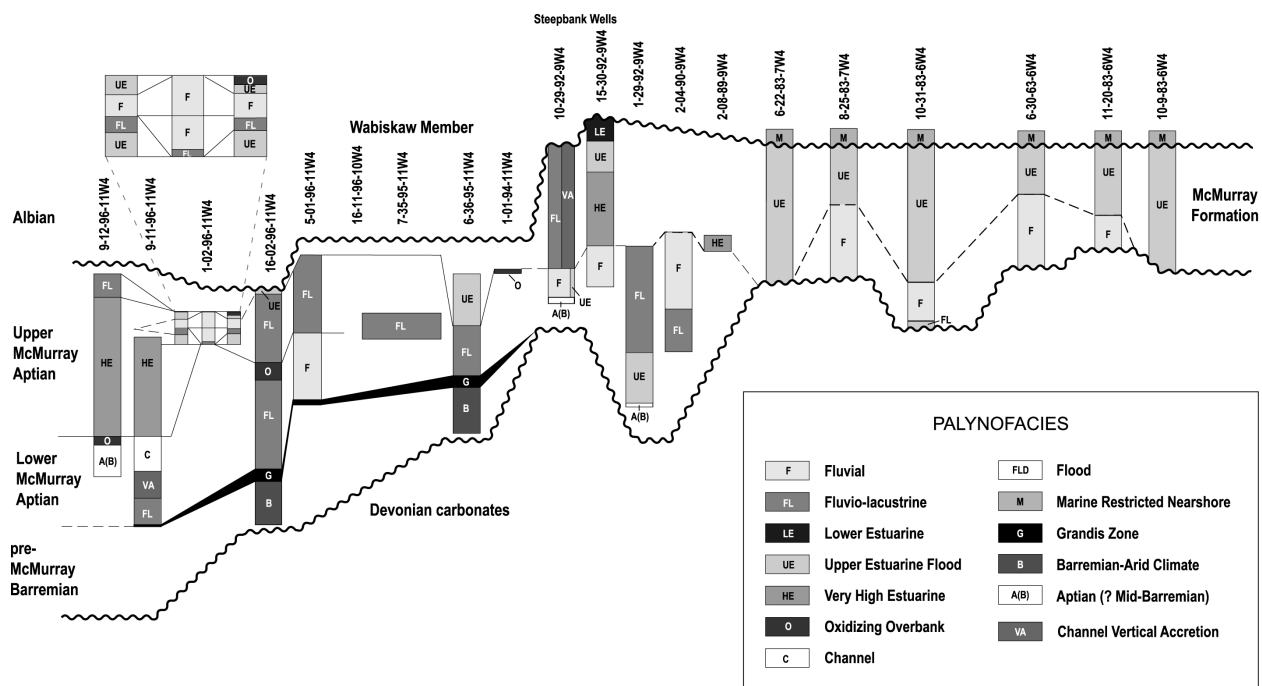


Figure 11. Schematic regional north-south section of the McMurray Formation showing rapid thinning along with a rapid reduction in accommodation space (from Hein et al., 2001).

In application of Badgley's lithological distinction between the McMurray and Wabiskaw, later workers, including Carrigy (1963) and Wightman et al. (1995), cite an occurrence of a 'steel-gray' or 'blue steel gray' shale as typical of the lowest Wabiskaw D shales. The Wabiskaw D is a true shale that exhibits prominent fissility, lacks a sand and silt component (more typical of McMurray mudstone), and generally lacks trace fossils, but where present are a different assemblage than the underlying McMurray (Wightman et al., 1995). Based on palynology, the Wabiskaw D shales show a true marine affinity, compared with McMurray mudstone that is wholly brackish and within a different time zone (Upper McMurray is Aptian, whereas Wabiskaw D is Early Albian, cf. Dolby in Hein et al., 2001; Hein and Dolby, 2001). In core, fracture patterns are distinctly different – McMurray mudstones have a hexagonal fracture pattern, compared with Wabiskaw D shale that has a thin, bedding parallel, marked platy fracture pattern. In addition to mudstone/shale differences between Wabiskaw and McMurray, the sands are also lithologically distinct, in cases where the basal Wabiskaw D is not reworked upper McMurray. The Upper McMurray is a tan, micaceous quartz sand, with interbedded, tan sandy-silty bioturbated mudstone, whereas sands within the Wabiskaw D mudstone (as burrow fills and thin interbeds) are litharenites.

It is clear some workers still using the tripartite terminology are placing the top of the McMurray at the base of the glauconitic Wabiskaw C sand, thereby mapping what others consider as Wabiskaw D to be 'upper' McMurray (M. Ranger, pers. comm., 2004). We do not agree with mapping the top of the McMurray at the base of the glauconitic sand, but place it lower at the contact between the McMurray and the Wabiskaw D shales. This point is not merely semantics, but goes to the heart of understanding the geology of the Wabiskaw-McMurray succession. The observed macroscopic features, lithological differences, along with distinctive wireline log signatures between the Wabiskaw D shale and underlying McMurray mudstones (cf. Alberta Energy and Utilities Board, 2003), all indicate these are different stratigraphic units and should not be mapped together. Thus the revised, albeit still informal, stratigraphy for the Wabiskaw-McMurray is Lower McMurray fluvial, Upper McMurray estuarine-coastal plain succession, Wabiskaw D fluvial estuarine incised valley fill, Wabiskaw D regional marine shale, and Wabiskaw C incised valley fills and regional marine sands (Hein et al., 2000, 2001; Alberta Energy and Utilities Board, 2003).

5 McMurray Formation

5.1 Depositional History and Reservoirs

The Athabasca Oil Sands deposit of northeast Alberta is notorious for its complex facies relationships, as well as a fragmentary preserved stratigraphic record. Determination of the relationship of different sedimentary packages to one another, near to far variations, and the identification of systems' tracts boundaries has been hampered in the past by the lack of a regional biostratigraphic framework linked to a regional lithostratigraphic framework.

The McMurray sediments were deposited within a karstic ridge and valley system developed on the regional sub-Cretaceous unconformity (Figures 4 and 12A). The Lower McMurray deposits represent a fluvial low-stand systems tract of braided bar and channel complexes, largely infilling lows on the unconformity (Figure 4, 12B and 13). Associated coals, lacustrine marls, rooted overbank fines and paleosols are preserved on top of carbonate paleohighs and within some of the karstic sinkholes along the sub-Cretaceous unconformity (Figure 12B). In outcrop and as mapped in the subsurface, there is evidence of a disconformity or unconformity separating the Lower and Upper McMurray (Figure 4; Surface E5, Figure 13). With transgression, some of the Lower Fluvial was eroded and reworked into fluvial-estuarine channel and point-bar complexes of the initial Upper McMurray succession (Figures 12C and 13). Through time, with continued overall transgression, paleotopographic features became blanketed, and by late Upper McMurray more nearshore coastal plain conditions prevailed (Figures 12D and 13). By time of deposition of the top of the Wabiskaw Member conditions were fully marine (Figure 13).

In terms of paleoenvironments, the interpretation of the Lower McMurray as fluvial remains. However, the proportion of the Upper McMurray represented by estuarine channel and point-bar units changes both in time and space. Comparisons with modern barrier islands and bays from the Maritimes of Eastern Canada show that much of what was previously interpreted as estuarine channel and point-bar successions can be reinterpreted as barrier island, crevasse/washover channel and bay-fill deposits. Facies models for these types of environments are significantly different from those for estuarine systems, with the most marked differences in channel sand continuity versus bay-fill shale continuity. In areas of reduced accommodation space (Figure 11, right side of diagram), not all environments are preserved and recognition of the proper paleoenvironmental setting is critical for prediction of reservoir heterogeneity.

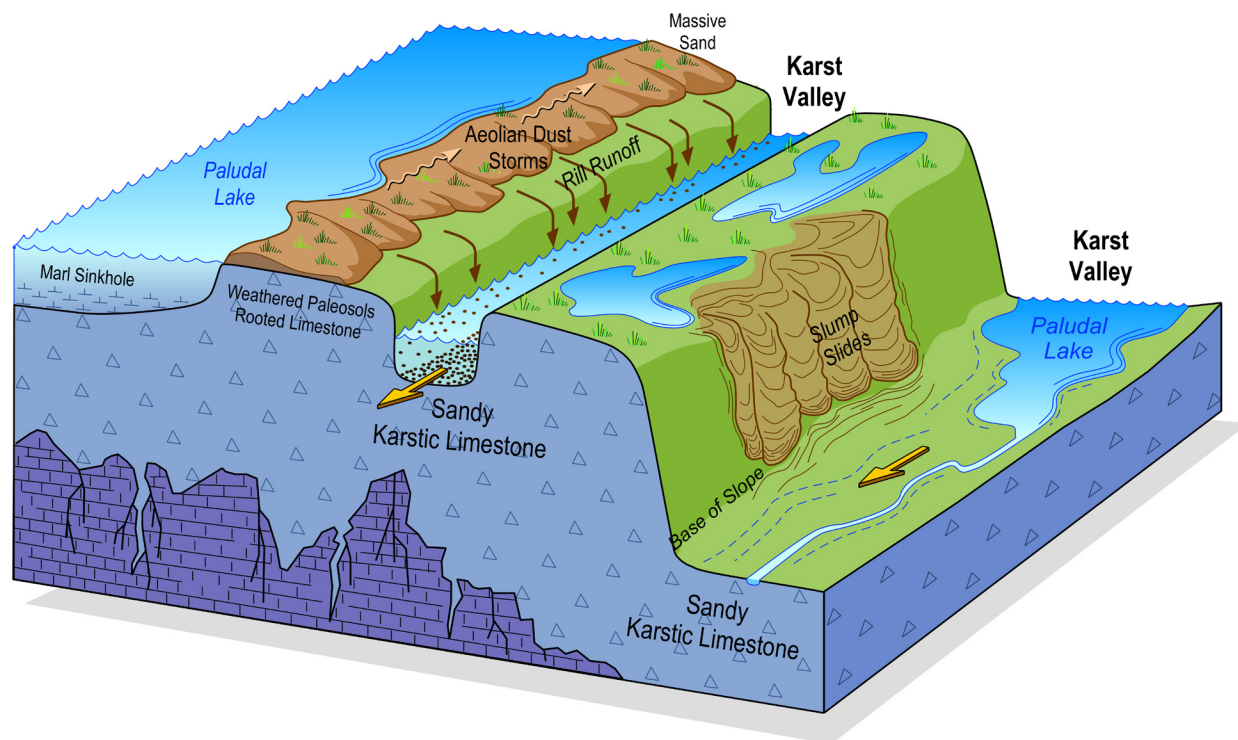


Figure 12A. Facies model for pre-McMurray silici/calci-clastic sedimentation along the karstic sub-Cretaceous unconformity.

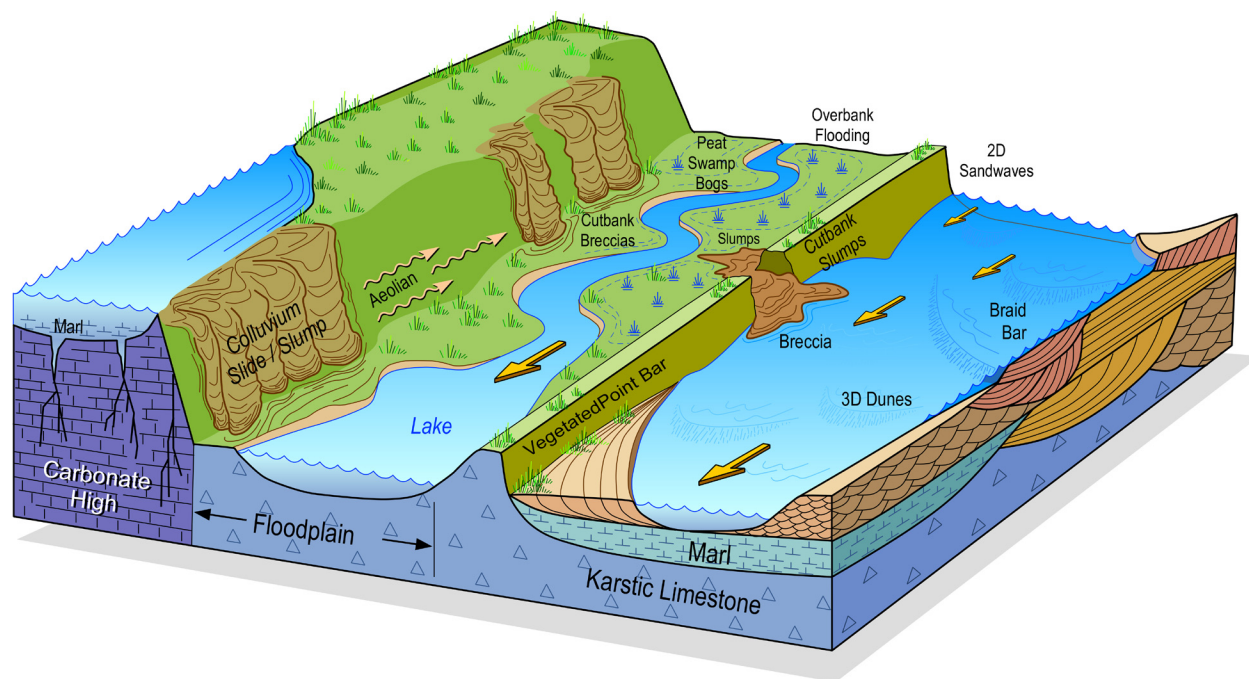


Figure 12B. Facies model for Lower McMurray fluvial and overbank sedimentation.

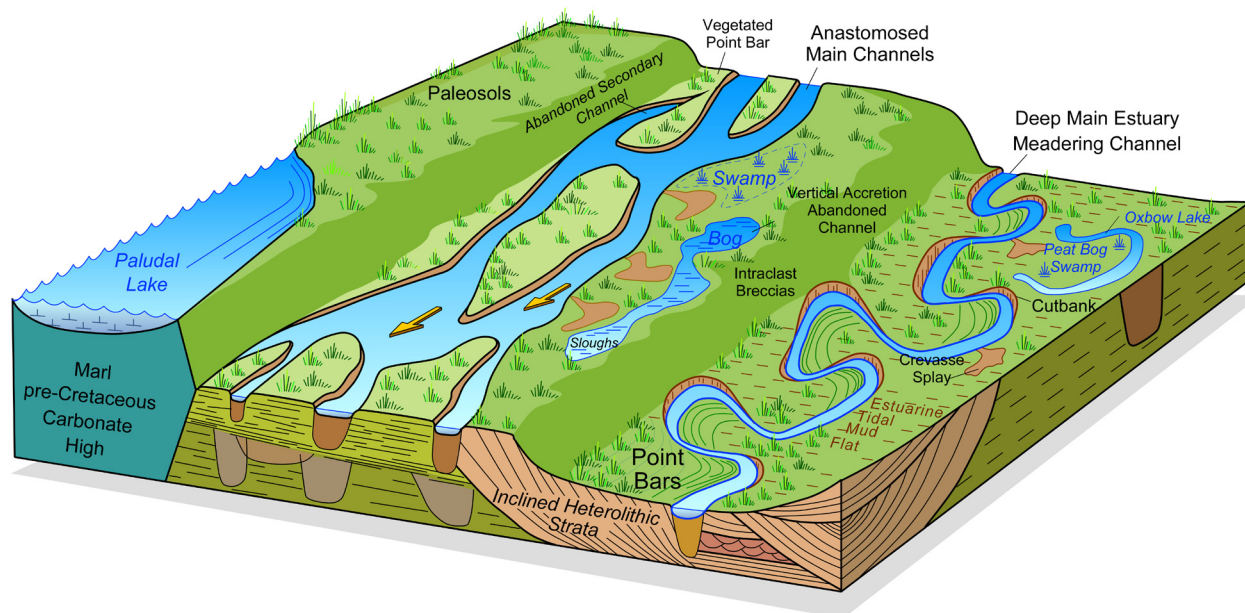


Figure 12C. Facies model for initial Upper McMurray fluvial-estuarine and overbank sedimentation.

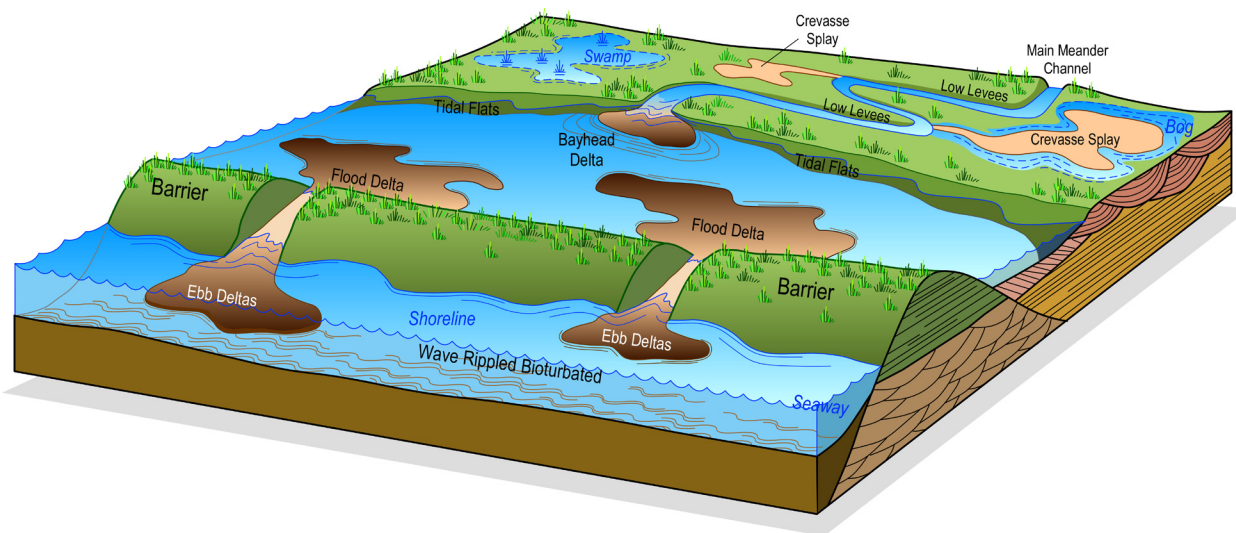


Figure 12D. Facies model for final Upper McMurray fluvial-estuarine, overbank, bay-fill back-barrier and barrier sedimentation.

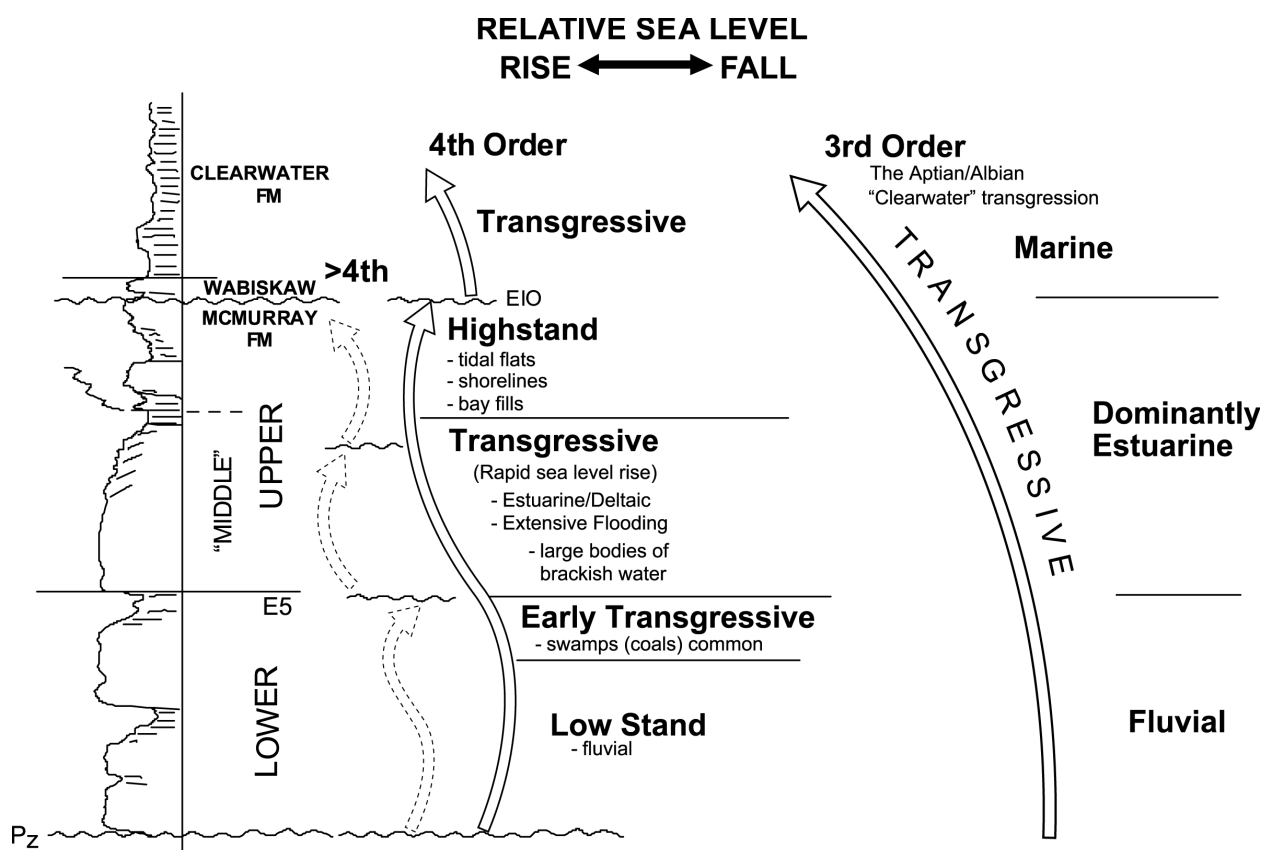


Figure 13. Sequence stratigraphy for the Wabiskaw-McMurray Athabasca deposit (from Flach and Hein, 2001; published in Hein and Langenberg, 2003).

6 Sedimentology of Channel Complexes

Unravelling the complex geology of the bitumen reservoirs relies on recognition that the fluvial-estuarine deposits are multistory complexes, and the preserved successions are a result of multiple transgressive and regressive pulses superimposed upon an overall transgression from the Lower McMurray fluvial low-stand deposits, to high-stand Wabiskaw deposits (Figure 13). The key to piecing the puzzle together lies in the basic concepts of estuaries and their origins; that is, using principles of geomorphology and concepts of sequence stratigraphy as applied to nonmarine successions (cf. Shanley and McCabe, 1991; Blum and Tornquist, 2000; Plint et al., 2001). To do this, one has to define the basic building block of the stratigraphy of the bitumen reservoirs. This building block is what we call a discrete, single-story, fluvial-estuarine 'channel complex.'

A discrete fluvial-estuarine 'channel complex' for the Athabasca Wabiskaw-McMurray deposit is defined as those units deposited as a result of the normal processes of erosion and deposition within a channel–point-bar system from a fluvial/estuarine setting. If one goes back to the classic point-bar model for a meandering stream (cf. Allen, 1964, 1965), sediments associated with a McMurray channel complex in the fluvial dominated part of the estuary would include the bottom channel, point-bar lateral accretion (Inclined Heterolithic Stratification, or IHS) and vertical accretion, associated overbank levee, crevasse splay, and floodplain sediments (B-B' in Figure 14A). Near the mouth of the estuary where there is a more marine influence, the channel complex would also include any associated estuarine bay, bay-head delta, interdistributary and tidal channels and bars, intertidal flats, and salt marshes (A-A' in Figure 14A).

Thus, facies that can be interpreted to form a discrete channel complex comprise those units associated with one cycle of relative base level fall-and-rise, not the stacked, multistory, channel complexes associated with successive cycles of relative base level fall-and-rise (compare Figures 14A, 15A with 14B, 15B). Single story channel complexes are differentiated from multistory channel complexes by the occurrence of a prominent scour surface that cut off the top of underlying successions; abrupt changes in facies, lithologies, or other sedimentary features; and in some cases, by divergences in paleoflow indicators (compare Figures 16A and 16B).

In summary, for the Wabiskaw-McMurray estuaries, the main controls on sedimentation were recurring sea level fluctuations coupled with local base-level adjustments associated with salt dissolution tectonics. In detail, superimposed upon the overall transgression from base McMurray to top Wabiskaw are the higher order cycles (Figure 13) that represent successive incision and infill of the separate estuaries, now preserved as multistory channel complexes (Figures 14B, 15B and 16B).

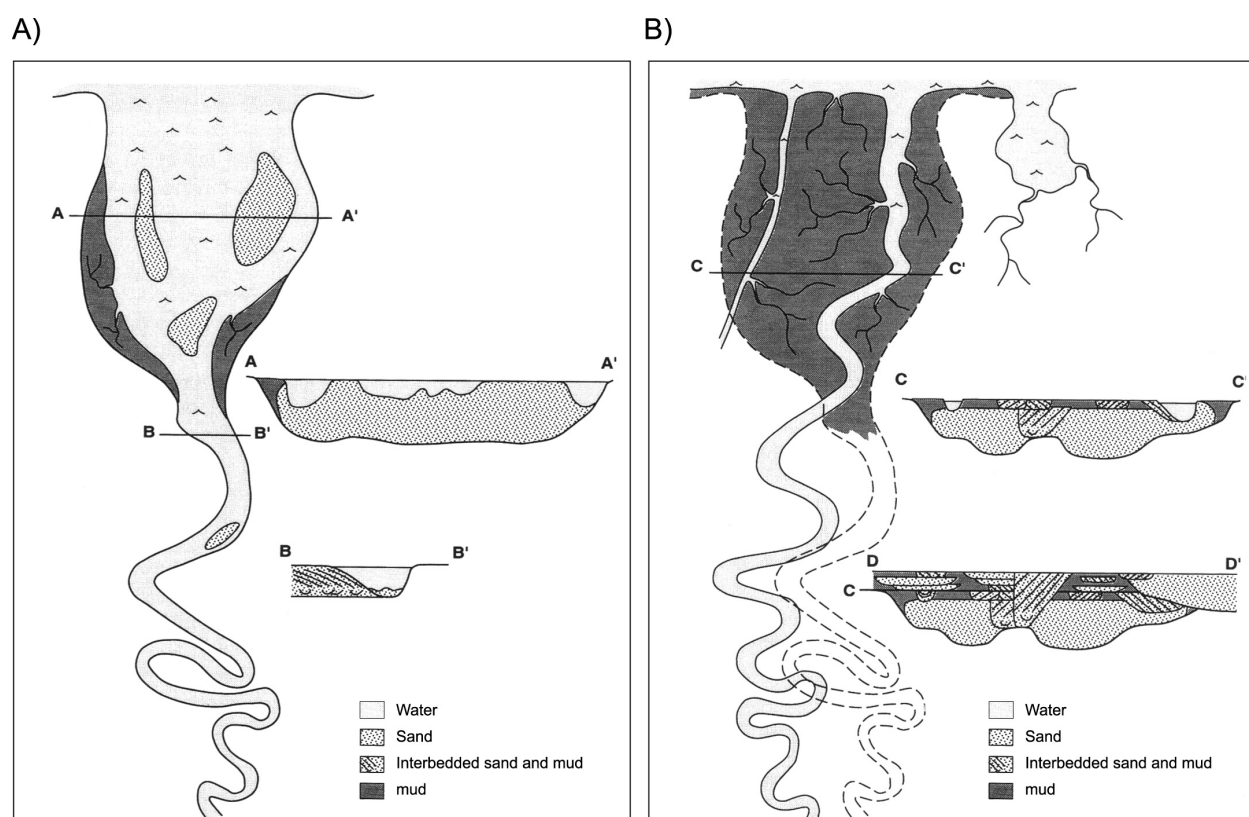


Figure 14. Schematic plan-view and cross-sections of A) singlestory fluvial-estuarine channel complex, B) multistory stacked fluvial-estuarine channel complexes (from Wightman et al., 1992, reprinted in Hein and Langenberg, 2003).

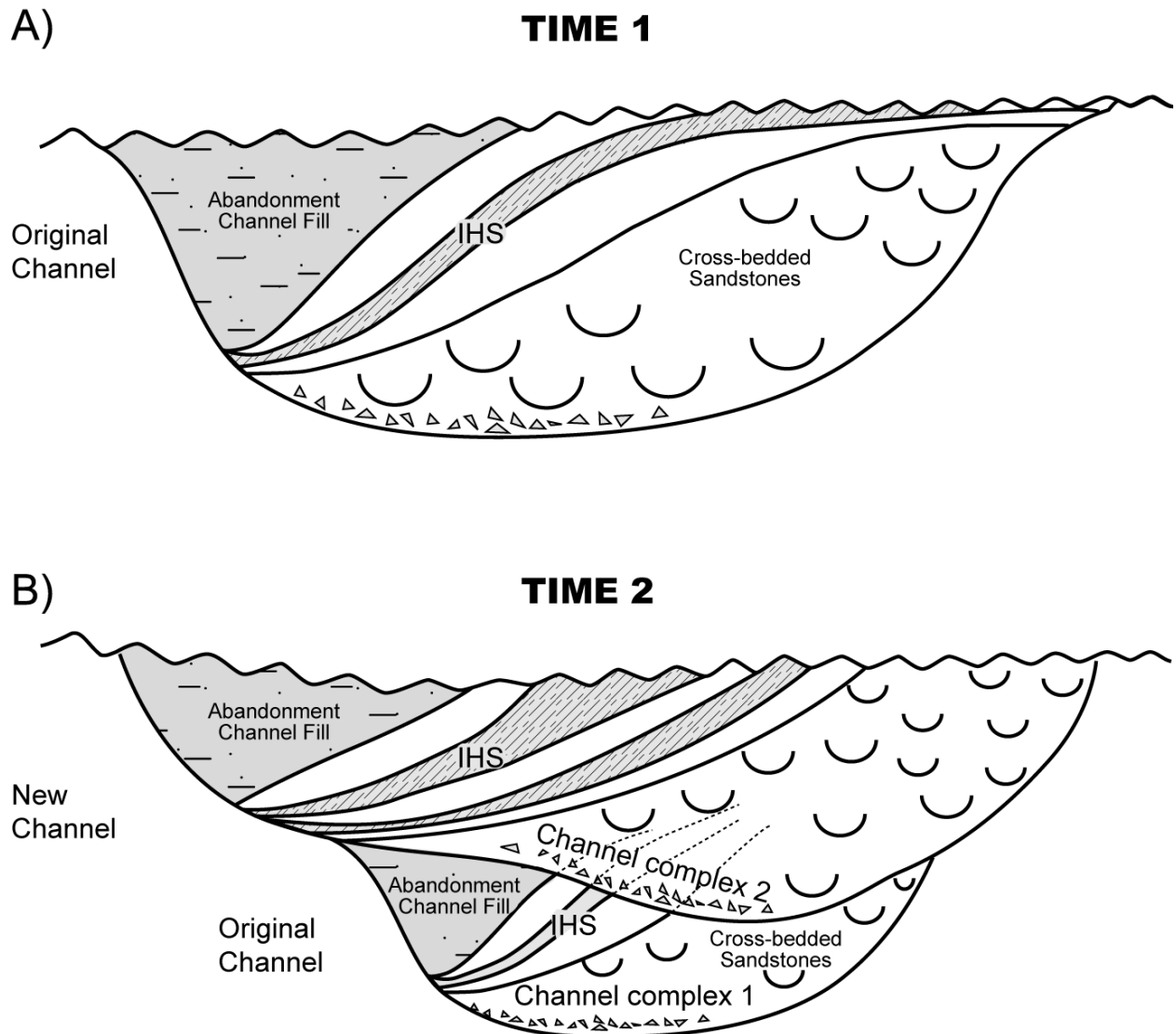
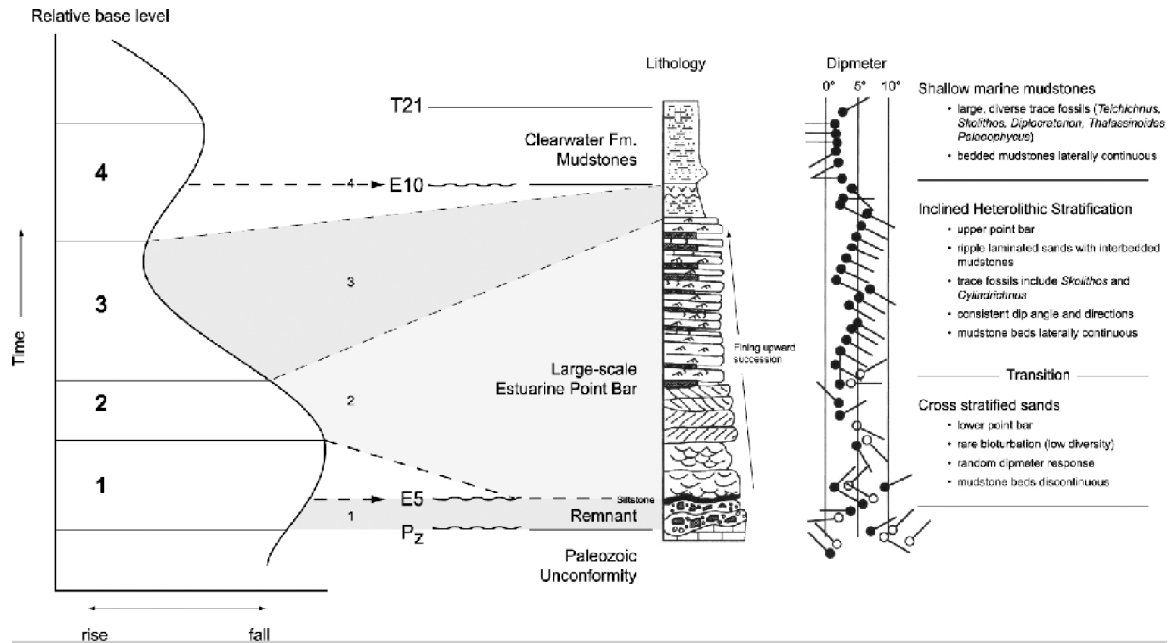


Figure 15. Stratigraphic model for preserved successions of a) singlestory fluvial-estuarine channel complex; b) multistory stacked fluvial-estuarine channel complexes (from Hein and Langenberg, 2003).

A)



B)

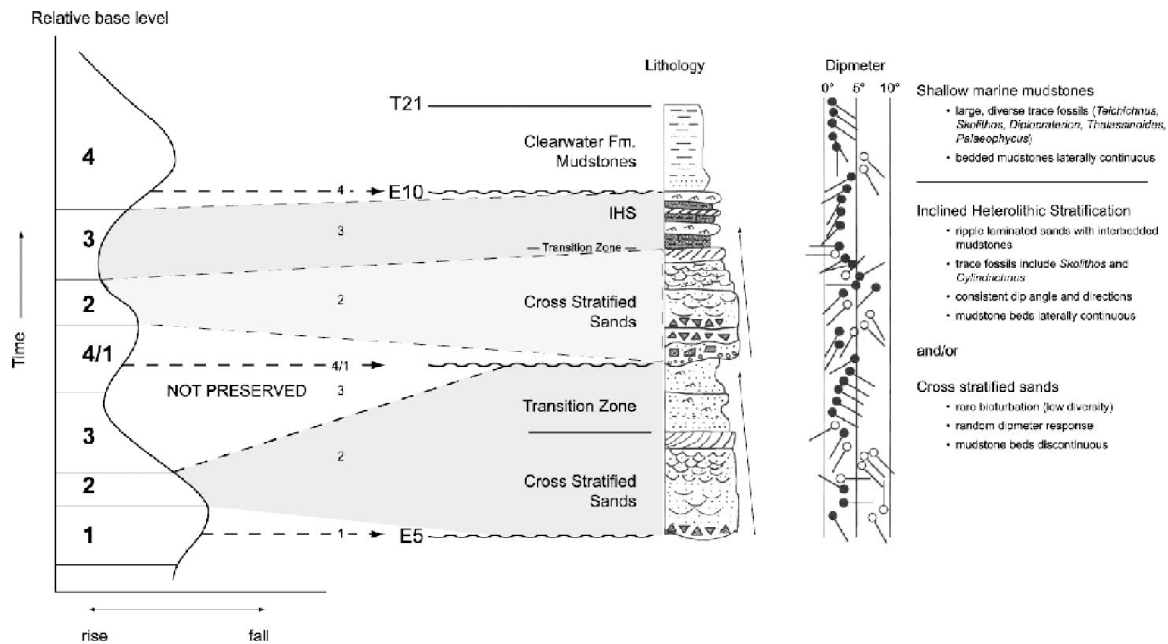


Figure 16. Sequence stratigraphy for preserved successions of a) single-story fluvial-estuarine channel complex; b) multistory stacked fluvial-estuarine channel complexes (from Hein and Langenberg, 2003).

7 Outcrop Descriptions: Day 1, Stop 1, McMurray Type Section

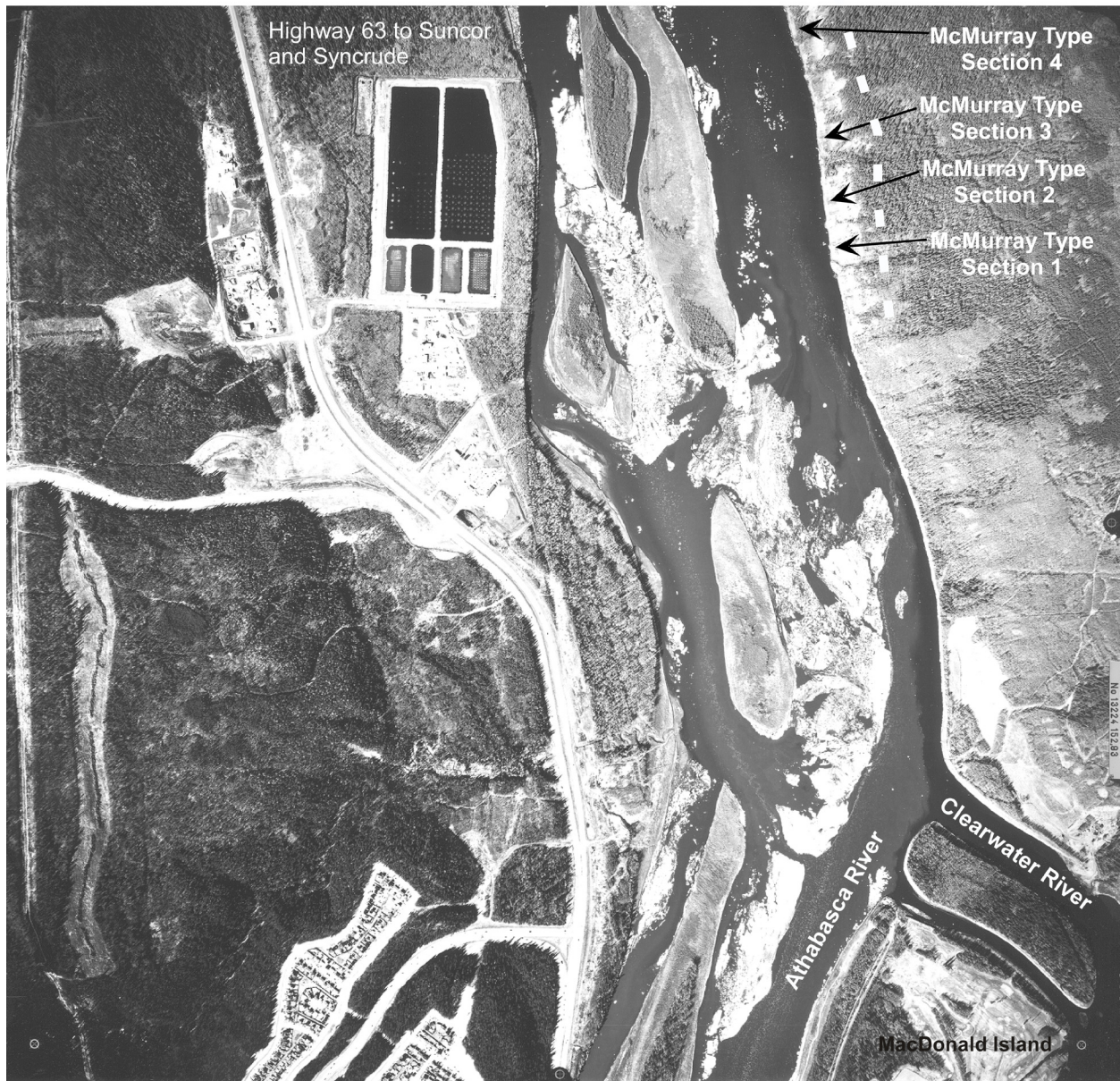


Figure 17A. Location and description of the McMurray Type Section, Athabasca River, aerial photograph.

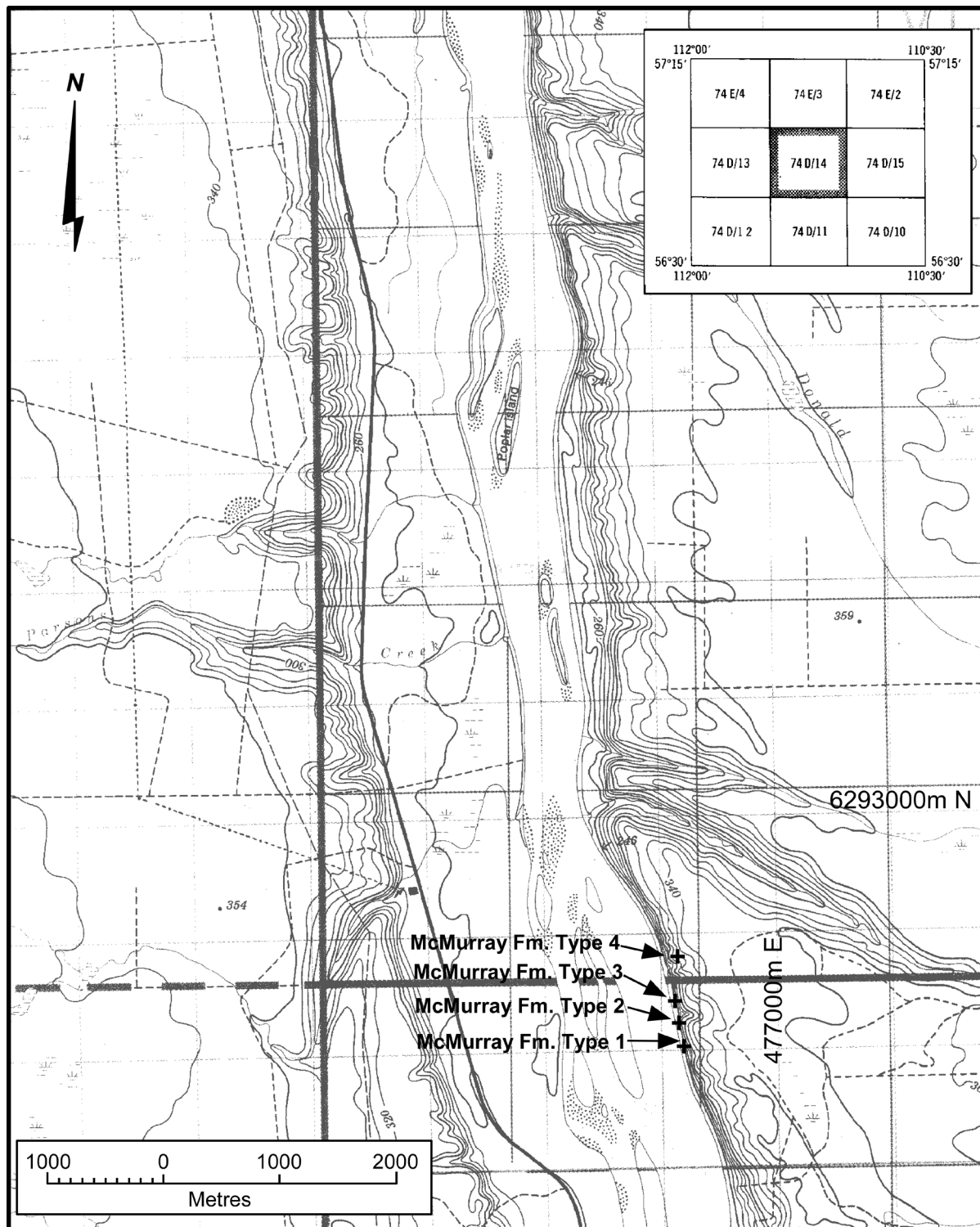


Figure 17B. Location and description of the McMurray Type Section, Athabasca River, topographic map.

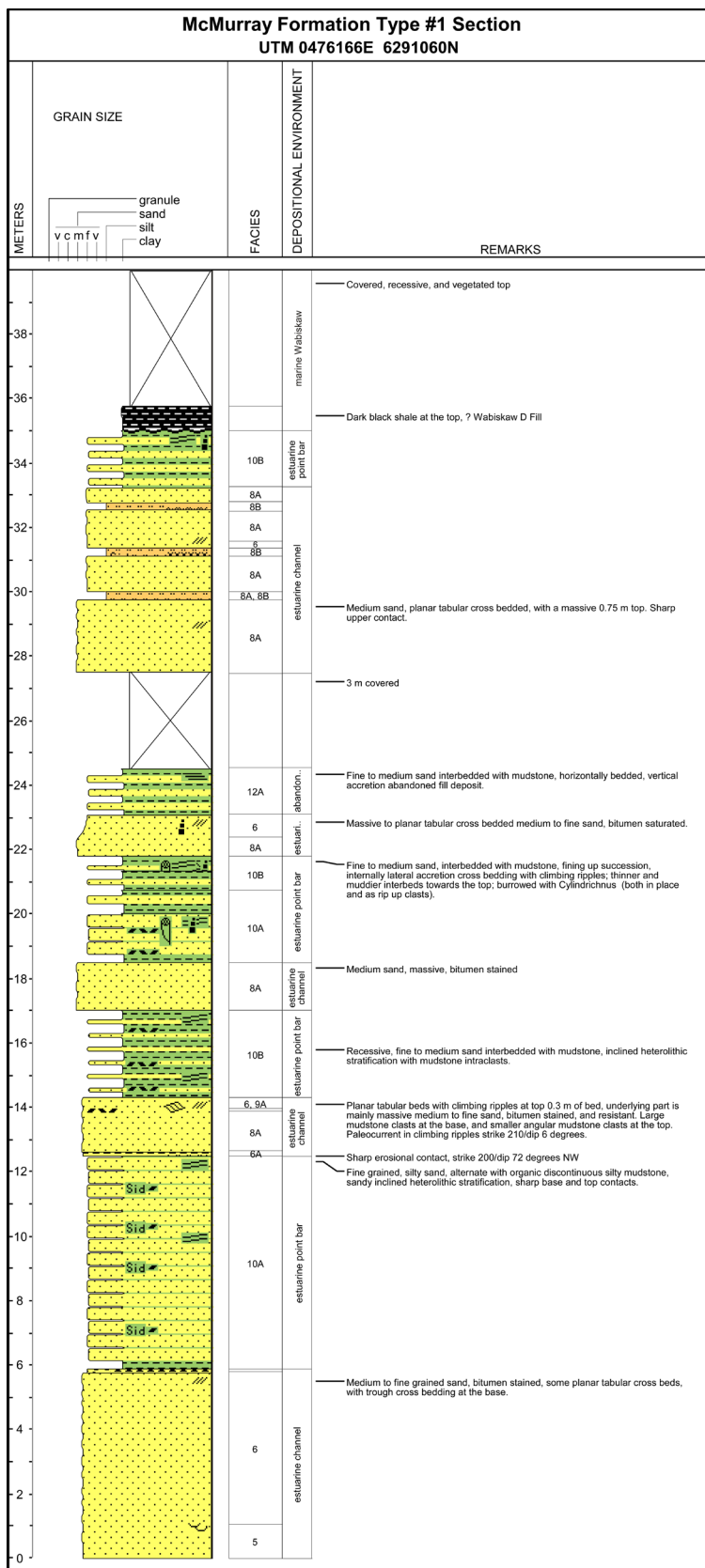


Figure 17C. Location and description of the McMurray Type Section, Athabasca River, measured McMurray Type #1 section.

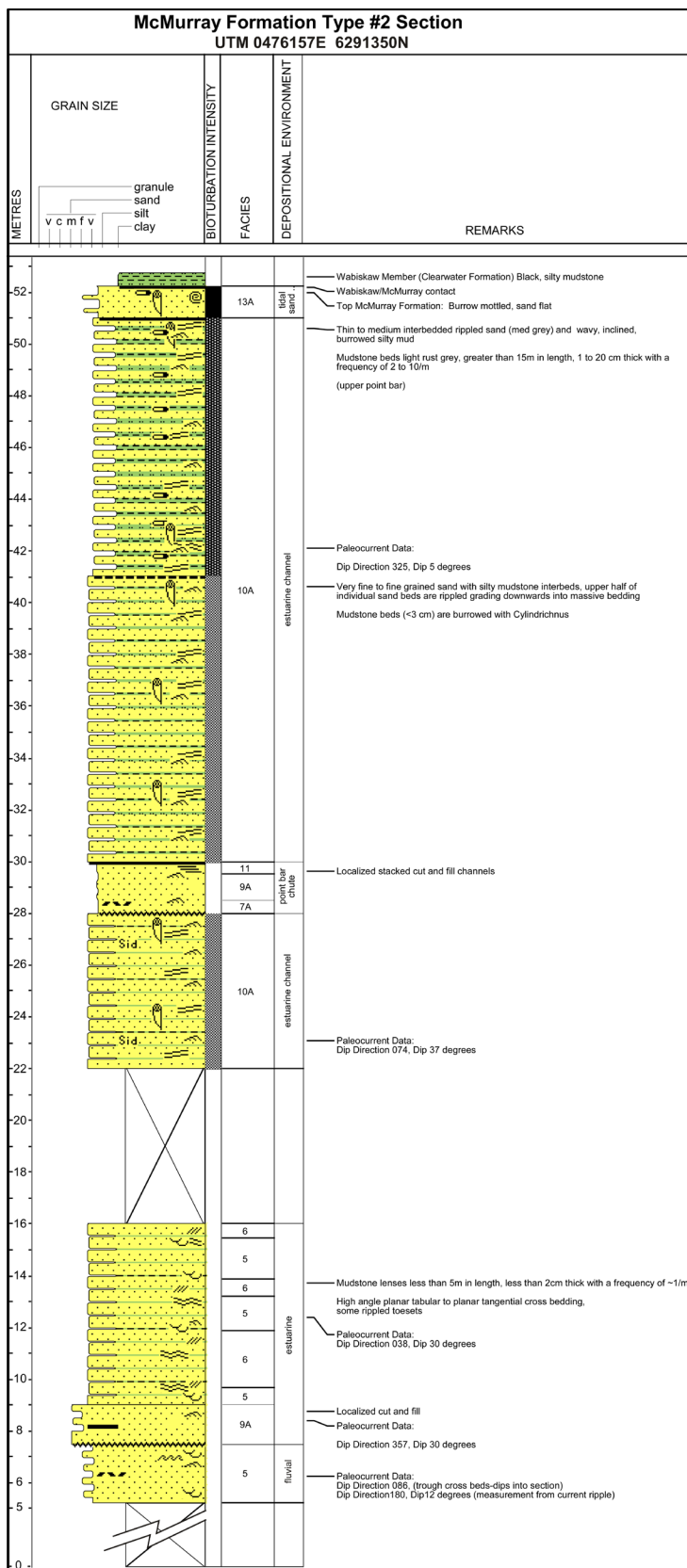


Figure 17D. Location and description of the McMurray Type Section, Athabasca River, measured McMurray Type #2 section.

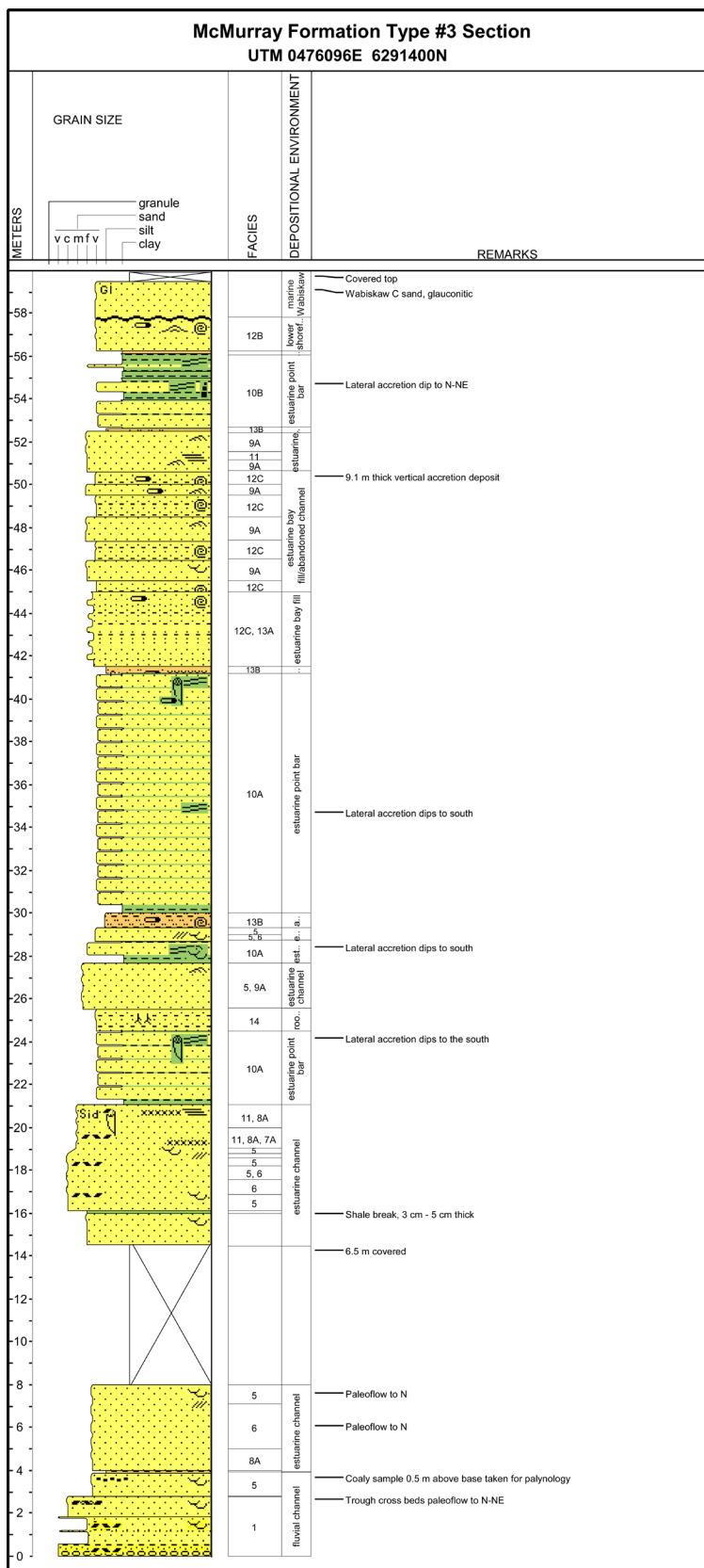


Figure 17E. Location and description of the McMurray Type Section, Athabasca River, measured McMurray Type #3 section.

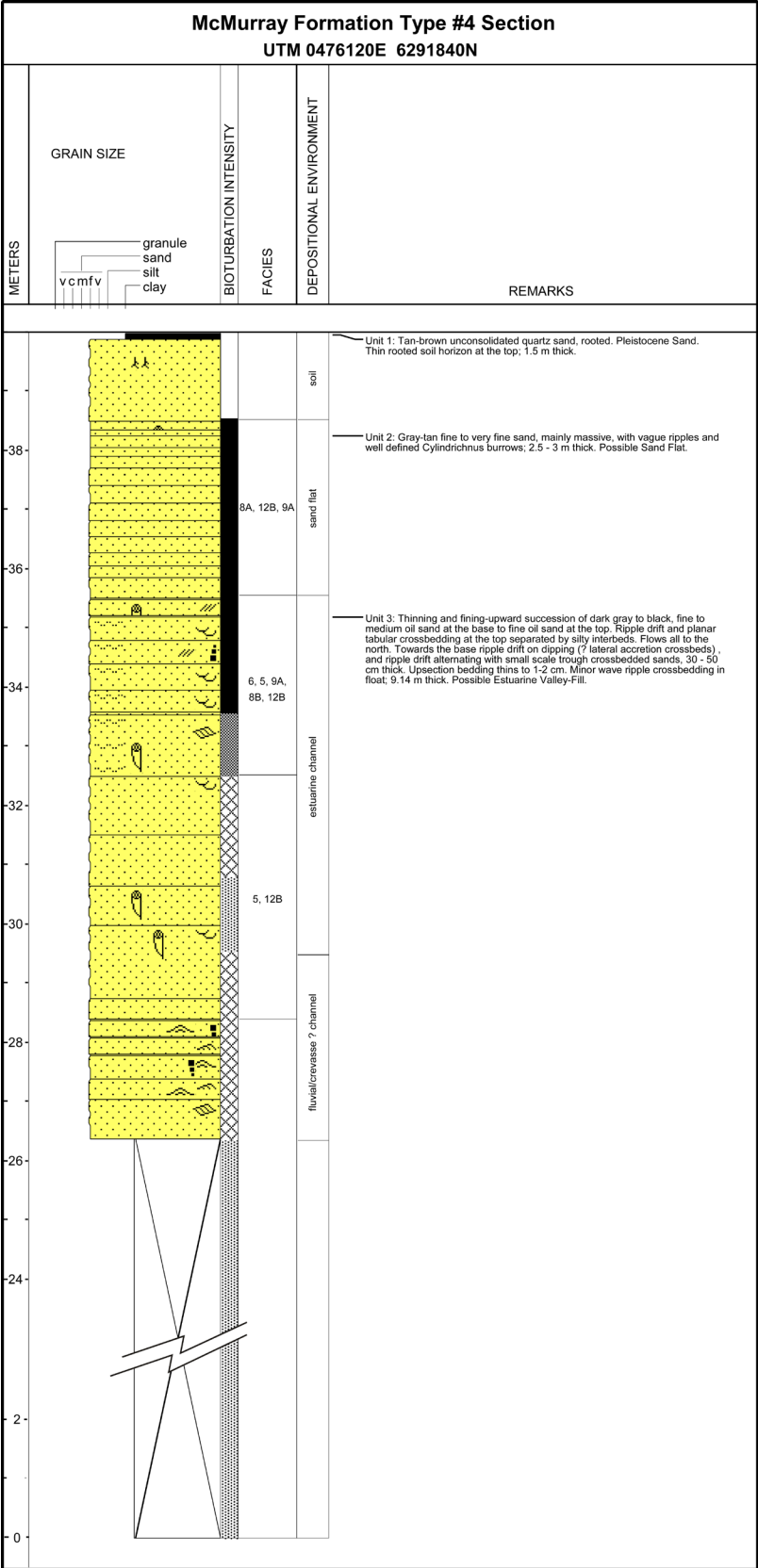


Figure 17F. Location and description of the McMurray Type Section, Athabasca River, measured McMurray Type #4 section.

7.1 Section McMurray Formation Type #1 Section

Map Coordinates: 74D/11 Fort McMurray, Scale 1:50 000, UTM 0476166E, 6291060N

Location and Access: This section is approximately 5 km downstream from the confluence of the Athabasca and Clearwater rivers on the east bank of the Athabasca River near the mouth of Clarke Creek (Figures 17A, 17B and 17C).

Highlights:

- Very thick, fining and thinning upwards, estuarine channel deposits, largely rippled or trough crossbedded.
- Well developed alternation of thick vertical accretion abandoned channel mudstones and crossbedded channel sands.
- Thin (< 1.5 m) Wabiskaw D shale at the top of the outcrop.

Description: In this outcrop section about 34 m of McMurray section is exposed (Figure 18). At the base the outcrop is a series of stacked, thick, crossbedded sands, with abundant planar-tabular or trough crossbedding, that along-strike interfinger with large scale, low angle, inclined heterolithic-stratified (IHS) sand and mudstone. Farther upsection the sands become thinner bedded, finer grained, more massive, and increase in the degree of bioturbation, with the most common types being *Cylindrichnus* and *Planolites*. The low angle sandy stratified units, in turn, fine upward into low-angle, muddy IHS sand and mudstone at the top of the McMurray succession. At the very top of the outcrop is exposed a thin (< 1.5 m) dark grey to black, bioturbated, silty mudstone, that is the Wabiskaw D shale (Clearwater Formation).

Interpretation: The stacked, thick crossbedded sands at the base of the section are interpreted as high energy, main estuarine channel deposits of the Upper McMurray succession. This is overlain by the interbedded, thin, low-angle inclined stratified units, interpreted as small scale estuarine channel and point-bar deposits. Paleoflows are unidirectional, mainly directed north, with rare paleoflows directed south. The finer grained, smaller estuarine channel and point-bar deposits are overlain by a topmost main estuarine channel fill that fines upward, at the top of the Upper McMurray Formation, into estuarine point-bar deposits.



Figure 18A. View from south of the McMurray Formation Type Section along the Athabasca River.



Figure 18B. Overview of the McMurray Type Section, Athabasca River at the Type #1 measured section.

7.2 McMurray Formation Type #2 Section

Map Coordinates: 74D/11 Fort McMurray, Scale 1:50 000, UTM 0476157E, 6291350N

Location and Access: This section is approximately 5.2 km downstream from the confluence of the Athabasca and Clearwater rivers on the east bank of the Athabasca River near the mouth of Clarke Creek (Figures 17A, 17B, 17D).

Highlights:

- Thick estuarine channel and point-bar sediment with rapid facies changes.
- Well developed crossbedding and bioturbation features in channel sands.
- Stacked packages of multistory inclined heterolithic-stratified sets.
- Unconformity between the Lower and Upper McMurray successions.

Description: In this thick outcrop section (about 50 m high), a thin remnant (2 m thick) of the fluvial sand occurs at the base. This fluvial deposit is often not seen due to its relatively unconsolidated nature (lack of bitumen cement) and slumped nature. When beds are exposed, coarse to fine-grained sand is seen, with large-scale planar-tabular and trough crossbeds (Figure 19B). Unconformably overlying this unit is the more typically tidal-bedded sands and interbedded sand and mudstone with low-angle inclined heterolithic stratification and moderate to high degrees of bioturbation (Figure 19A and 19C). Mudstone interbeds increase in frequency and thickness going upsection. Concomitant with this increase in mudstones, there is also an increase in bioturbation intensity, with the most common types being *Cylindrichnus* and horizontal *Planolites*, and rare vertical *Skolithos*. Locally, toward the base of the interbedded sand and mudstone unit, there are divergences in paleoflows (Figures 19A and 19B). Upsection, toward the middle and top of this outcrop, paleoflow patterns become more unidirectional, generally oriented north (Figure 19C).

At the very top of the outcrop is exposed a thin (< 1 m), bioturbated, black, silty mudstone that is the Wabiskaw D shale (Clearwater Formation), that unconformably overlies the McMurray Formation in this area.

Interpretation: The pebbly and finer sand at the base of the section with the prominent crossbedding and lack of interbedded mudstones or bioturbation features is interpreted as Lower McMurray fluvial deposits. This is overlain by a very thick succession of stacked estuarine interbedded sand and mudstone deposits. Some of these estuarine sands are massive or show abundant crossbedding and are interpreted as estuarine channel sands. The sands that are interbedded with mudstone as inclined heterolithic stratification that interfinger with and/or are crosscut by the channel sands are interpreted as estuarine point-bar deposits.



Figure 19A. Pinstriped, large scale crossbedded, fine-grained sand (Upper McMurray Formation) at the base of the McMurray Type #2 measured section.



Figure 19B. Coarse-grained, trough crossbedded (laterally discontinuous cut and fill), overlying fine-grained, trough crossbedded sand (Lower McMurray Formation) of the McMurray Type #2 measured section.

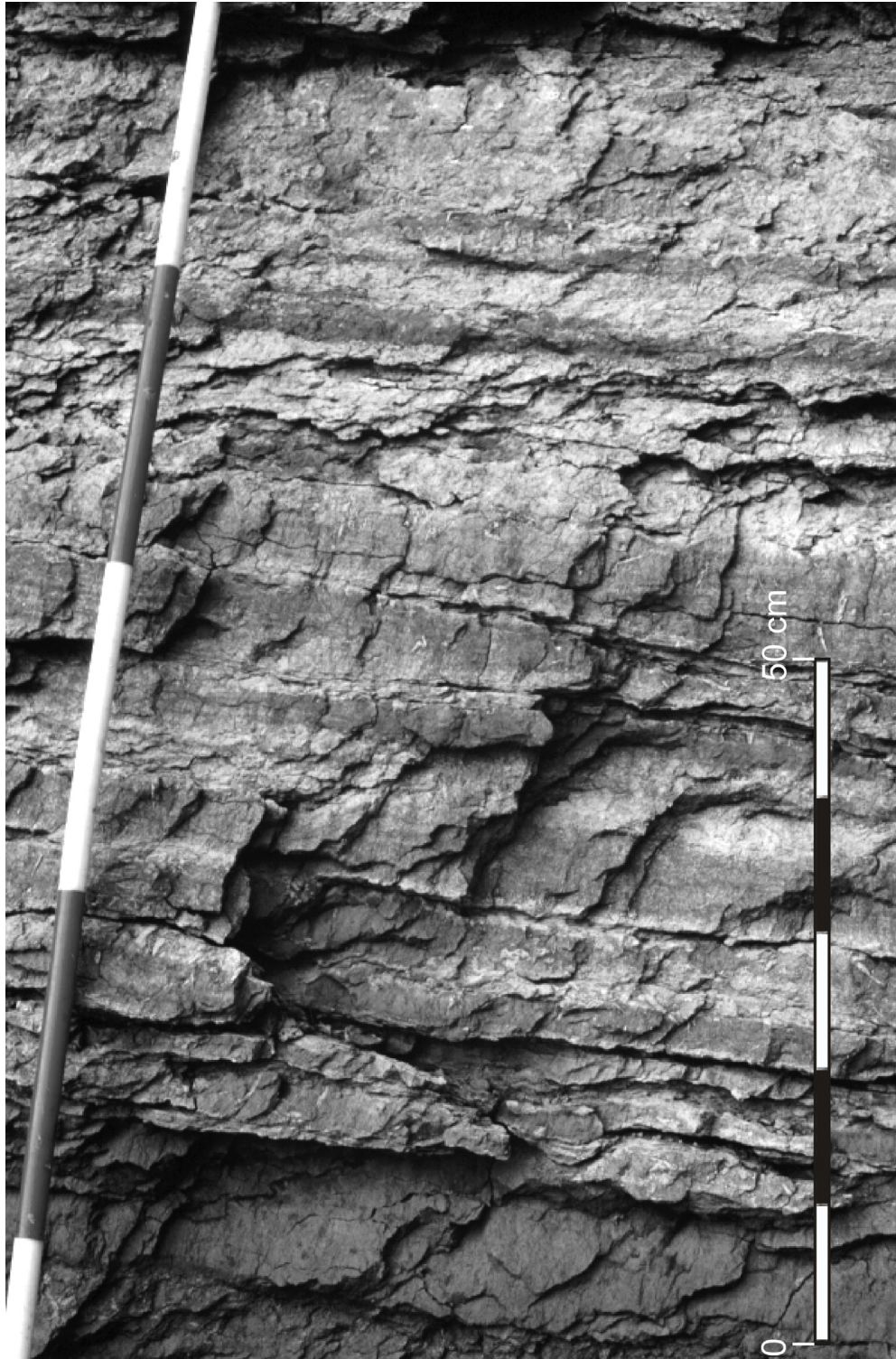


Figure 19C. Bioturbated, mud-dominated, inclined heterolithic stratification (IHS) (Upper McMurray Formation) of the McMurray type #2 measured section.

7.3 McMurray Formation Type #3 Section

Map Coordinates: 74D/11 Fort McMurray, Scale 1:50 000, UTM 0476096E, 6291400N

Location and Access: This section is approximately 5.4 km downstream from the confluence of the Athabasca and Clearwater rivers on the east bank of the Athabasca River near the mouth of Clarke Creek (Figures 17A, 17B, 17E).

Highlights:

- Thin remnant of fluvial channel sand at the base.
- Very thick, fining and thinning upward, estuarine channel deposits, largely rippled or trough crossbedded, grading upward into multiple sets of low-angle, inclined heterolithic-stratified sand and mudstone.
- Well developed alternation of vertical accretion (? tidal flat, back-barrier bay fill) deposits at the top of the McMurray.
- Thin (< 2 m) glauconitic Wabiskaw C sand at the top of the outcrop.

Description: In this outcrop section about 57 m of McMurray section is exposed (Figure 20). At the base of the outcrop is a 3m thick unit of crossbedded quartz-pebble sands, with abundant trough crossbedding. Mudstone intraclasts and carbonaceous debris are common, with some mummified logs and twigs. At the top of this unit is a siderite-cemented sandstone.

Unconformably overlying the lower crossbedded sands are massive and crossbedded fine sands that lack the cement, are unconsolidated and lack bitumen staining. Internally, the sands show planar-tabular and trough crossbedding, with rare dispersed mudstone intraclasts that are bioturbated. Farther upsection the sands and mudstone interbeds show an overall fining upward succession that becomes thinner bedded, finer grained and more bioturbated, with the most common types being *Cylindrichnus* and *Planolites*. Rare root traces are within a small coarsening upward succession (22-26 m from the base) that may represent crevasse splay and overbank sedimentation.

The next succeeding 15 m of section consists of fining-upward succession of IHS sand and mudstone. The IHS is abruptly overlain by a bioturbated, complex sand and mudstone unit (42-57 m). This unit shows a variety of physical sedimentary structures, including large-scale convolute lamination, trough, current and wave ripples, parallel lamination and contorted bedding. Siderite bands are common and continuous across the outcrop. Bedding style of this uppermost unit is even and parallel at the base, becoming more wavy and discontinuous upsection. At the very top of the outcrop is exposed a thin (< 2 m) green, bioturbated, silty sand of the Wabiskaw C (Clearwater Formation).

Interpretation: The stacked, thick crossbedded sands at the base of the section are interpreted as high energy, main fluvial deposits of the Lower McMurray Formation. This is capped by the siderite cemented zone, likely a disconformity surface between the Lower/Upper McMurray. The overlying Upper McMurray is dominated by thick, high energy, estuarine channel sands at the base that become finer grained and thinner bedded upsection, into estuarine point-bar deposits and vertical accretion tidal flat or back-barrier bay fills.



Figure 20. Overview of the McMurray Type #3 measured section.

7.4 McMurray Formation Type #4 Section

Map Coordinates: 74D/11 Fort McMurray, Scale 1:50 000, UTM 0476120E, 6291840N

Location and Access: This section is approximately 6 km downstream from the confluence of the Athabasca and Clearwater rivers on the east bank of the Athabasca River near the mouth of Clarke Creek (Figures 17A, 17B and 17F). Land along the bank and climb the slump face about 20 m in height to a terrace along the Athabasca River valley. Walk inland about 0.5 km to a small scarp face at the eastern edge of the terrace. The measured section is about midway along the outcrop face.

Highlights:

- Very thick, fining and thinning upwards, estuarine channel deposits, largely rippled or trough crossbedded.
- Well developed crossbedding and bioturbation features in channel sands.
- Possible sand-flat deposits at the top of the Upper McMurray succession.
- Thin Quaternary fill (< 1 m thick).

Description: In this outcrop section about 14 m of section is exposed. The outcrop is a thick, crossbedded sand unit with abundant ripples, including current, ripple-drift and wave types and less commonly, planar-tabular or trough crossbedded units. Finer grained siltstone/mudstone interbeds are rare. Toward the base of the outcrop, the sands are somewhat finer grained, becoming coarser within the basal 2 m of section, and have an abundance of ripple drift and wave-ripple crossbeds. Farther upsection the crossbedded sands become thinner bedded and finer grained, and show an increase in the degree of bioturbation, with the most common types being *Cylindrichnus* and *Planolites*. At the very top of the outcrop is exposed a thin (< 1 m), rooted, tan-brown, unconsolidated quartz sand that is interpreted as Quaternary cover.

Interpretation: The coarsening upward sand at the base of the section is interpreted as possible crevasse splay overbank deposits of the Upper McMurray succession. This is overlain by a very thick succession of estuarine channel deposits. Most of these estuarine sands are rippled throughout and, where sandy-inclined heterolithic stratification occurs, the internal ripple-drift and wave-ripples dominate the bedding on sets. Such inclined heterolithic stratification is rare. Paleoflows are unidirectional, mainly directed north. There is a general absence in the occurrence of lateral accretion crossbedding and the dominance of small-scale bedform features, which indicates relatively little lateral migration of meandering channel/point-bars. This is suggestive that the estuarine sands are a result of vertical accretion and infill of secondary channels, high up within the drowned estuarine valley, perhaps near a sandy tidal flat setting. Such secondary channels may be vertically accreting, anastomosed channel deposits within an overbank to tidal flat area, flanking the main estuarine valley.

7.5 Reservoir Analogues: McMurray Type Section, Athabasca River

At the McMurray type section the fluvial pebbly sand remnants are preserved along paleotopographic lows along the unconformity. The Lower McMurray is interpreted as amalgamated braided fluvial channel-and-bar complexes that would have very good to excellent porosity and permeability, likely forming sheet sands within the bedrock-confined paleovalleys along the sub-Cretaceous unconformity. As shown in the outcrops, there are local basal water sands that interfinger with the Lower McMurray bitumen sands. As indicated by Flach and Hein (2001), these water sands may be interconnected along the bases of the main paleovalleys, but more localized outside the main paleovalleys. In core, fluvial coarse to pebbly sand is commonly bitumen saturated, with trough and/or planar-tabular crossbedding and scattered intraclasts (Figure 21). On geophysical logs this facies association is represented by a blocky or coarsening then fining-up response (Figure 21). Minor disruptions to fluid flow within reservoir sands occur in mudstone-clast breccia zones (Figure 22) or in reservoir sands where there is sideritization, both as isolated caps or as replacement of mudstone clasts/beds (Hein et al., 2000).

Next in sequence are the Upper McMurray estuarine channel bitumen sands that interfinger along-strike and grade up into the sand/mudstone beds with IHS, interpreted as estuarine point-bar deposits. Overall at the type section, the facies become muddier and thinner bedded, as well as increasing in bioturbation intensity up section. There are no thick continuous sections that are uniformly coarsening upwards, as would be represented in a deltaic succession. Rather there is variability along-strike depending upon whether one is in a channel or the adjacent point-bar/overbank succession. Local, thin, coarsening-upwards units are interpreted as crevasse splays formed along the margins of the estuarine channels. In core, the estuarine channel sands tend to be massive, with mudstone intraclasts (Figure 22), and are interbedded with units showing low-angle IHS (Figure 23). Associated mudstone clasts and mudstone interbeds are commonly bioturbated (Figure 23), which increase in intensity upsection within a given fining-upwards channel/point-bar succession. On geophysical logs, this facies association consists of a gradually fining-up unit, often capping the more blocky underlying estuarine channel sands (Figures 23 and 24). As indicated by Flach and Hein (2001), the amalgamated, multistory, estuarine meandering channel-and-point-bar complexes have somewhat lower porosity and permeability, compared with the underlying Lower McMurray fluvial reservoirs. Additionally, baffles to flow occur as mudstone-intraclast breccias and within the mud beds of the IHS which is juxtaposed with the cleaner, more porous/permeable channel sands (Hein et al., 2000). Overall the porosity/permeability would decrease upsection in response to the increasing mud content of the succession. In core, this is represented by rhythmically laminated, thinly interbedded, very fine sand and mudstone that occurs within bioturbated IHS units (Figure 25). On geophysical logs, the muddier IHS shows complex grading patterns and a much higher mud response (Figure 25).

The top of the McMurray Type #3 section shows a complex, highly bioturbated sand and mudstone succession. These were interpreted as vertical accretion fill that developed on the top of abandoned, but still flooded, estuarine channel/point-bars. The high degree of bioturbation indicates a relatively low, although episodic, sedimentation rate. In core, such facies associations are represented by heavily bioturbated, laminated and thinly interbedded, muddy sand and mudstone (Figure 25). Geophysical log responses show a mud-dominated succession, with complex grading patterns (Figure 25). The overall porosity and permeability are dependent upon the interconnectivity of the sand burrow networks and their orientations (i.e., vertical, subparallel to bedding or oblique). Thus, it is difficult to predict the porosity/permeability of this unit, but it may be similar to the underlying multistory IHS units; certainly less than associated channel facies. The limited extent of this unit in outcrop suggests it may be a baffle (as opposed to a barrier) to fluid flow in the subsurface. The increased continuity of the associated sideritized interbeds may also provide a hinderance to subsurface flow.

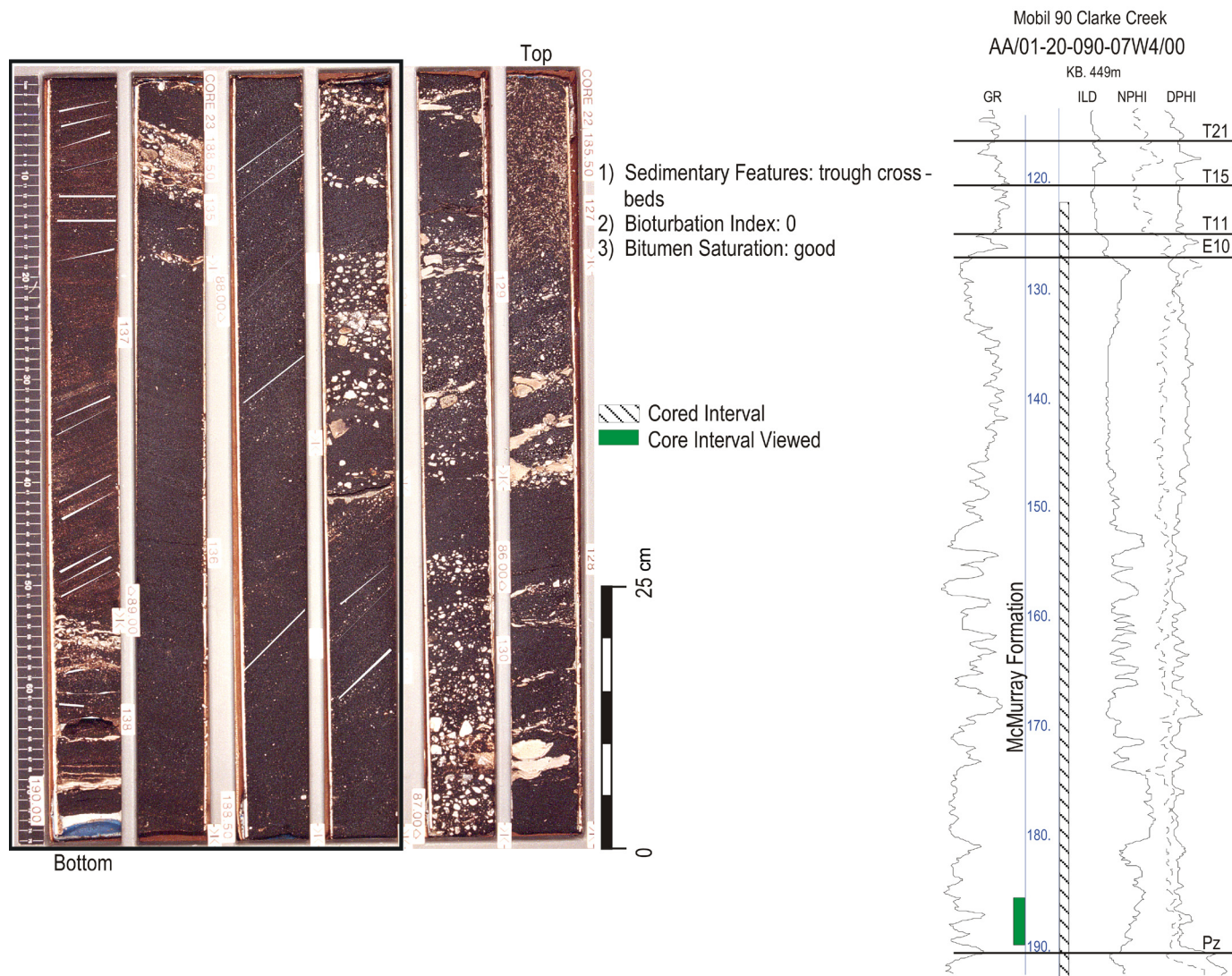


Figure 21. Core photographs and wireline logs of the Mobil 90 Clarke Creek well, location: AA/01-20-090-07W4.

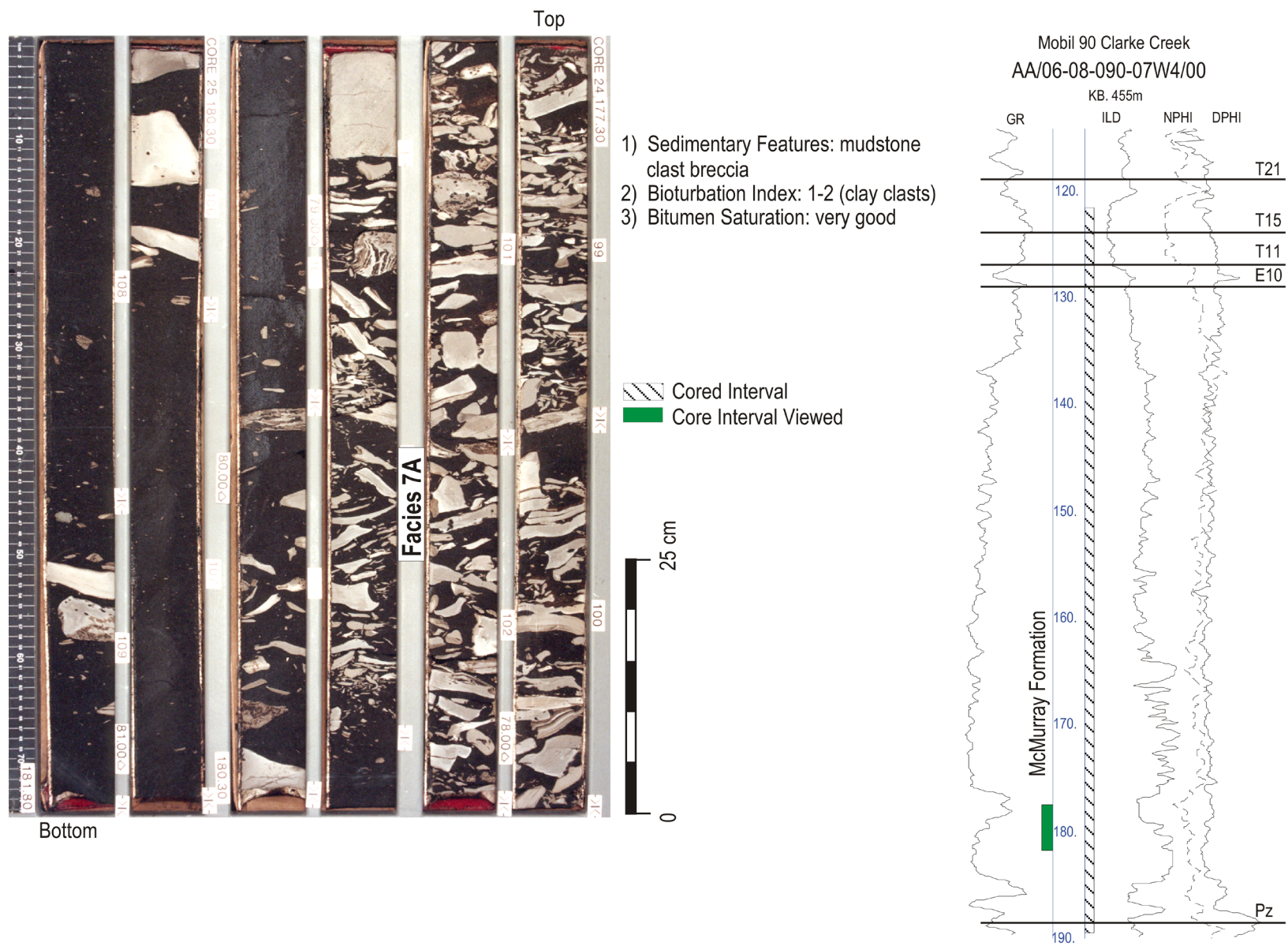


Figure 22. Core photographs and wireline logs of the Mobil 90 Clarke Creek well, location: AA/06-08-090-07W4.

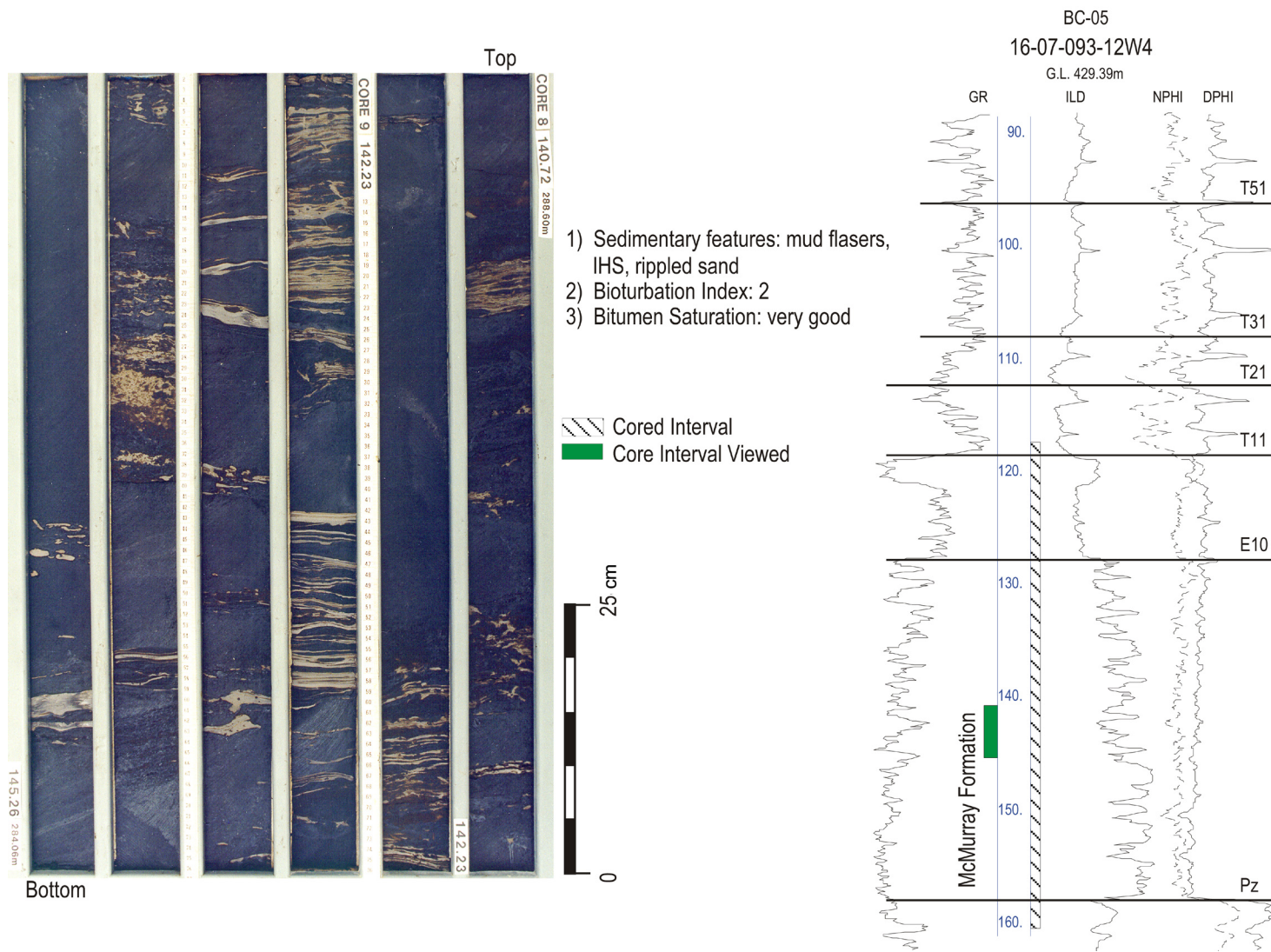


Figure 23. Core photographs and wireline logs of the UTF site BC-08, location: 00/16-07-093-12W4.

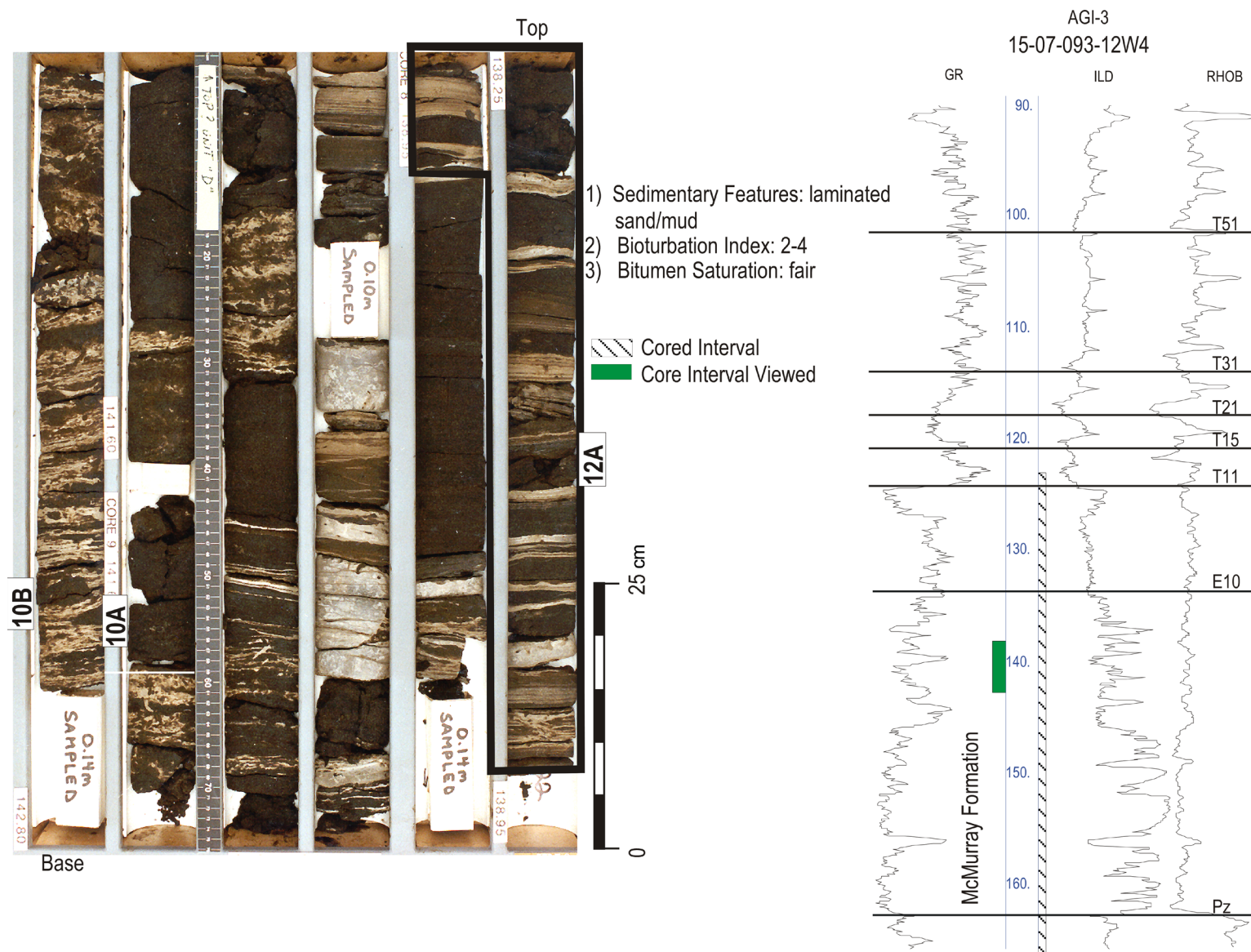


Figure 24. Core photographs and wireline logs of the UTF site AGI-3 well, location: 00/15-07-093-12W4.

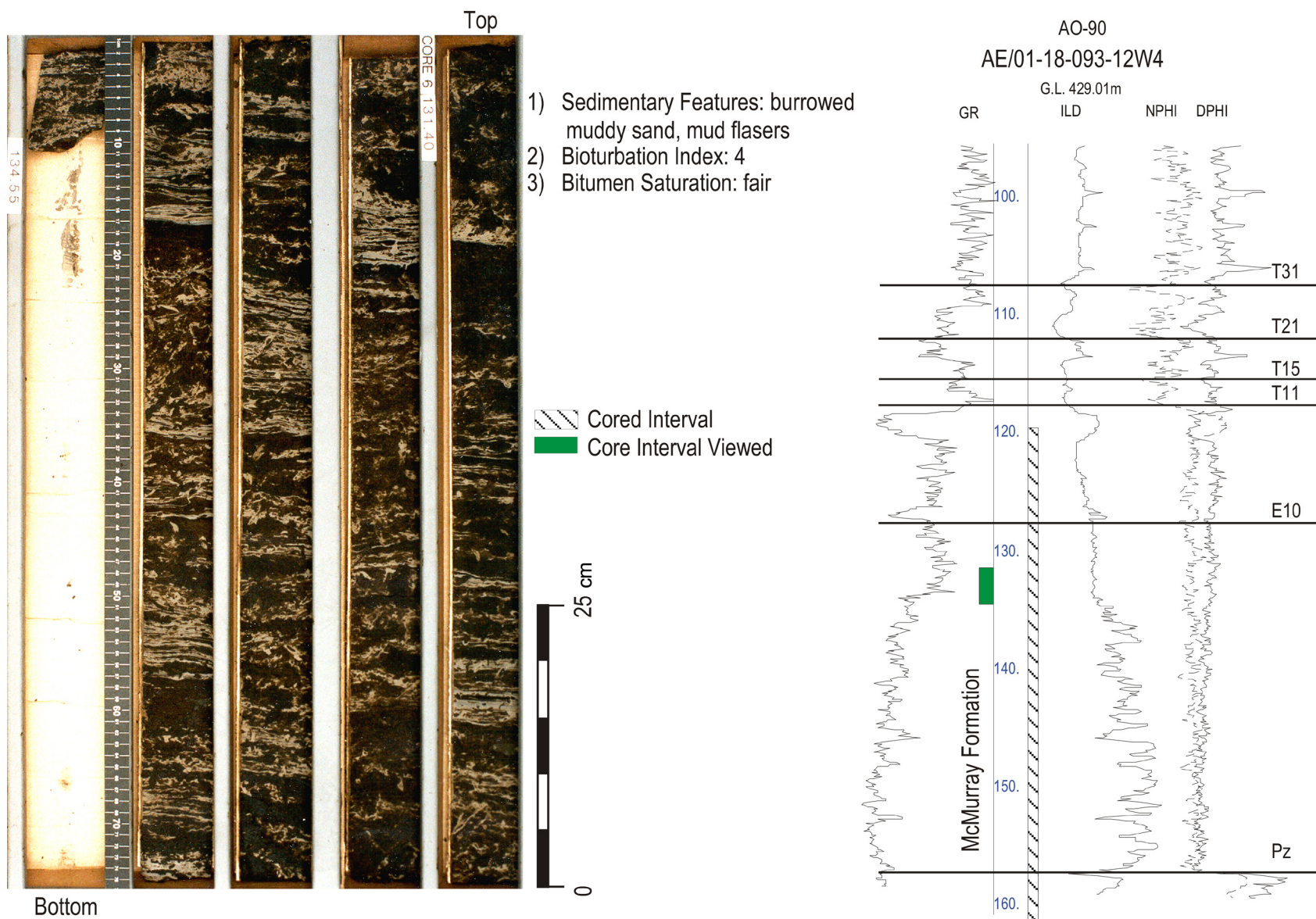


Figure 25. Core photographs and wireline logs of the UTF site AO-90 well, location: AE/01-18-093-12W4.

8 Outcrop Descriptions: Day 1, Stop 2, Marl Section

8.1 Fluvial Marl Section

Map Coordinates: 74D/14 Wood Creek, Scale 1:50 000, UTM 0474746E, 6305712N

Location and Access: This section is approximately 18 km downstream from the confluence of the Athabasca and Clearwater rivers on the east bank of the Athabasca River near the mouth of McLean Creek (Figures 26A, 26B and 26C).

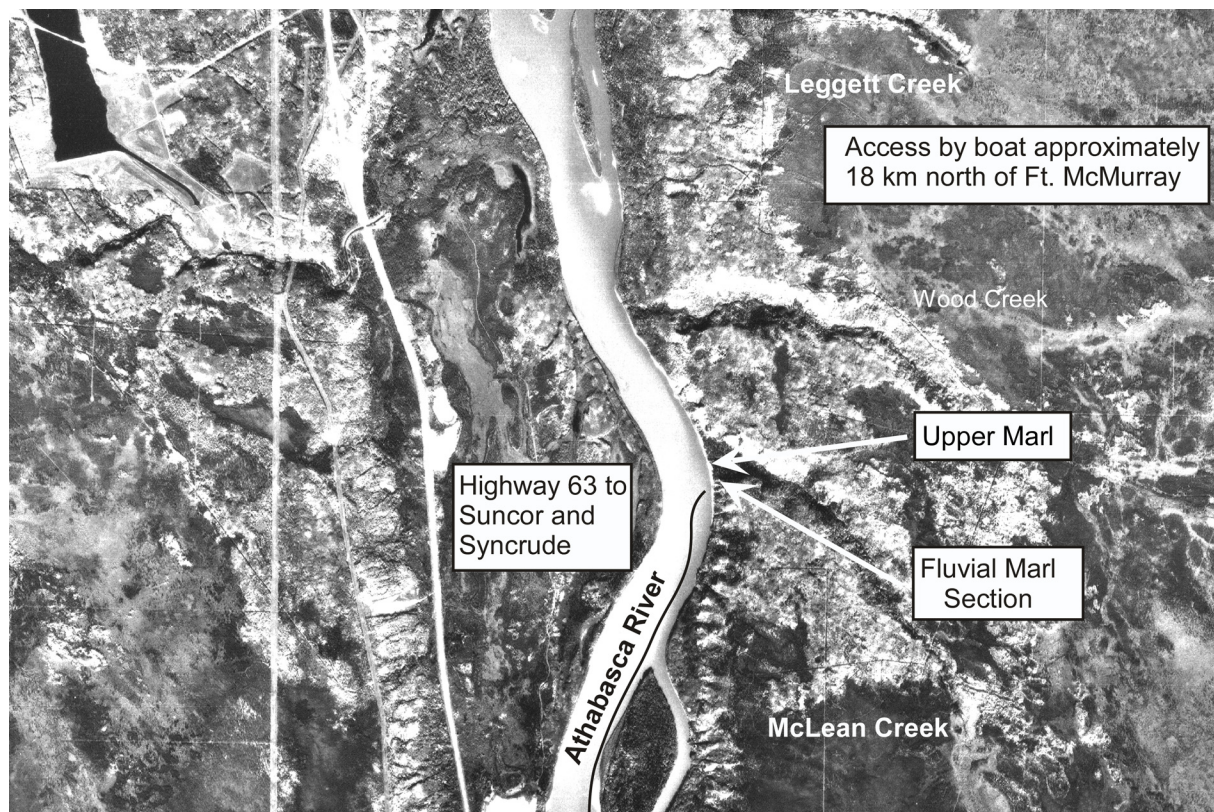


Figure 26A. Aerial photograph showing location and description of the Marl section, Athabasca River.

Highlights:

- Marly muddy sand, paleosol, carbonaceous mudstone and fluvial sand, generally slumped.
- Some of the oldest Lower Cretaceous sediment in the area.

Description: In this small outcrop (about 5 m high), some of the oldest Lower Cretaceous sediment that unconformably overlies the Devonian limestone in the area is exposed (Figures 27A and 27B). Here is exposed a slumped section of paleosol/marly muddy sand, with interbedded carbonaceous mudstone and minor crossbedded granule sand that occupies a paleotopographic low on the pre-Cretaceous unconformity. Note the general absence of bitumen staining, the abundance of organics and ironstone concretions, and the generally unconsolidated nature to the sediment.

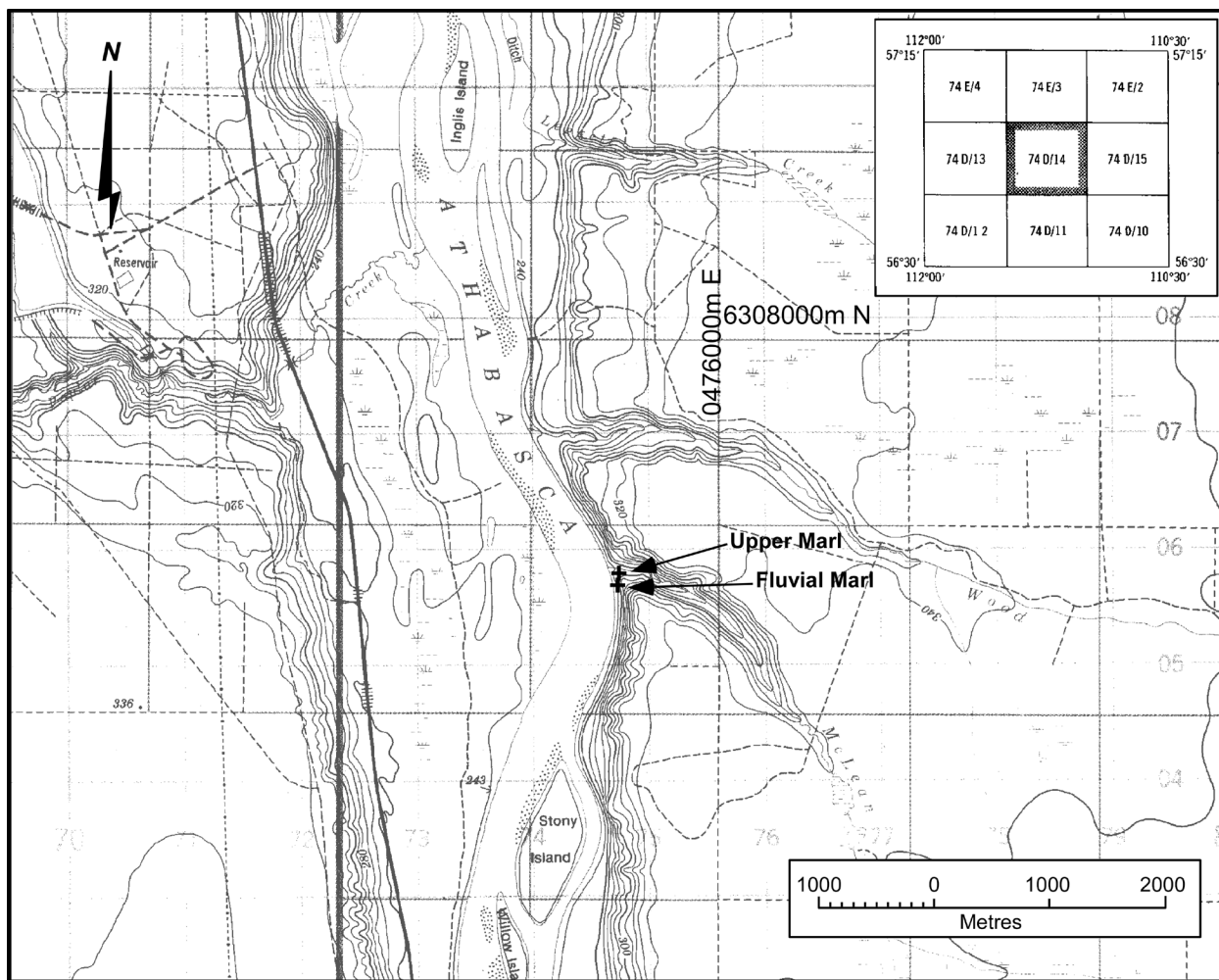


Figure 26B. Topographic map showing location and description of the Marl section, Athabasca River.

Interpretation: Possible paleosols, lacustrine marl and fluvial sand remnants are preserved in this generally recessive and slumped outcrop. Regional mapping suggests this location is typical of areas that were originally paleotopographic lows along the karstic pre-Cretaceous unconformity. Originally the unit was probably water bearing, since exposure along the Athabasca River valley has become further eroded and slumped along the bank. One hypothesis that accounts for the lack of bitumen staining in this part of the section is that the original medium to heavy crude was emplaced laterally along-strike at a stratigraphic interval higher than that represented by the marl section. This unit, although Cretaceous, may be older than the McMurray Formation.



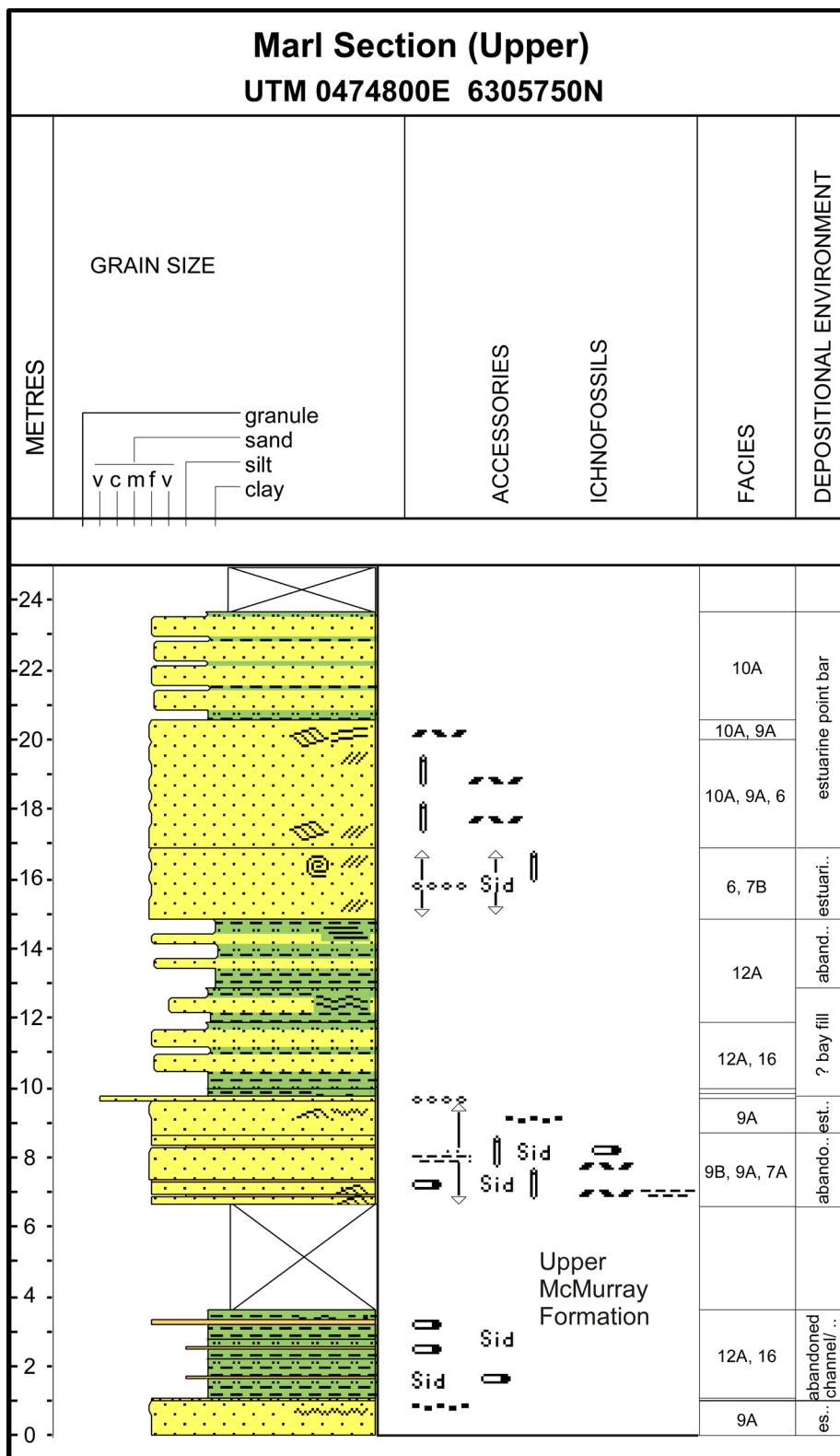


Figure 26D. Measured Marl upper section (from Hein et al., 2000).



Figure 27A. Marl section, Athabasca River, showing argillaceous limestone of the Devonian Waterways Formation overlain by fluvial marl deposits.



Figure 27B. Marl section, Athabasca River, showing marl deposit occupying a low on the sub-Cretaceous unconformity, Fluvial marl section.

8.2 Marl Upper Section

Map Coordinates: 74D/14 Wood Creek, Scale 1:50 000, UTM 0474800E, 6305750N

Location and Access: This section is approximately 18.2 km downstream from the confluence of the Athabasca and Clearwater rivers on the east bank of the Athabasca River near the mouth of McLean Creek (Figures 26A, 26B and 26D). From the Fluvial Marl Section continue along the east bank of the Athabasca River for a couple hundred metres and access a low terrace section via small gullies in the bank. The measured outcrop is behind the treed bank in a slumped cutbank about 100 m above the river level, and set back in the trees by about 70 m. This section is not easily seen from the river bank. The measured section starts approximately 13 m above the vegetated bank that sits above the Fluvial Marl Section.

Highlights:

- Even and horizontal bedding style alternating with wavy bedding.
- Large-scale convolute lamination and oversteepened crossbedding within thick cliff forming sands that laterally along-strike interfinger with mudstone deposits.

Description: In this steep outcrop (about 25 m high) is a largely inaccessible and partially slumped section of interbedded sand and mudstone. Toward the base, fine sand is interbedded with thin silty mudstone, partially burrowed and sideritized. Bedding is wavy with local coarse pebble lags. Sands are generally rippled throughout, and an isolated coal boulder clast occurs in the lowermost sand. Next is a covered, recessive, 3 m thick interval. Overlying the recessive unit, is a 7 m thick succession of bioturbated, fine to very fine sand, interbedded with silty mudstone. Bedding is wavy or even and horizontal, and bioturbation is more prominent toward the base, with mainly *Planolites* and *Skolithos* types. Mudstone intraclasts and thin mudstone breccias occur throughout the interbedded sand and mudstone units. Carbonaceous content is also high within these interbedded parts of the outcrop. The thick cliff-forming sands are about 6 m high, consisting of pebbly sand that fine upwards into fine to medium sand with dispersed mudstone intraclasts. Toward the base within the pebbly units, the sands are sideritized. Crossbedding is deformed and dewatering features and large-scale convolute laminations are common. Sands are bioturbated with *Skolithos* traces. Crossbedding includes planar-tabular and ripple drift. Toward the top of the cliff sands is sandy-inclined heterolithic stratification. Overlying the cliff-forming sands is an inaccessible, interbedded unit of grey sand and mudstone.

Interpretation: The pebbly and bioturbated sand at the base of the section is interpreted as high energy, estuarine channel deposits of the Upper McMurray succession. This is overlain by a very thick succession of stacked estuarine deposits. Some of these estuarine sands are massive, or show abundant crossbedding, and are interpreted as estuarine channel sands. Other sands occur with mudstone that interfinger with and/or are crosscut by the channel sands. Where accessible, these interbedded units are horizontally bedded and may be vertical, accretion-abandoned channel deposits.

8.3 Reservoir Analogues: Marl Section, Athabasca River

The slumped section of marly muddy sand, with interbedded carbonaceous mudstone and minor crossbedded granule sand, occupies a paleotopographic low on the pre-Cretaceous unconformity. It is also the oldest dated material within the outcrops studied in the Fort McMurray area. There is no bitumen staining, an abundance of organics and common siderite concretions. In the subsurface, such sediment would represent a lower water-sand succession, locally preserved within paleotopographic lows along

the sub-Cretaceous unconformity. Paleolows along the unconformity often contain water-bearing sands. These basal water sands most likely reflect paleo-water/oil contacts (Hein et al., 2000). The mixed clastic and carbonate paleovalley fills, including the marls and paleosols observed in this slumped section, are not well connected to one another, as shown by their patchy and unpredictable outcrop and subsurface occurrence.

For the most part, these units would be poor reservoirs. However, any associated water sands may significantly affect in situ steam production of overlying bitumen reservoirs, if horizontal injection and production wells intersect these paleotopographic lows (Hein et al., 2000). Other potential problems of production of reservoirs with associated marls relates to their high organic content, alteration of clays due to pedogenesis and later siderite cementation. Local mineralization (mainly sulphides, mostly pyrite) is common in sediments with higher organic concentration. Clays may present a migration of 'fines' problem, whereas the siderite, pyrite and other sulphides are acid sensitive to HCl. The marl has a high calcium carbonate content, and calcite tends to form scale with incompatible fluids (Hein et al., 2000). Siderite concretions may represent baffles to flow.

In core, the mottled sandy marl is represented by waxy, very carbonaceous sandy clay, which is overlain by organic, carbonaceous, silty mudstone (Figure 28). On geophysical logs, the marl is too thin for a 'carbonate' response; however, the log responses indicate a mud-dominated package (Figure 28).

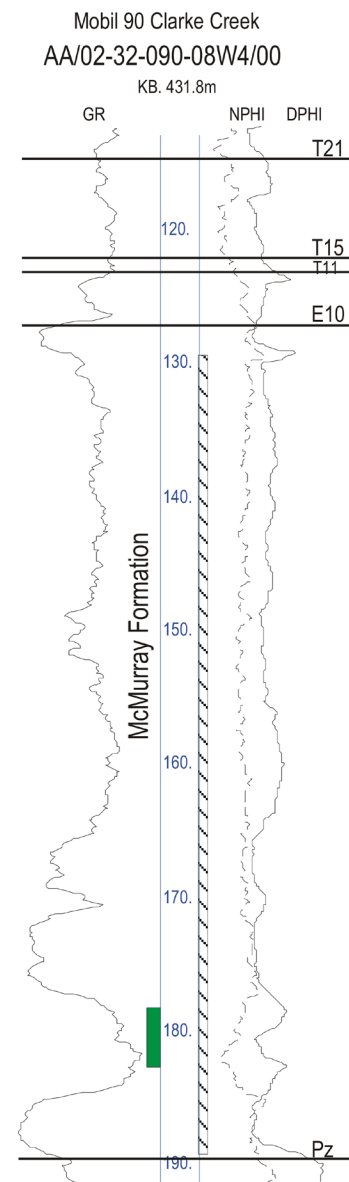
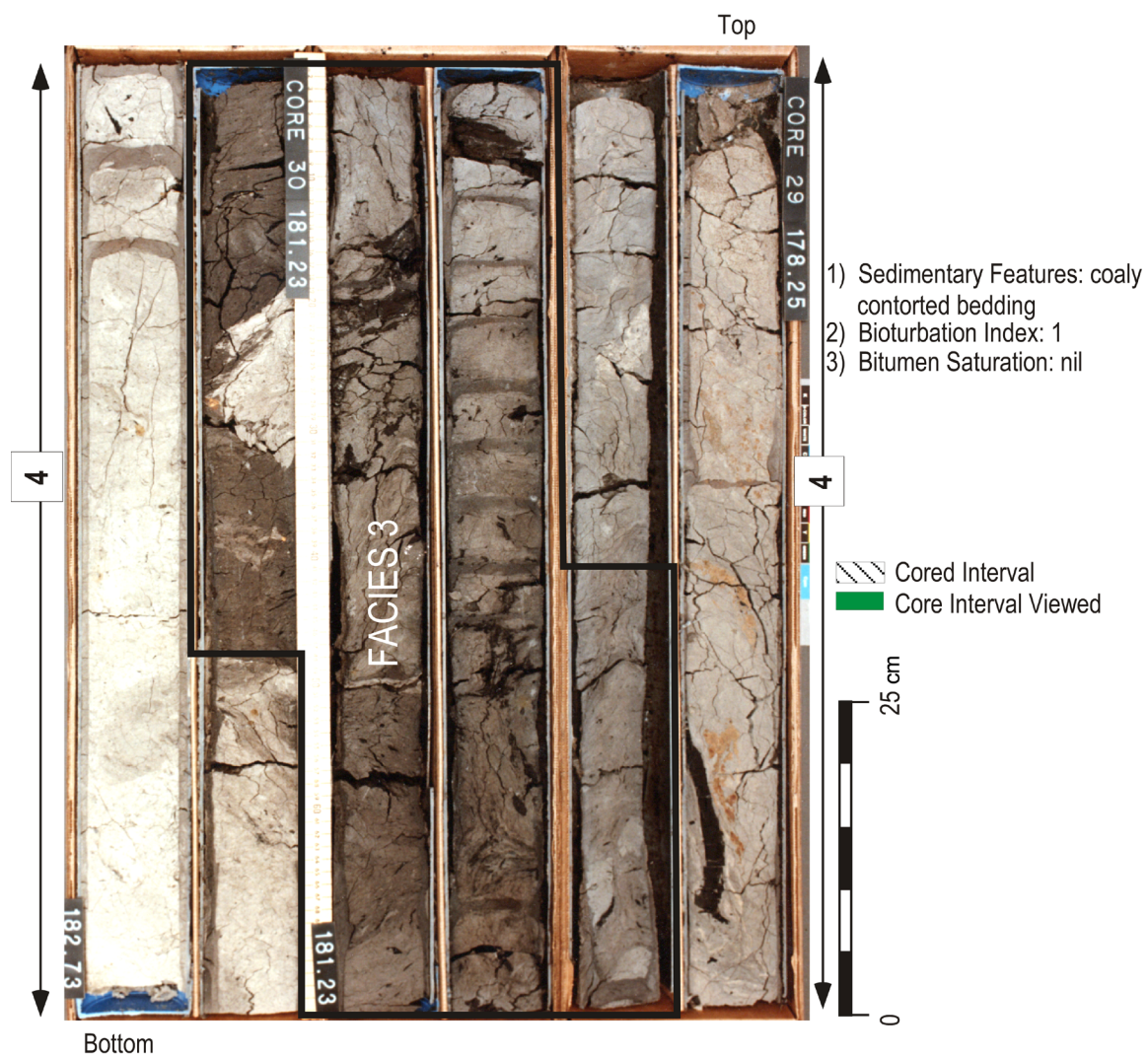


Figure 28. Core photographs and wireline logs of the Mobil 90 Clarke Creek well, location: AA/02-32-090-08W4.

9 Outcrop Descriptions: Day 1, Stop 3, Tar Island

9.1 Tar Island Fluvial Section

Map Coordinates: 74D/14 Wood Creek, Scale 1:50 000, UTM 0472210E, 6313710N

Location and Access: This section is approximately 0.5 km upstream (south) from the Tar Island tailings pond for the Suncor mine, along the western bank of the Athabasca River (Figures 29A and 29B).

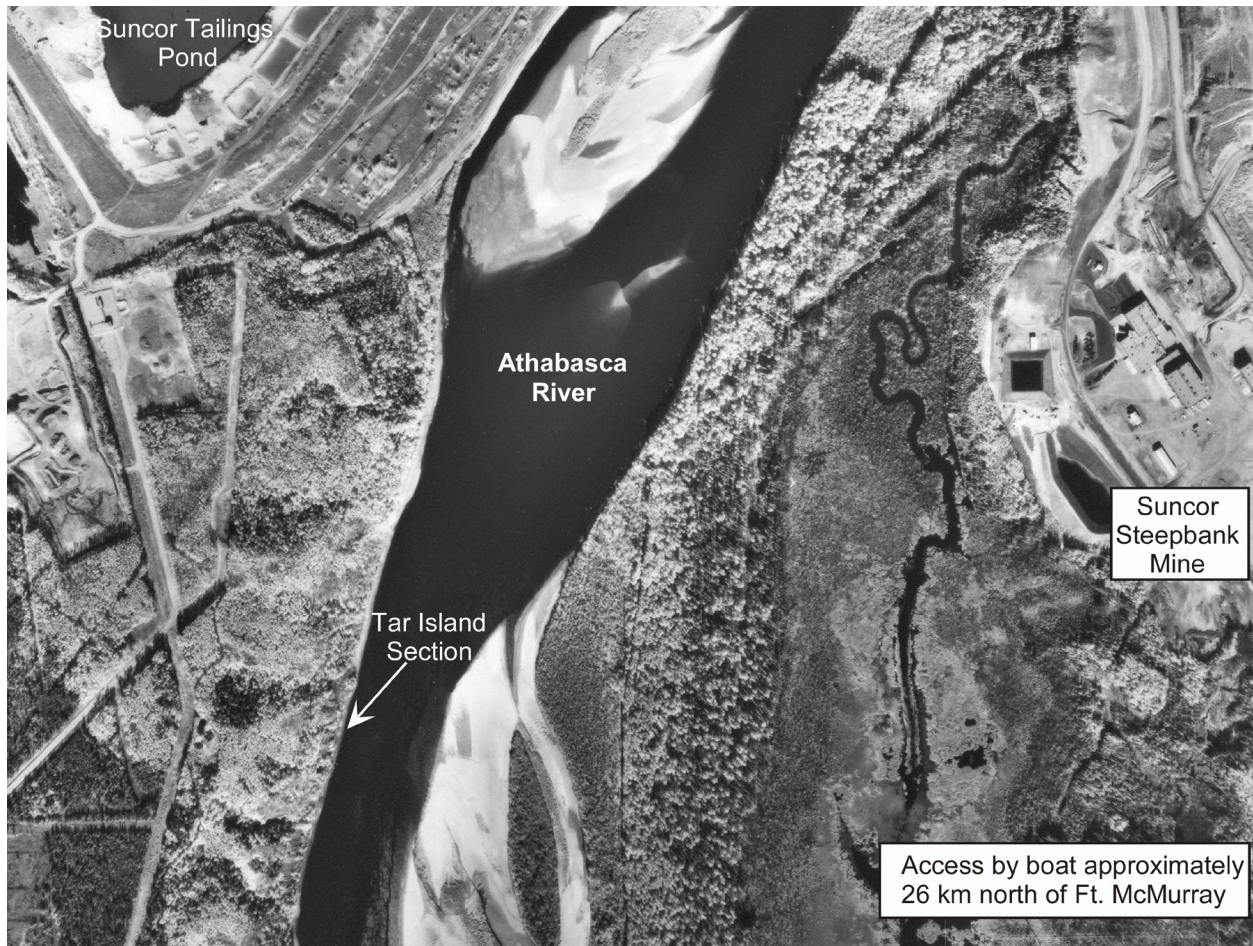


Figure 29A. Aerial photograph showing the location and description of the Tar Island section, Athabasca River.

Highlights:

- Sideritized and ironstone-cemented, mudstone-clasts, pebbly sands and conglomerate.
- Thick stacked, Lower McMurray fluvial channel pebbly sand and conglomerate with excellent planar-tabular and trough crossbeds.
- Unconformity between Lower McMurray and Upper McMurray successions, marked by a transgressive lag, overlain by estuarine channel and point-bar sands.
- Discordant contact between sideritized sands, clean white sands and bitumen saturated sand.

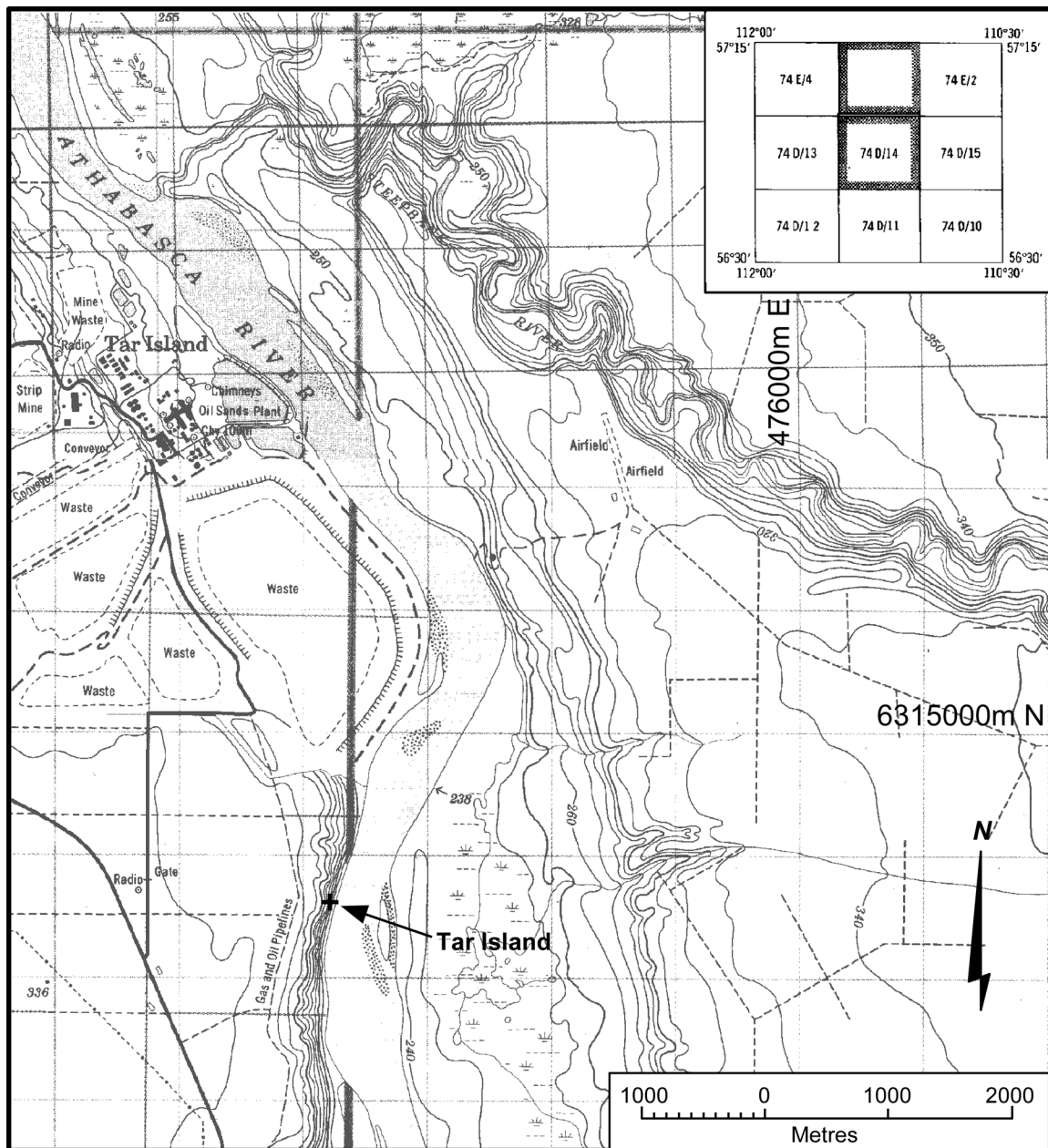


Figure 29B. Topographic map showing the location and description of the Tar Island section, Athabasca River.

Description: At this outcrop (about 9 m high), fluvial sediments are exposed at the base and are unconformably overlain by estuarine sediments (Figure 29C, 30A and 30F). Most notable in the section are the common occurrences of siderite cement and sideritized intraclasts within the fluvial channel deposits (Figures 30D, 30E and 30F), and a prominent conglomerate, up to 1-m thick, along the unconformable contact between the fluvial and estuarine units (Figures 30F and 30G). The conglomerate starts as a thin (single pebble thick) layer at the downstream end of the outcrop (or is absent), reaching its maximum at the upstream end of the outcrop. The conglomerate is poorly sorted, but does display a distinct upward fining. The clasts within the conglomerate tend to be fairly well rounded, and the lithologies are generally more resistant rock types, such as vein-quartz and quartz-pebbles. About half way upstream along the outcrop exposure is a prominent, discordant contact with the lower fluvial

Tar Island Fluvial Section UTM 0472210E 6313710N					
METRES	GRAIN SIZE v c m f v granule sand silt clay	BIOTURBATION INTENSITY	ACCESSORIES ICHOFOSSILS	FACIES	DEPOSITIONAL ENVIRONMENT

Figure 29C. Measured Tar Island fluvial section (from Hein et al., 2000).



Figure 30A. Coarse-grained, bitumen-free, fluvial trough crossbedded sand (Lower McMurray Formation), overlain by bitumen-saturated lateral accretion deposits of the Upper McMurray Tar Island fluvial section, Athabasca River.



Figure 30B. Overview of the basal oil-water contact with the Lower McMurray succession along the Tar Island fluvial section, Athabasca River.

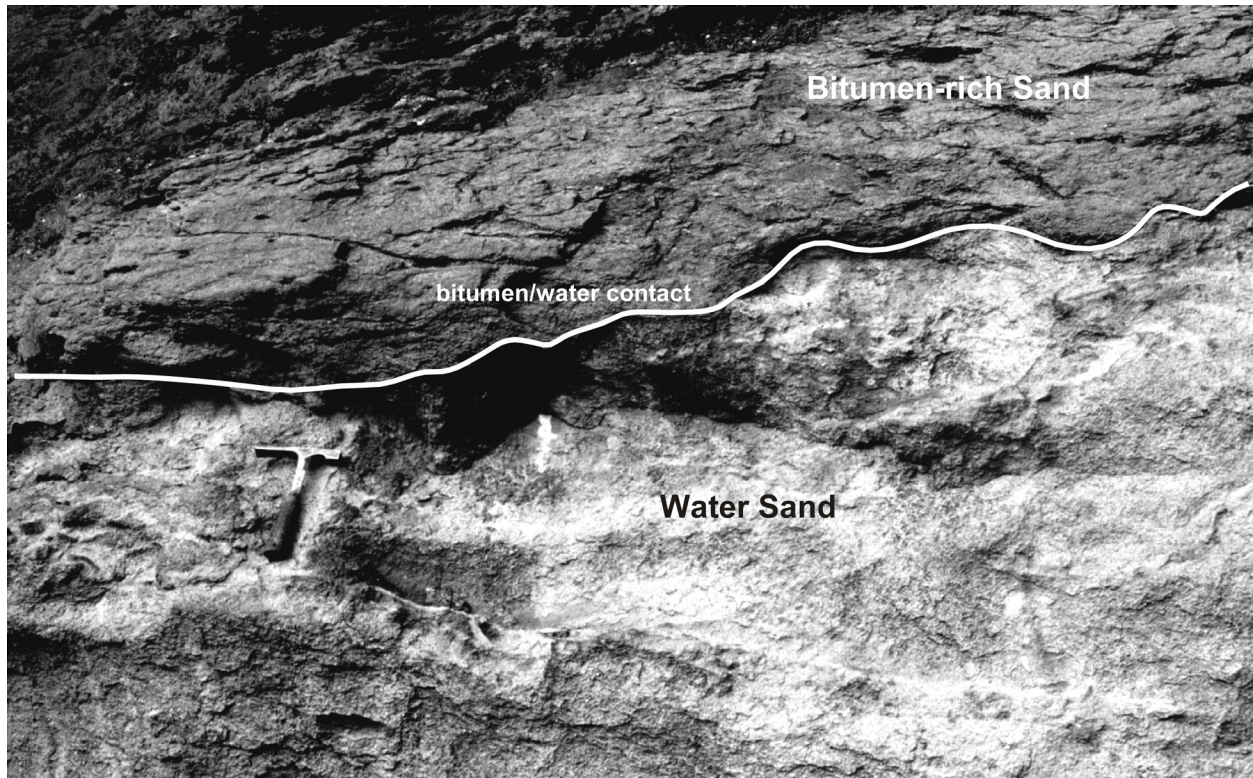


Figure 30C. Detailed view of the oil/water contact within coarse-grained fluvial deposit of the Lower McMurray Formation along the Tar Island fluvial section, Athabasca River.



Figure 30D. Trough crossbedded, coarse-grained sand with siderite clasts (Lower McMurray) along the Tar Island Fluvial Section, Athabasca River.

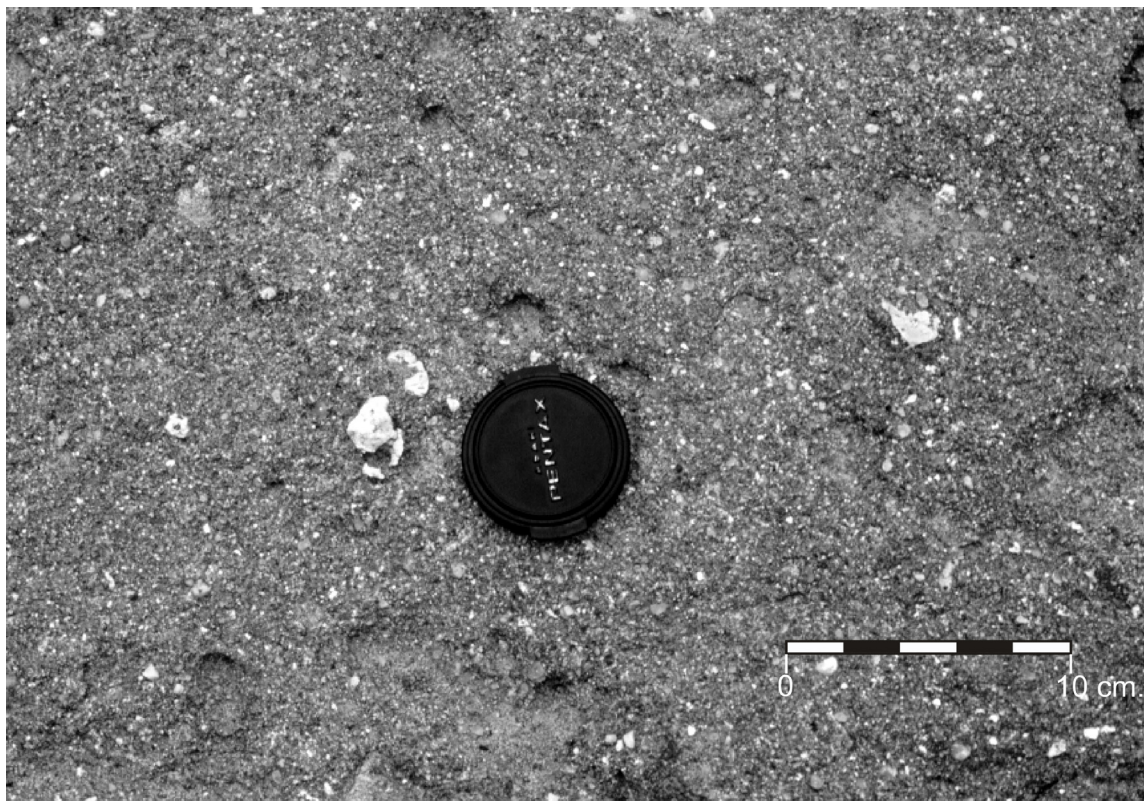


Figure 30E. Detailed view of poorly sorted, coarse to granular, gravelly, fluvial crossbedded sand (Lower McMurray) along the Tar Island fluvial section, Athabasca River.

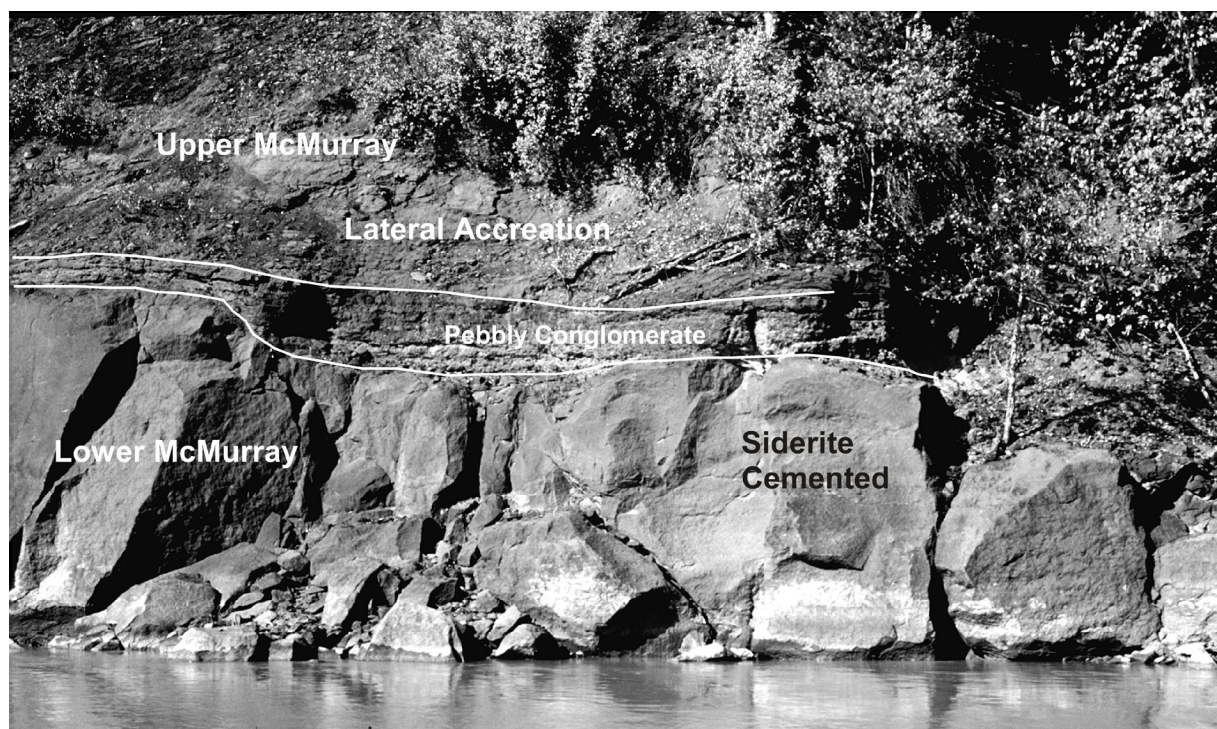


Figure 30F. Gravel separating siderite-cemented fluvial sand (Lower McMurray) from estuarine sands (Upper McMurray) along the Tar Island fluvial section, Athabasca River.

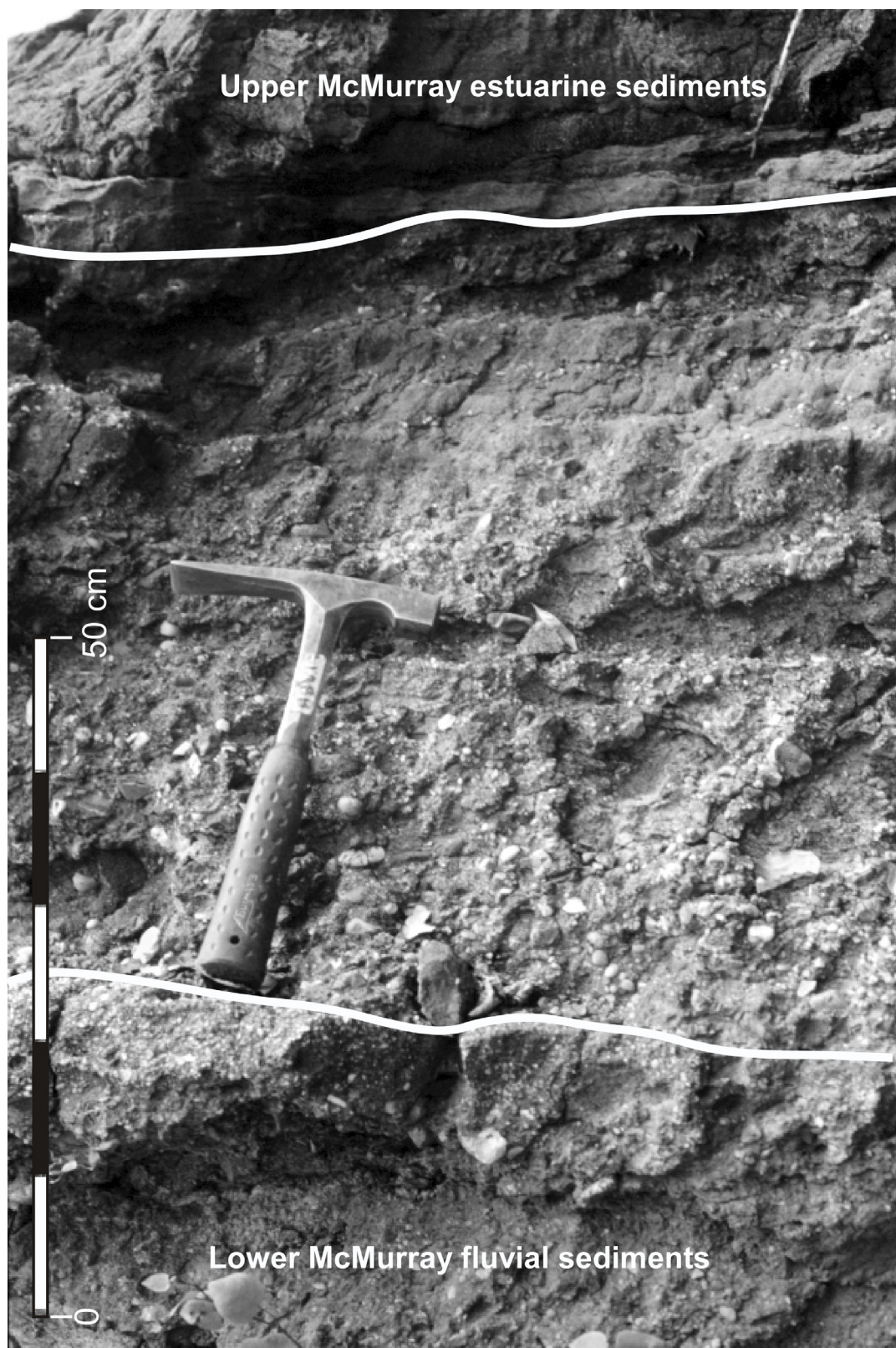


Figure 30G. Detailed view of the fining upward pebbly gravel (transgressive lag) separating coarse-grained, fluvial deposits (Lower McMurray) from fine-grained, estuarine deposits (Upper McMurray) along the Tar Island fluvial section, Athabasca River.

succession between the basal unconsolidated white sands and the bitumen-bearing oil sands (Figures 30B, 30C and 30F). Associated with this discordant contact is an apparent 'roll-front' as shown in the siderite-cemented unit (Figure 30B).

Interpretation: The conglomerate between the fluvial and estuarine deposits is interpreted as a transgressive lag above the unconformity, and is related to the onset of marine flooding in the area. This marine flooding emplaced the estuarine deposits of the Upper McMurray above the fluvial lowstand deposits of the Lower McMurray. It is possible this outcrop marks the original oil-water contact within the Lower McMurray sediment, prior to degradation of the oil to bitumen. As with the marl section, one hypothesis that might explain a lack of bitumen staining at the base of the section, below the sideritized roll-front, is that the original medium to heavy crude was emplaced laterally along-strike at a stratigraphic interval higher than that represented by the sideritized section. The sideritization may have occurred early in the history of the McMurray succession, and may have been the result of cementation associated with either connate or groundwater conditions.

9.2 Reservoir Analogues: Tar Island Fluvial Section, Athabasca River

At the Tar Island fluvial section, the lowermost fluvial gravel and pebbly sand remnants are preserved along a paleotopographic low along the unconformity. As shown in the outcrops, there are local basal water sands, that interfinger with the Lower McMurray bitumen sands, that may be interconnected along the bases of the main paleovalleys (Flach and Hein, 2001). As seen in this outcrop, the basal water sands may also be more localized. In core, the fluvial coarse gravel to pebbly sand may be bitumen saturated, with diffuse stratification and scattered intraclasts (Figure 31). On geophysical logs, this facies association is represented by a blocky to fining-up response (Figure 31). Minor disruptions to fluid flow within reservoir gravels/sands occur where there was sideritization of the dispersed mudstone clasts (Hein et al., 2000).

The oblique bitumen/water contact below the contact between the Lower and Upper McMurray may have reservoir implications to using bitumen/water contacts in mapping out individual reservoir bodies – as shown in this outcrop there can be significant variation in the contact even at an outcrop scale (Figures 30A, 30B, 30C and 30F).

The graded gravels of the transgressive lag separating the Lower and Upper McMurray successions would be excellent reservoirs, with very high porosity and permeability (Flach and Hein, 2000). However, exposure of this unit indicates it is of limited extent and likely difficult to map in the subsurface. As discussed by Hein et al. (2000), one of the more common occurrences of the graded gravelly facies is along the contact between the Lower and Upper McMurray, perhaps indicative of a rapid transgressive flooding event along the disconformity that separates the Lower fluvial lowstand from the Upper transgressive estuarine deposits. In some cases, this contact is difficult to pick because the gravelly Lower McMurray unit has been partially or completely reworked into the overlying Upper McMurray during transgression.

The Upper McMurray multistory estuarine/point-bar successions at this outcrop have a similar distribution of facies as seen at the McMurray Type section, and will not be discussed here.

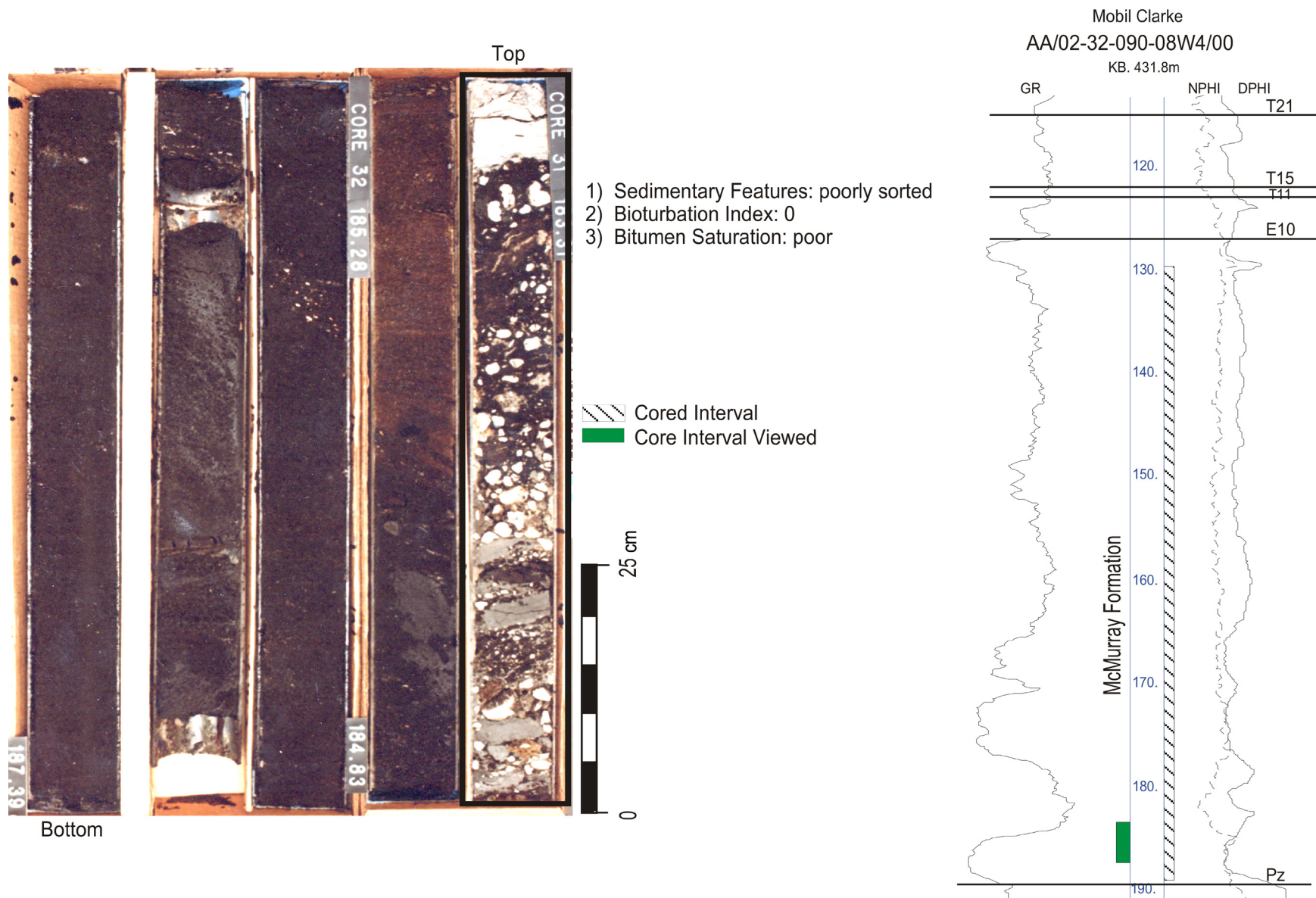


Figure 31. Core photographs and wireline logs of the Mobil Clarke well, location: AA/02-32-090-08W4.

10 MacKay River Sinkhole Sections Day 1, Stop 4

Note: Optional only done if high water level and accessible by boat.

10.1 MacKay River Karst-Fill #1 Section

Map Coordinates: 74E/4 Fort MacKay, Scale 1:50 000, UTM 0459500E, 6338650N

Location and Access: This outcrop is the cutbank section immediately downstream from the Amphitheatre #1 section on the opposite cutbank (Figures 32A and 32B).



Figure 32A. Aerial photograph showing the location and description of the MacKay River sinkhole sections.

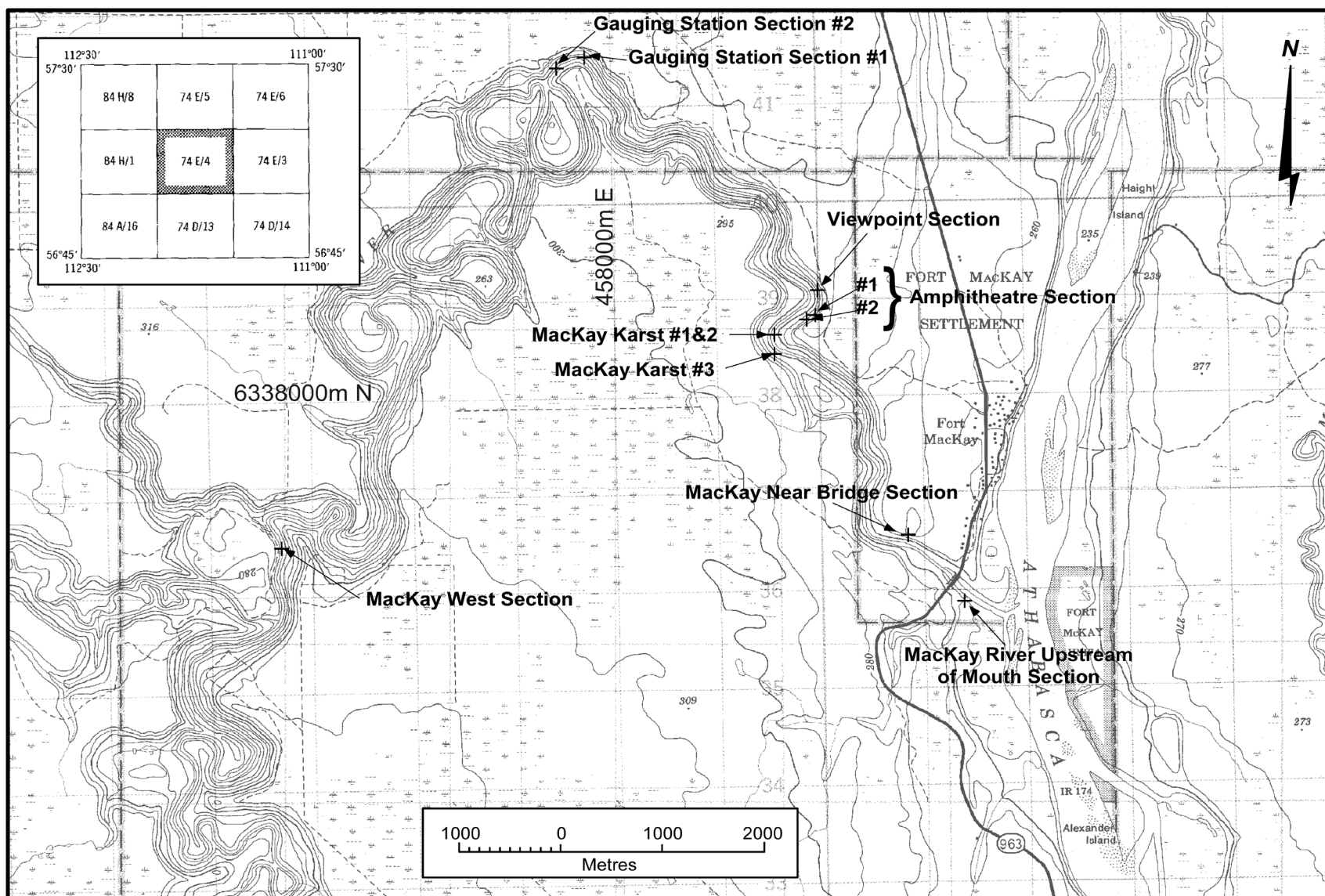


Figure 32B. Topographic map of the MacKay River sinkhole sections.

Highlights:

- Paleokarst fill.
- Sulphide mineralization and alteration of fractured sands.

Description: This measured section starts about 100 m downstream from a major karstic knob-and-hollow topographic feature along the sub-Cretaceous unconformity (Figures 33A, 33B and 33C). The upstream end of this outcrop section at this site is generally poorly exposed, with the lower half covered by slumping (Figure 33C). The downstream part starts at river level and exposes approximately 18 m of McMurray sediment (Figure 32C). Along the sub-Cretaceous unconformity, a vertical fault contact occurs between the McMurray oil sands and altered Devonian carbonates. Locally, green clay infill occurs within vertical fractures along the faulted contact between the Cretaceous and Devonian successions (Figure 33D).

The lowermost portion of the measured section consists of mottled, granular oil sand that is poorly to very poorly sorted and has abundant siderite nodules that contain sulphide mineralization. A rind brownish-red to pink sulphide mineralization, fractured and altered sand caps the basal unit. Overlying this alteration rind is a 6.75 m thick, highly fractured white sand that shows abundant mineralization of siderite and sulphide along fractures. This altered sand forms a local promontory along the cutback section (Figure 33C). Internally, the sand comprises altered medium to coarse-grained massive sand. Overlying the altered sand is a 4 m thick, upward fining succession that starts at the base with massive to trough crossbedded sand and gravel that contain abundant white, altered clay clasts randomly dispersed within the sand. Directly overlying the gravelly sand is organic fine to medium-grained sand with scattered pebbles. This unit is rippled to parallel laminated at the base and more massive at the top. Following this are approximately 1.7 m of carbonaceous mudstone and thin coals interbedded with coarse to fine-grained sand. Physical sedimentary structures, where developed, are dominantly parallel stratification, less commonly convolute lamination and rippling. A rooted 3 m cap of Quaternary colluvium disconformably overlies the McMurray succession at this site.

Interpretation: The section is interpreted as infill along a karstic sinkhole margin, marked by the altered promontory of sand. Internally, the features of the sediments appear to be Lower McMurray fluvial overlain by Upper McMurray open estuarine successions, capped by more organic rich coastal plain deposits in the upper half of the measured section.

10.2 MacKay River Karst-Fill #2 Section

Map Coordinates: 74E/4 Fort MacKay, Scale 1:50 000, UTM 0459500E, 6338650N

Location and Access: This outcrop section is approximately 25 m downstream from MacKay River Karst-Fill #1 section along the same cutbank exposure (Figures 32A and 32B).

Highlights:

- Paleokarst fill.
- Pebbly sands overlain by carbonaceous mudstone and coal.

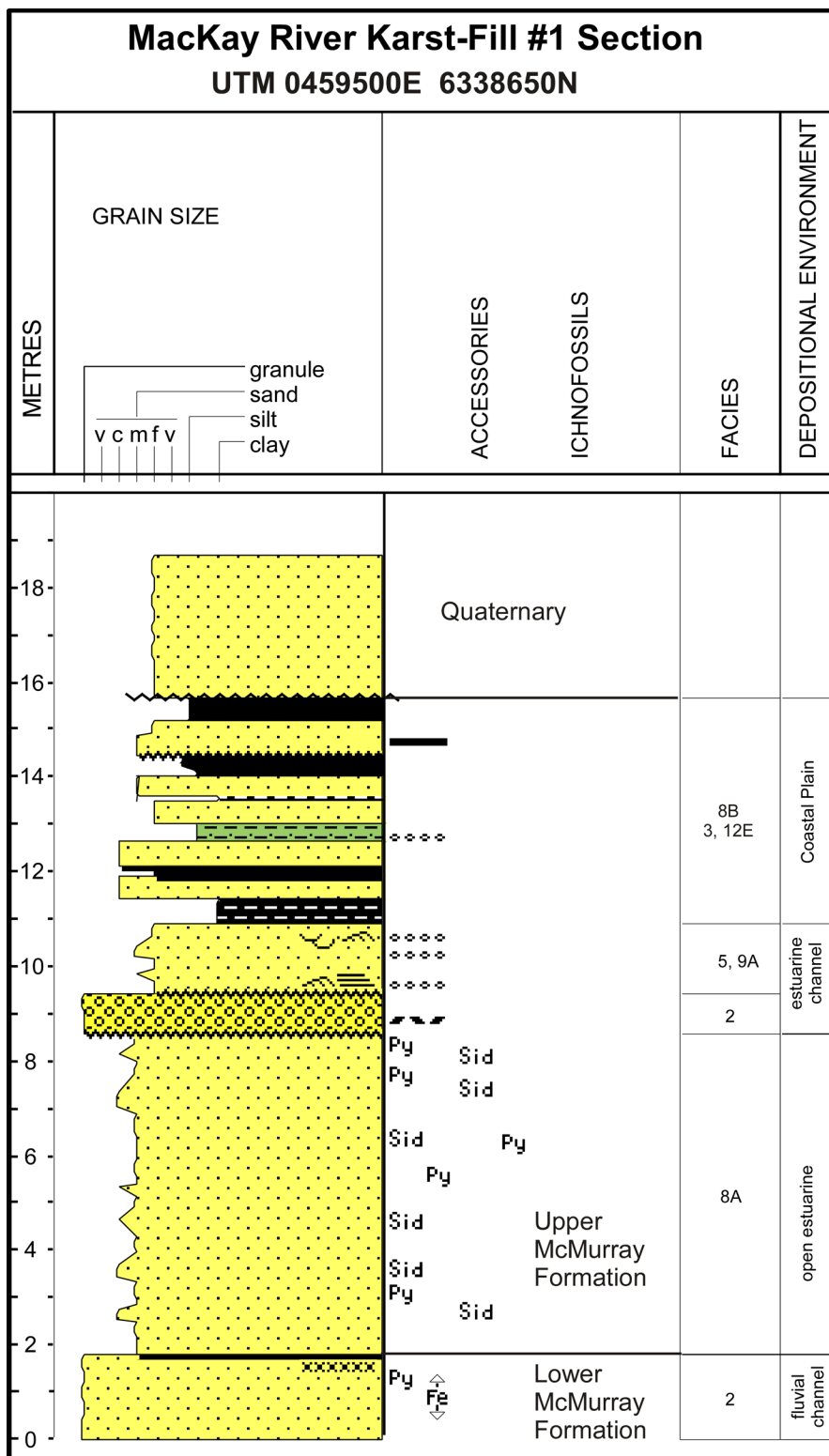


Figure 32C. Measured MacKay River Karst-Fill #1 Section along the MackKay River sinkhole sections.

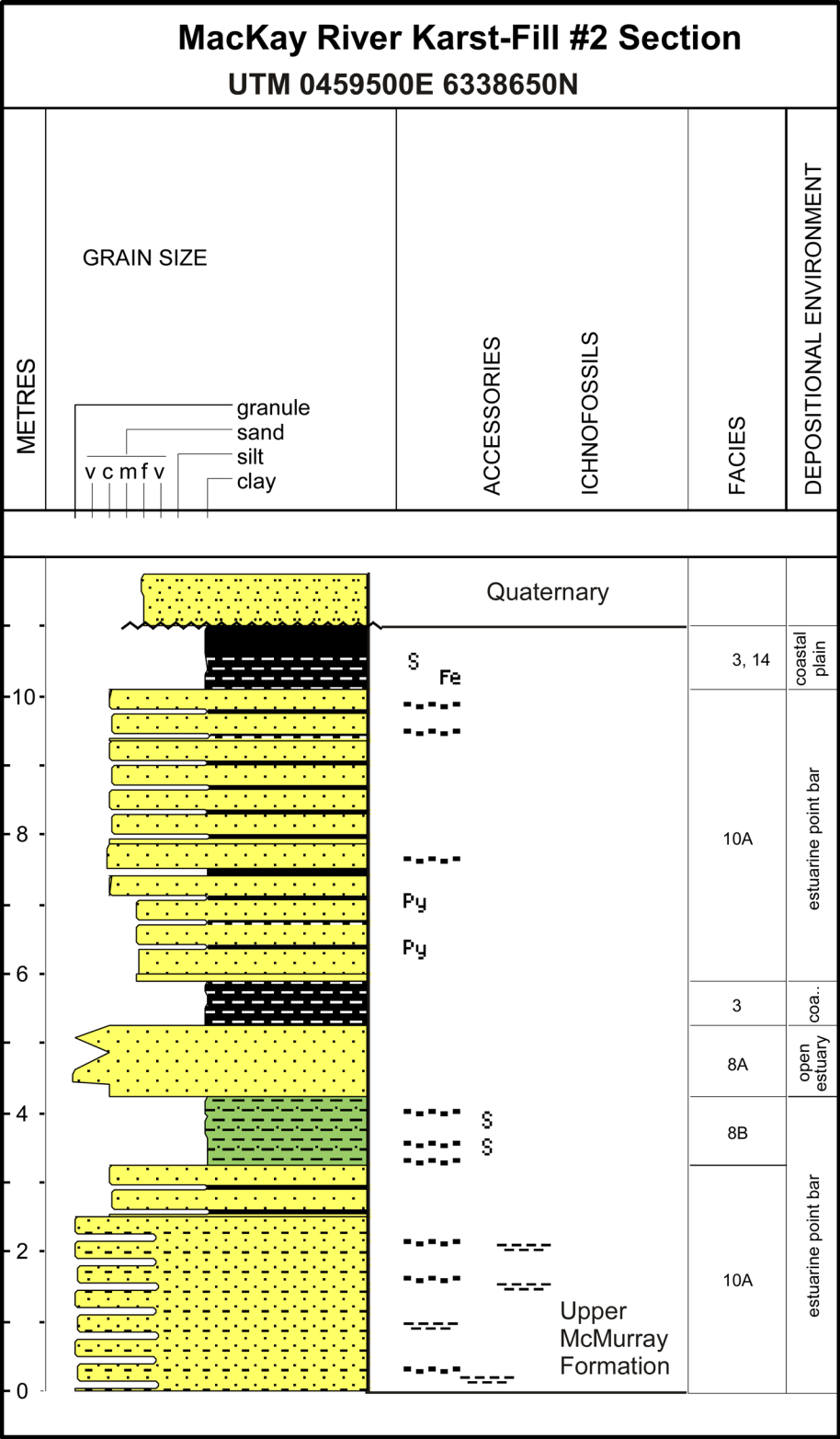


Figure 32D. Measured MacKay River Karst-Fill #2 Section along the MacKay River sinkhole sections.

MacKay River Karst-Fill #3 Section						
UTM 0459500E 6338450N						
METRES	GRAIN SIZE	BIOTURBATION INTENSITY	ACCESSORIES	ICHNOFOSSILS	FACIES	DEPOSITIONAL ENVIRONMENT
	granule sand silt clay v c m f v					
28					10A	sandy point bar
26					5	est.
24					10A	sandy point bar
22					12B	upper point bar
20					1	estuarine
18					6	estuarine
16					10A	sandy point bar
14					5	estuarine channel
12					2	flu.
10					1	flu.
8					10A	sandy point bar
6					5	estuarine channel
4					2	flu.
2					1	flu.
0					Upper McMurray Formation Lower McMurray Formation	

Figure 32E. Measured MacKay River Karst-Fill #3 (from Frein et al., 2000) along the MacKay River sinkhole sections.



Figure 33A. View about 100 m upstream from MacKay River Karst #1 Section showing the paleo-karst topography of the sub-Cretaceous unconformity, MacKay River sinkhole sections.



Figure 33B. Karst-fill feature (sinkhole at the base of the McMurray succession directly overlying the sub-Cretaceous unconformity, MacKay River sinkhole sections.



Figure 33C. Karst feature (sinkhole within the McMurray succession on the MacKay River (Karst Fill #1 Section).

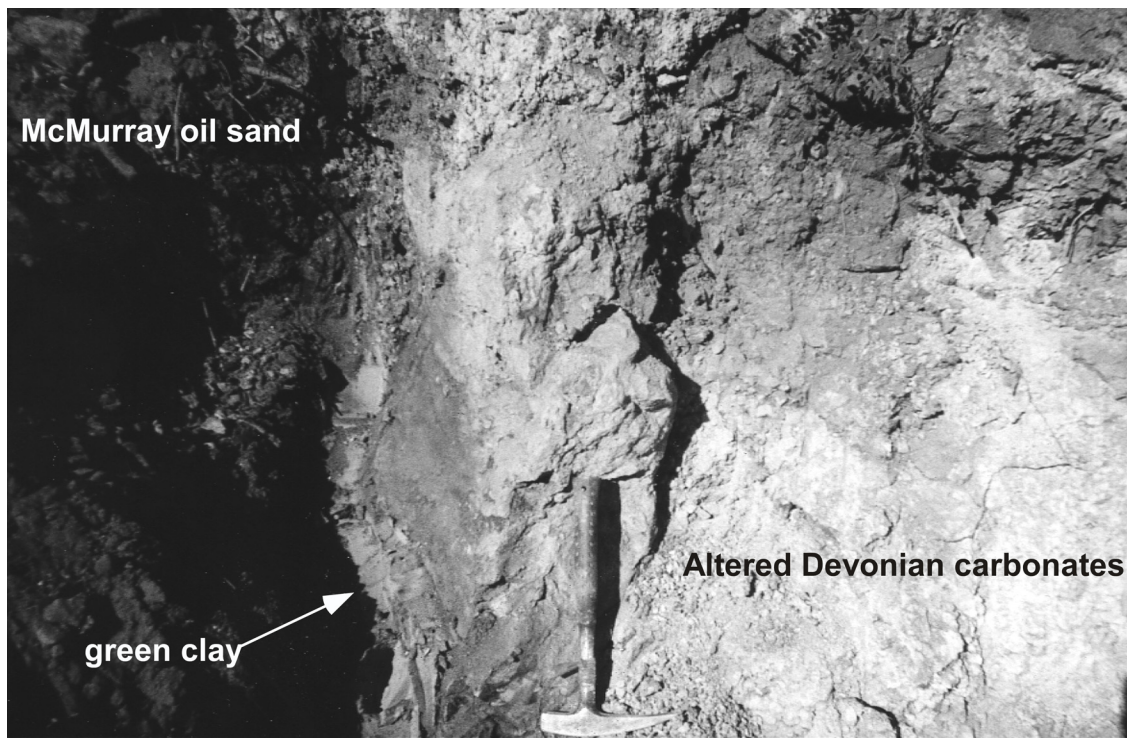


Figure 33D. Green clay lining along vertical-faulted contact between McMurray oil sand and altered Devonian carbonates (about 500 m upstream from MacKay River Karst-Fill #1 Section).

Description: The cutbank outcrop section at this site is generally poorly exposed, with the lower half covered by slumping. The section starts a few m above the river level, and exposes approximately 12 m of the McMurray succession (Figure 32D). The lowermost two to three m of this section consist of pebbly to granular sand that is poorly sorted and contains abundant reworked organic debris. Pebble and granular size material occurs throughout as thin pebble trains or along the bases of trough crossbeds. The pebble and granule material is subangular and dominantly quartz. Directly overlying the pebbly sand is a very organic, dark brown mudstone, with native sulphur and a flaky weathering pattern. Following this is approximately 3 m of carbonaceous mudstone and coals interbedded with quartzose coarse to fine-grained sand. The top 2 to 3 m of the outcrop consists of an upward-fining succession from coarse sand with abundant organic detritus, overlain by organic coarse sand with discontinuous coals, capped by a thick, dark brown, organic-rich carbonaceous mudstone and a coaly interval, that is iron stained and has native sulphur weathering out. Physical sedimentary structures are dominated by parallel stratification, less commonly convolute lamination and rippling. The McMurray succession at this site is disconformably overlain by a rooted 0.75 to 1 m cap of Quaternary colluvium.

Interpretation: The lower pebbly and granular sand is interpreted as coarse-grained alluvial fill, possibly fluvial input as karst-fill. Without palynological dating it is difficult to know the age of the fill; however, the abundance of muddy inclined heterolithic stratification is more typical of the Upper McMurray Formation. The coalbeds seem to be present over or around the margins of the karst sinkhole; this outcrop may be an analogue (although at a much smaller scale) to the development of the Firebag coal basin to the northwest, where significant coal is present within a heavily karsted area. In the Firebag River area, increased thickness of coals and carbonaceous material accumulated within paleokarstic sinkholes that were subsiding during sedimentation. A similar environment may be represented at this section, and by analogy to the Firebag section, the facies at this section are interpreted as organic-rich, vertical accretion deposits that may have been associated that accumulated within boggy paleotopographic lows along an actively subsiding karstic surface.

10.3 MacKay River Karst-Fill #3 Section

Map Coordinates: 74E/4 Fort MacKay, Scale 1:50 000, UTM 0459500E, 6338450N

Location and Access: This outcrop section is at the next cutbank section downstream and on the same side of the river as the cutbank exposure for the MacKay River Karst-Fill #1 and #2 sections (Figures 32A and 32B). Although karst features and sinkhole margins do not occur at this outcrop, its designation as Karst-Fill #3 Section indicates its close proximity and immediate downstream location to the Karst Fill #1 and #2 sections.

Highlights:

- Weathering profile with mineralization interpreted as the disconformity between the Lower and Upper McMurray Formation.
- Sand-dominated, low-angle, inclined heterolithic stratification, changing downstream along the outcrop into mud-dominated, low-angle, inclined heterolithic stratification.

Description: The cutbank outcrop section at this site is generally poorly exposed, with the lower half covered by slumping. The section starts about 15 m above the river level and exposes approximately 30 m of McMurray sediment (Figure 32E). At the upstream end of the outcrop is 25 m of sand and mudstone-dominated inclined heterolithic crossbedding. The coarser interbedded sands display planar-tabular and ripple crossbedding. About 100 m downstream is exposed a pebbly and granular sand that

is poorly sorted with vague trough crossbedding. Directly overlying the pebbly sand is a dark brown to dark-red/green brown weathering surface that may have been sideritized with sulphide mineralization, and is now highly weathered. Overlying beds are dominantly medium to coarse-grained sands, with scattered granule and pebble material and mudstone intraclasts. Physical sedimentary structures are very well developed and include trough crossbedding, wave and current ripple crossbedding, sand-dominated inclined heterolithic stratification and planar-tabular crossbedding. These crossbedded sands are the downstream lateral equivalents to the sand and mudstone-dominated inclined heterolithic crossbedding at the upstream end of the cutbank exposure. The sand-dominated inclined heterolithic stratification at the top of the section shows abundant crosscutting and sand-on-sand contacts. Approximately 100 m downstream the section grades into a mud-dominated inclined heterolithic-stratified unit within the top 1/3 of the outcrop. At the upstream end of the exposure the McMurray Formation is unconformably overlain by inaccessible, glauconitic Wabiskaw C sand, that downstream is cutout and unconformably overlain by Quaternary sediment.

10.4 Reservoir Analogues: Karst Fill Sections, MacKay River

As seen in the karst-fill sections along the MacKay River, the base of the McMurray Formation is marked by the regional unconformity that juxtaposes weathered, argillaceous Devonian carbonates against the siliciclastic sediments of the McMurray Formation (Figures 33A and 33B). Locally there is profound relief along this contact, with some of the McMurray oil sands infilling the paleokarst lows, and in other cases offlapping karstic paleohighs. It is difficult to predict reservoir geometry in areas of significant karstification. In some cases, synsedimentary tectonics has also been involved with the salt-dissolution, downdropping reservoir sands into fault-bounded 'mini-graben' structures and, in other cases, folding the successions into syncline-anticline pairs. On a small scale, synsedimentary slumps and faults may also affect the McMurray reservoirs.

Other complicating factors include the leaching of carbonates and clays, mineralization of sulphides (mainly pyrite), as well as sideritization along the unconformity. The carbonate erosional surface often displays a weathered profile that penetrates a few metres into the Devonian limestone. The karst features observed in the outcrop include isolated sinkholes, larger depressed regions and local karst breccias (Hein et al., 2000).

Due to the marked contrast in lithologies across the unconformity surface, on logs the unconformable contact can usually be easily picked, unless there is significant karstification and infill of clastics down into the cavities within the Devonian carbonates (compare Figures 34, 35 and 36). In cases where the Cretaceous marl sits upon Devonian carbonate, the contact is impossible to discern on logs, and the pick must be done in core. Cores cut through sinkholes display alternating units of collapsed carbonate breccia and karst-infill calci/siliciclastic sediments that may be overturned, brecciated and supported within a calcareous muddy matrix (Figures 35, 36).

Mixed clastic/carbonate paleokarst fills along the unconformity are not well connected and would be poor reservoirs (Hein et al., 2000). The main effect of the karstification in the subsurface is in the unpredictability of recognition and mapping of the carbonate bedrock and the potential of some bitumen sands to be outliers as karst-fill lower down in the section, below the unconformity. Altered clays and mineralization along the unconformity may affect fluid flow in the subsurface by creating migration of 'fines' problems and reducing the permeability of potential reservoirs, as well as being local baffles to fluid flow. Calcite within carbonate clasts and matrix may form scale with incompatible fluids (Hein et al., 2000).

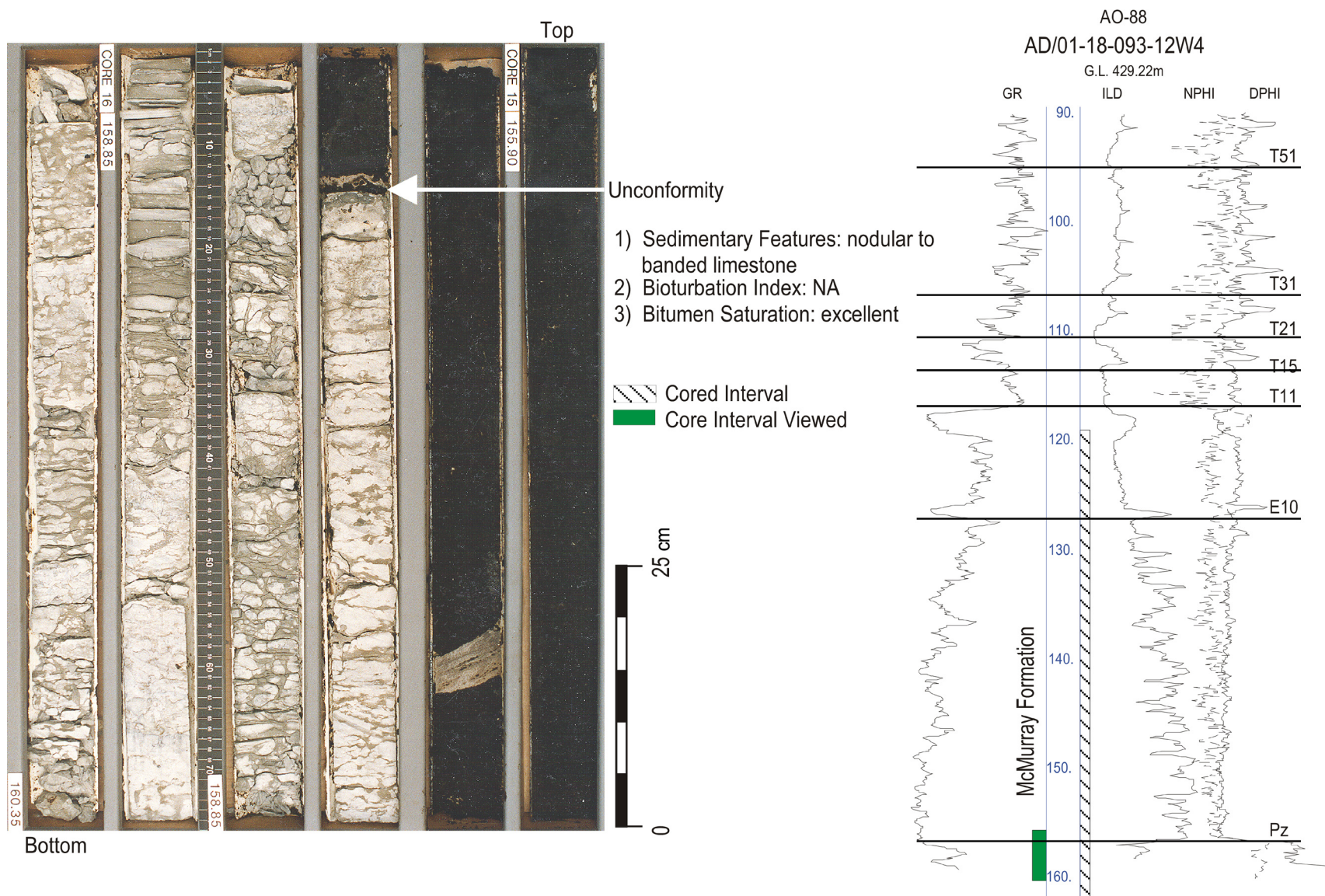


Figure 34. Core photographs and wireline logs of the UTF site AO-88 well, location: AD/01-18-093-12W4.

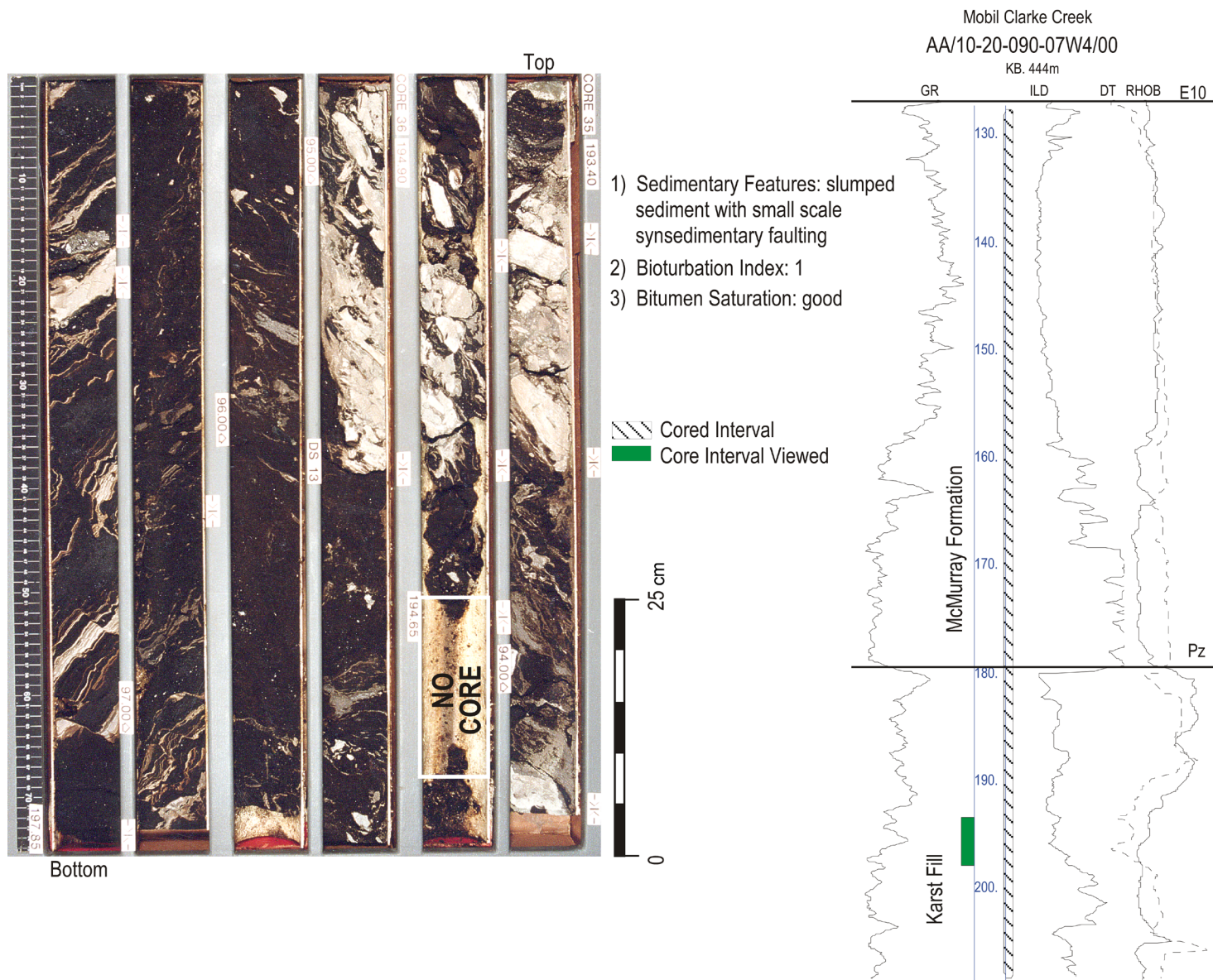


Figure 36. Core photographs and wireline logs of the Mobil Clarke Creek well, location:AA/10-20-090-07W4.

11 MacKay River Amphitheatre, Day 1, Stop 5

Note: Optional if high water level and accessible by boat; if low water this stop will be done on Day 3, Stop 11, by van and road access.

11.1 MacKay River Amphitheatre Sections

Map Coordinates: 74E/4 Fort MacKay, Scale 1:50 000, UTM 0459500E, 6338650N

Location and Access: These outcrop sections comprise the large, double cutbank immediately upstream from the MacKay River Karst-Fill #1 section on the north side of the river (Figures 37A and 37B).



Figure 37A. Aerial photograph of the MacKay River amphitheatre sections.

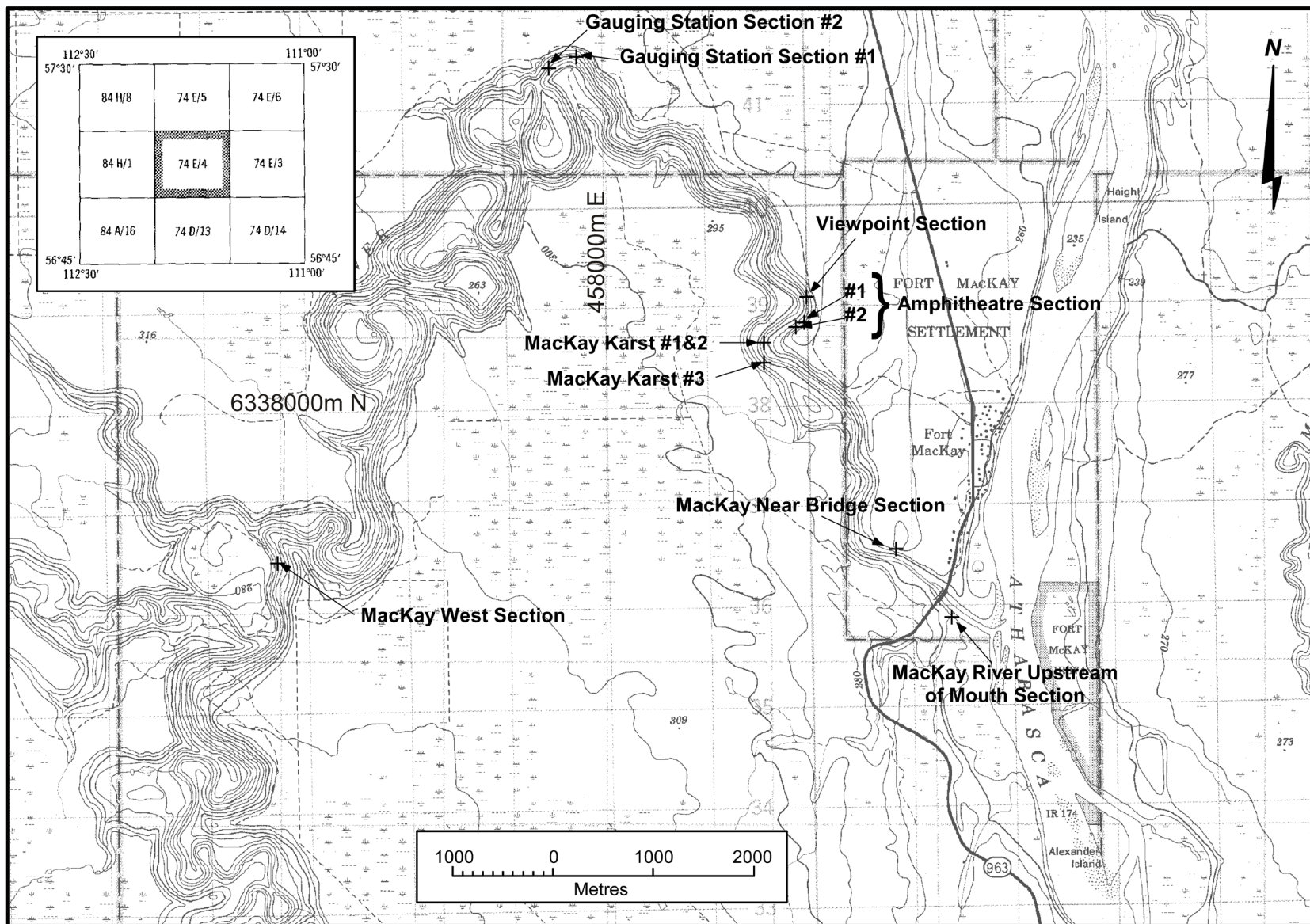


Figure 37B. Topographic map of the MacKay River amphitheatre sections.

Highlights:

- Excellent burrow structures in the float.
- Thick, muddy, vertical accretion, abandoned channel-fill deposits.
- Tidal channel and tidal flat sediments.
- Glacial-scour and thrust contacts between the Quaternary and McMurray units.

Description: At the very base of the amphitheatre section along the MacKay River is a thick succession of poorly exposed, organic shaly siltstone and coaly siltstone/shale within a paleokarst low along the pre-Cretaceous unconformity (due to very poor outcrop exposure this occurrence was not measured). The overlying contact with the more typical coarse-grained channel facies of the Lower McMurray Formation is covered (Figures 37C, 38A). Most of this outcrop exposes dominantly fine-grained sand, with high-angle planar-tabular, trough and ripple crossbedding structures and bioturbation features (Figures 38A-38I). *Cylindrichnus* burrows, both in place and as resedimented mudstone intraclasts, are common (Figures 38G and 38H). Rare resedimented coaly detritus, as coalified and mummified stems and logs, occur about half way upsection (Figure 38B), but mainly within the inaccessible cliff faces.

Capping the burrowed sands is a succession of interbedded sand and mudstone (Figures 37C and 38A), with intense bioturbation consisting of predominantly *Cylindrichnus* and *Teichichnus* trace fossils. The contact with the underlying sediments is sharp, often containing isolated siderite blocks and coalified logs and coaly laminae (Figure 38B). Where accessible, grey, fine-grained bioturbated sands that show parallel lamination with ripple structures overlie the interbedded and bioturbated fine-grained interval, and minor ironstone (siderite) cementation associated with coaly detritus. The unit becomes muddier upsection, with sands showing current-rippled, wave ripple, combined-flow and herringbone structures. The bedding style of this uppermost unit is very even, has a high degree of bioturbation and high amount of interbedded fines.

Low cliffs strike along the valley wall at the southern end of the amphitheatre outcrop exposure. This section starts fairly high uphill (about 2/3 the way upslope) from river level. Here is exposed part of the upper portion of the section that is generally inaccessible within the main amphitheatre outcrop, and is called the Amphitheatre #2 Section (Figure 37D). A thick succession of sands dominates the section (Figure 38C), comprising stacked, 'pin-striped,' high-angle planar-tabular and herringbone (Figure 38F) crossbedded facies (Figures 38D and 38E), some of which have been deformed into oversteepened crossbedding or large-scale convolutions (Figure 38I). Flows are predominantly to the north. The trace fossils include *Skolithos*, *Cylindrichnus*, escape burrows and reworked *Cylindrichnus* burrows as intraclasts derived from underlying estuarine point-bar deposits (Figures 38G and 38H). At the top of the section, the burrowed sands are disconformably overlain by a thin (4 m) grey, muddy, fine-grained sand that is thin bedded with an even-bedding style, and is intensely burrowed with traces similar to those in the upper portion of the main amphitheatre section (mainly *Cylindrichnus* and *Teichichnus*). Wightman et al. (1992) reported sea anemone trace fossils and escape burrows were found at this outcrop.

Interpretation: The organic section that was not measured at the base of the main amphitheatre outcrop is a remnant of the Lower McMurray succession. Most of the amphitheatre outcrop exposure is interpreted as part of the Upper McMurray estuarine channel system, with less common lateral accretion estuarine point-bar deposits, interbedded with the channel sands. At the top of the Amphitheatre #1 Section, the fine-grained muddy interval with a high degree of bioturbation and continuous, even bedding style is indicative of a vertical accretion, possibly an abandonment fill or tidal flat deposit. The 'pin-striped' sands located in the Amphitheatre #2 Section are inferred to be part of a tidal channel complex, including flooded estuarine, vertical accretion, abandoned channel deposits and tidal bars within estuarine open-bay settings.

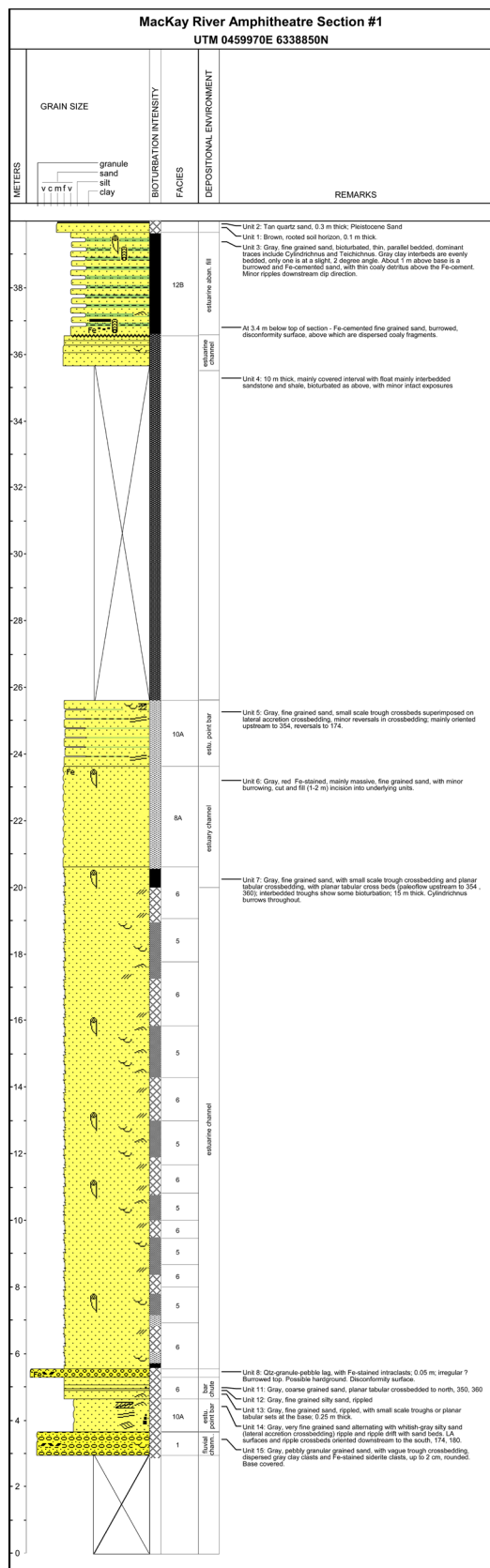


Figure 37C. Measured Amphitheatre #1 Section of the MacKay River amphitheatre sections.

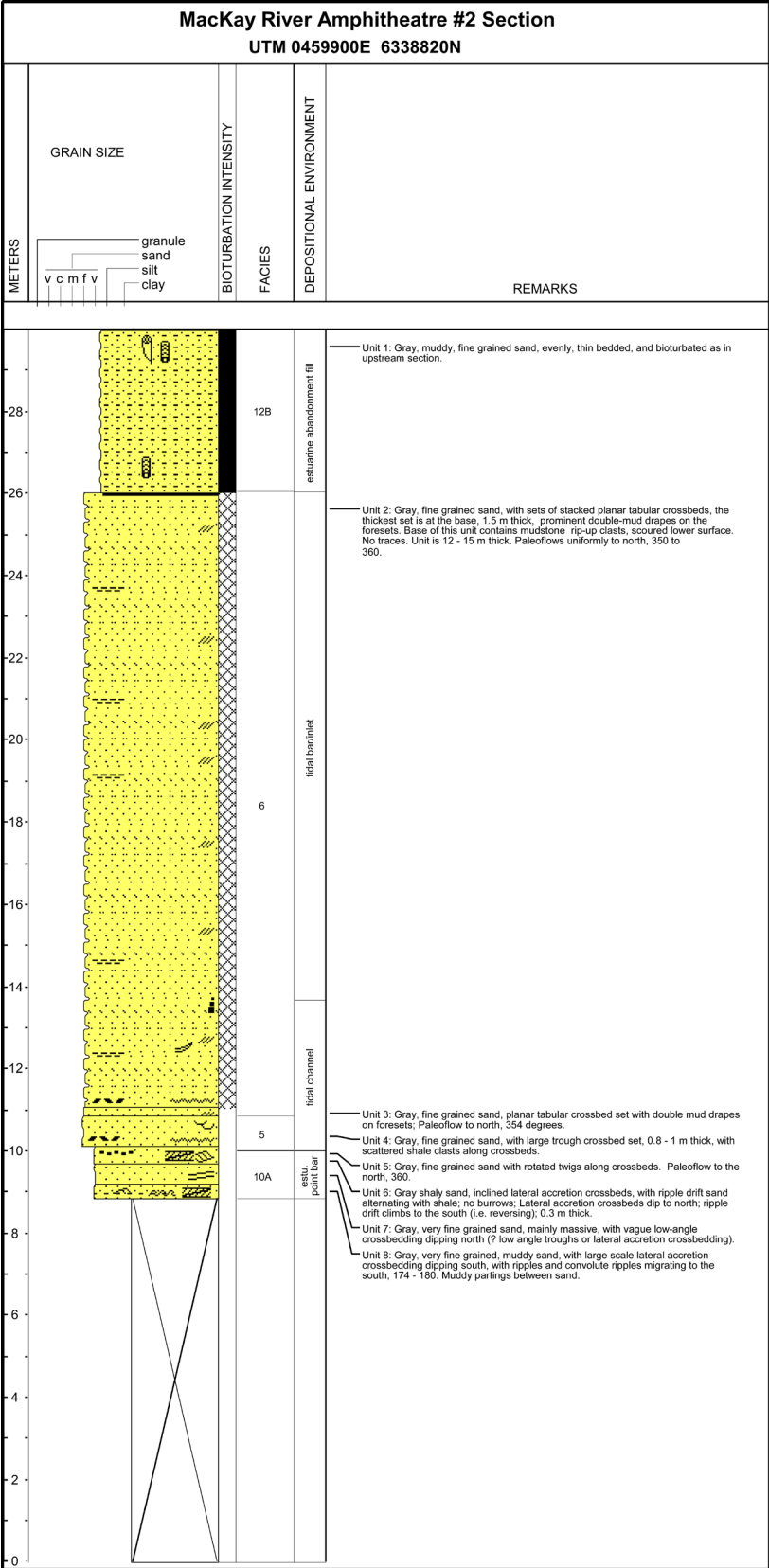


Figure 37D. Measured Amphitheatre #2 Section (from Hein et al., 2000) of the MacKay River amphitheatre sections.



Figure 38A. Southern limit of the Amphitheatre Section #1 of the MacKay River Amphitheatre Section #1.

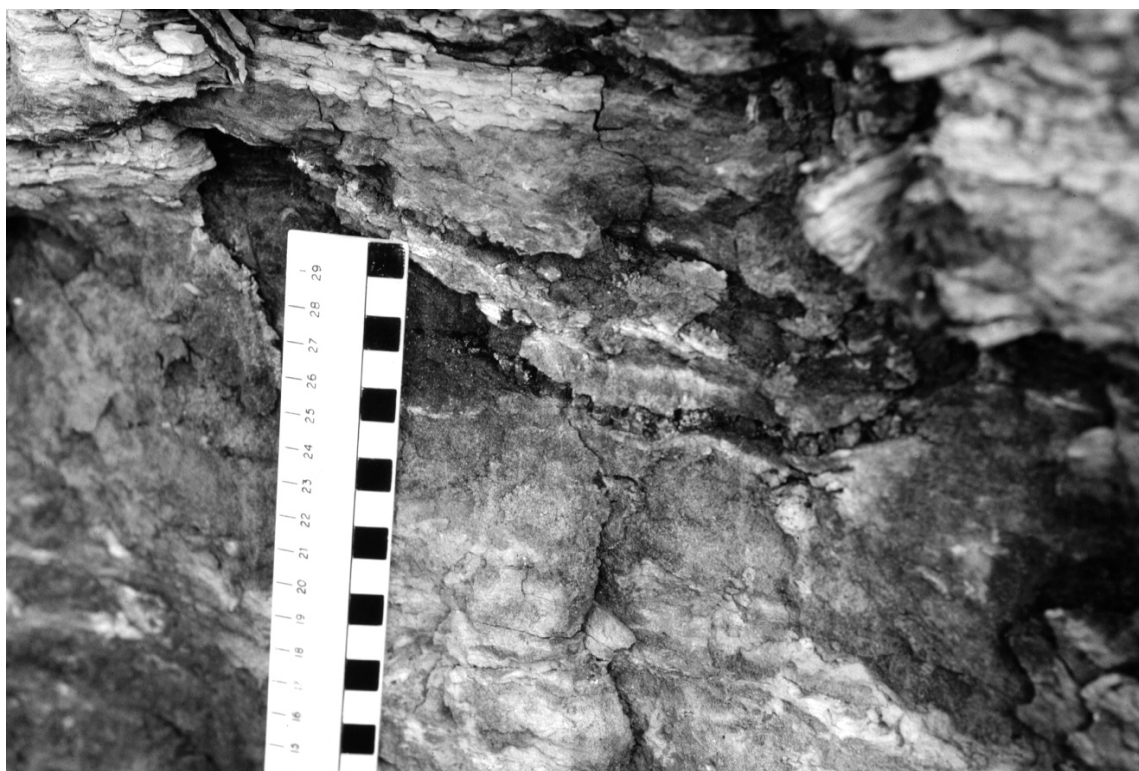


Figure 38B. Coaly debris intermixed with mud and sand at the base of the abandonment-fill unit of the MacKay River Amphitheatre Section #1.



Figure 38C. Large-scale, trough crossbedded sand of the MacKay River Amphitheatre Section #1.

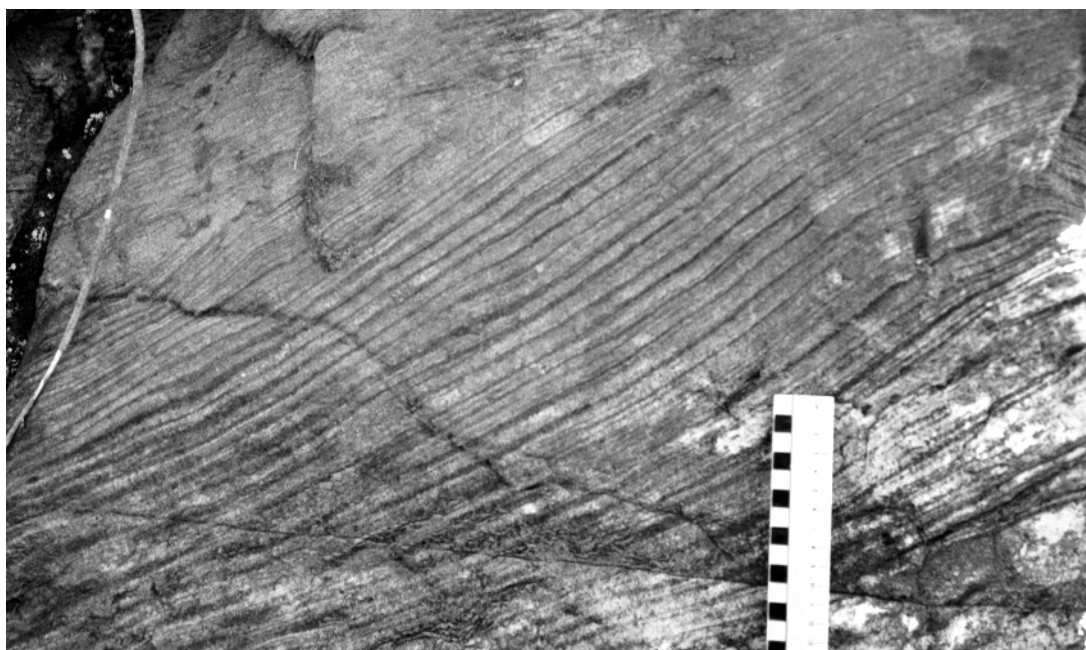


Figure 38D. Pin-striped, high-angle, planar-tabular to tangential crossbedding, slightly oversteepened at the MacKay River Amphitheatre Section #1.

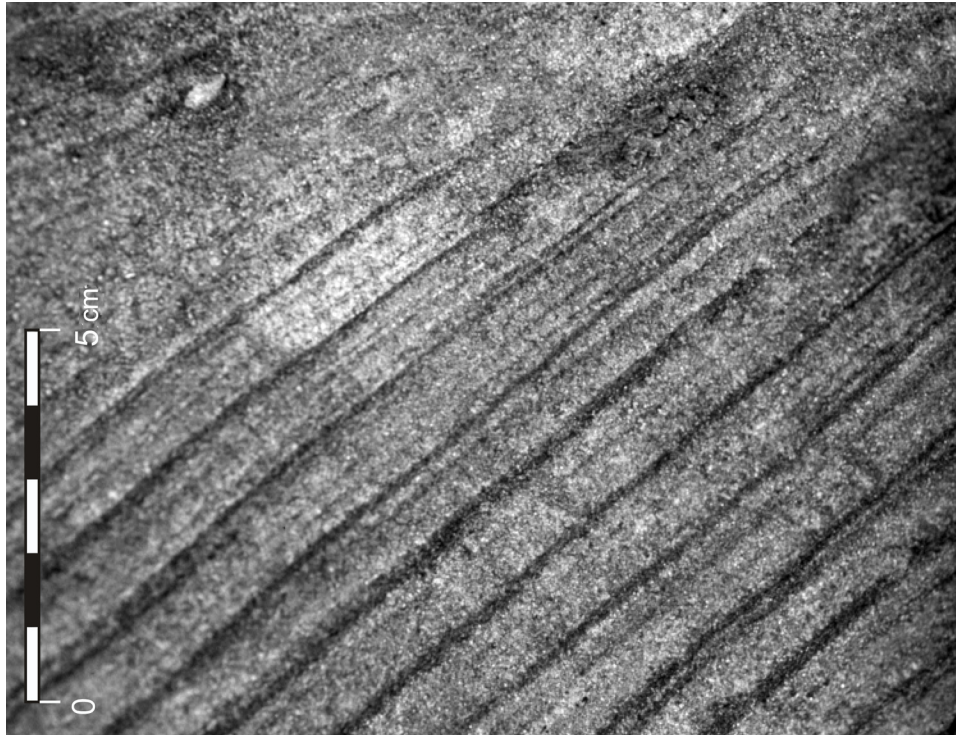


Figure 38E. Detail of planar-tabular cross-lamination of the MacKay River Amphitheatre Section #1.



Figure 38F. Large-scale planar-tabular crossbedding with alternation of paleocurrent directions, minor convolute lamination along crossbeds at the MacKay River Amphitheatre Section #1.

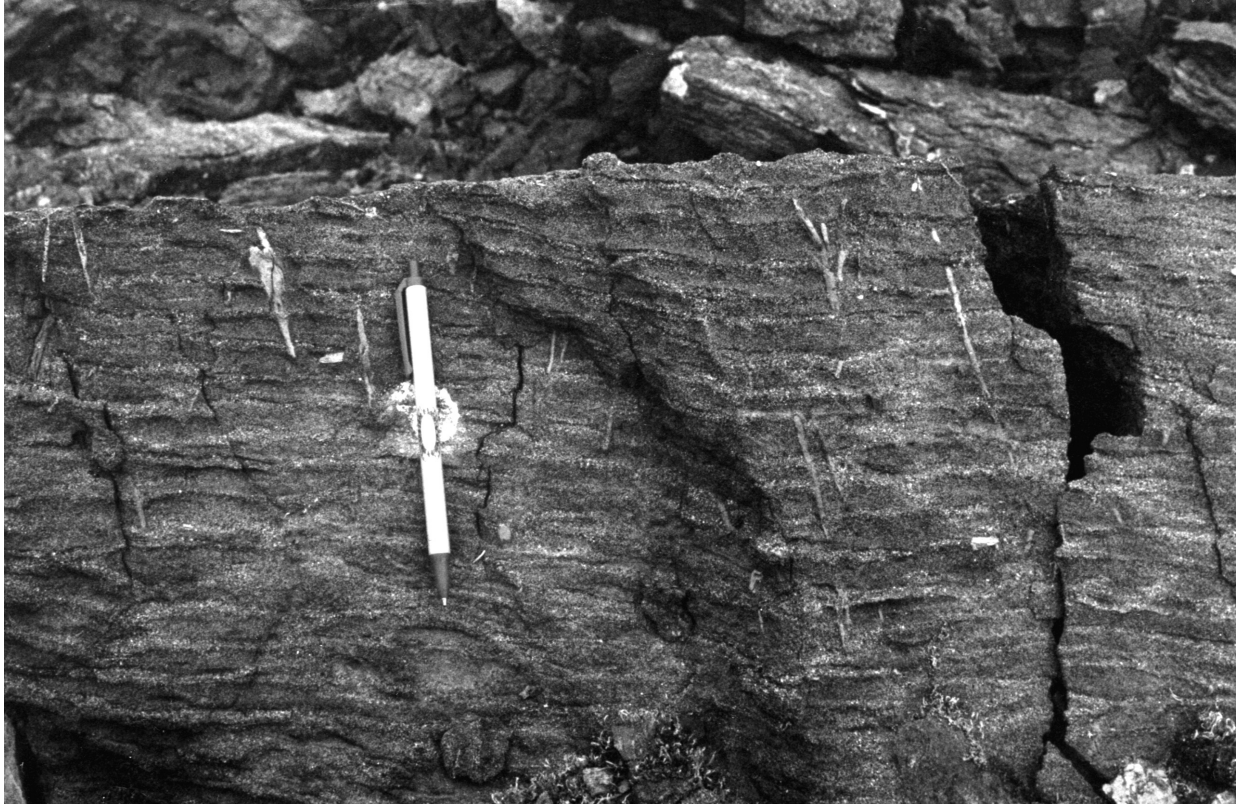


Figure 38G. *Skolithos*, *Cylindrichnus* and escape burrows crosscutting small scale trough crossbedding in medium to coarse sand at the MacKay River Amphitheatre Section #1.

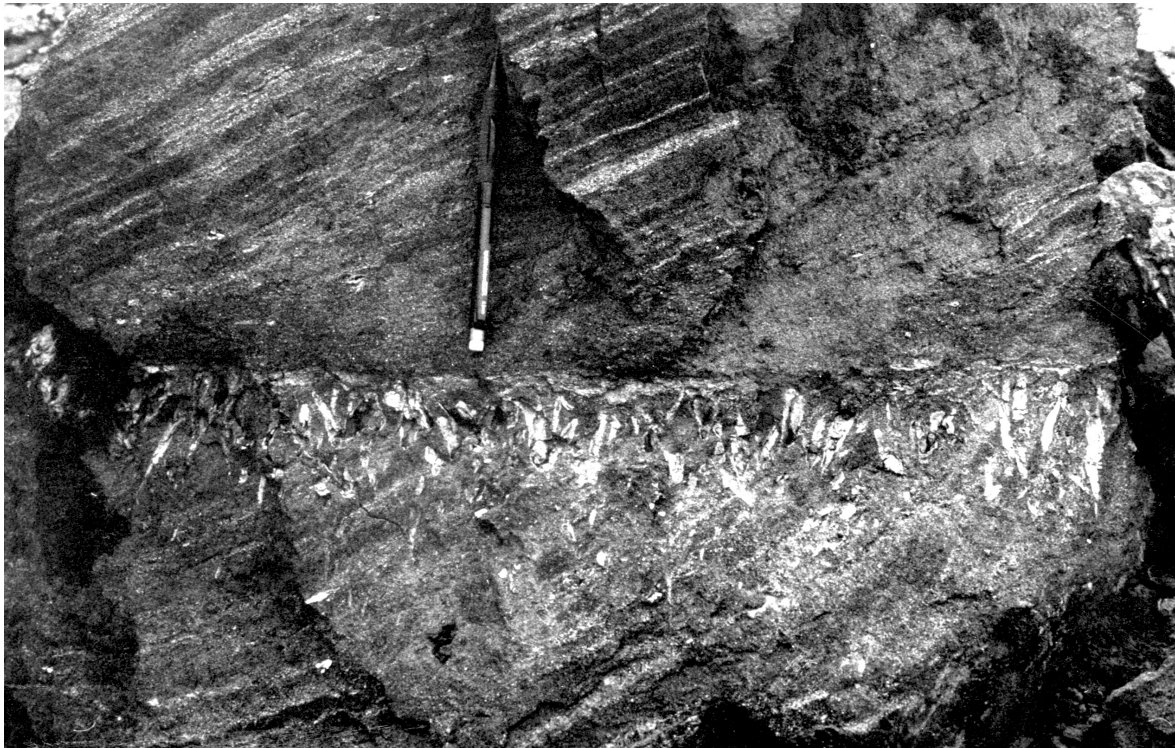


Figure 38H. Mud-filled *Cylindrichnus* burrows crosscutting oversteepened planar-tabular crossbedded medium to coarse sand at the MacKay River Amphitheatre Section #1.



Figure 38I. Large-scale convolute lamination due to dewatering of crossbedded sand at the MacKay River Amphitheatre Section #1 (from Hein et al., 2000).

11.2 Reservoir Analogues: Amphitheatre Sections, MacKay River

At the amphitheatre section the lowermost coals and overbank sediments are preserved along a paleotopographic low along the unconformity. These sediments are water bearing, and mapping by Flach and Hein (2001) shows that the local basal water sands may be interconnected along the bases of the main paleovalleys in the Fort MacKay–Ells River area. As seen in this outcrop, the basal water sands may also be more localized and the fine-grained floodplain sediments and coals would be poor reservoirs and, because of their location within a paleokarst low, would have poor connectivity to the overlying bitumen reservoirs.

The regionally thick, apparently connected water sands and the other smaller, isolated water sands as seen at the base of the Amphitheatre are significant within the Lower McMurray succession (Hein et al., 2000). Along the north-trending main valley much of the Lower McMurray is water saturated, where locally the water sands may exceed 50 m in thickness (Flach, 1984; Wightman et al., 1995). These water sands, mapped at a regional scale of four wells per township, appear to be a well connected network. Outside the main valley trend, water-bearing sand tends to occupy the karstic lows on the sub-Cretaceous unconformity. Water sands, particularly within the main valley, may significantly affect potential in situ steam-assisted bitumen production in the overlying bitumen reservoirs (Hein et al., 2000).

The Upper McMurray multistory estuarine/point-bar successions at the Amphitheatre Section #1 have a similar facies distribution as seen at the McMurray Type Section, and these will not be discussed here. What differs from other outcrops at the amphitheatre outcrop is the the open-estuarine tidal complex at the eastern edge of the outcrop in the Amphitheatre #2 Section. Here, composite, tidal-influenced sand packages are > 10 m thick. These very thick amalgamated packages are likely part of a less confined, high-energy, open estuarine system that is locally preserved. The stacked sands have very good porosity and permeability and because of their thickness would form excellent reservoirs. The laterally adjacent, vertical accretion fine-grained deposits at the top of the Amphitheatre #1 Section are discontinuous and do not form a continuous cap to the eastern reservoir sands, and thus, are not expected to be a barrier to fluid flow in the subsurface (Hein et al., 2000).

In core, it may be difficult to recognize the tidal complex without very detailed mapping in areas of close core spacing. Because of the narrow diameter of core, it may not be possible to discern the tidal master bedding as seen in outcrop, and in areas of heavy bitumen saturation the tidal couplets may be masked. Additionally, in core it is difficult to differentiate planar-tangential and planar-tabular crossbeds from trough crossbeds. What may be seen in core is likely flaser bedding on higher-scale master bedding surfaces, and with mudstone clasts marking amalgamation surfaces (Figure 39). Geophysical log responses would show a mainly blocky or slightly coarsening-upward succession (Figure 39). The well developed convolute lamination and ball-and-pillow structures seen in outcrop would be represented in core by convolute lamination, syndimentary folds and/or over-steepened crossbedding (Figure 40).

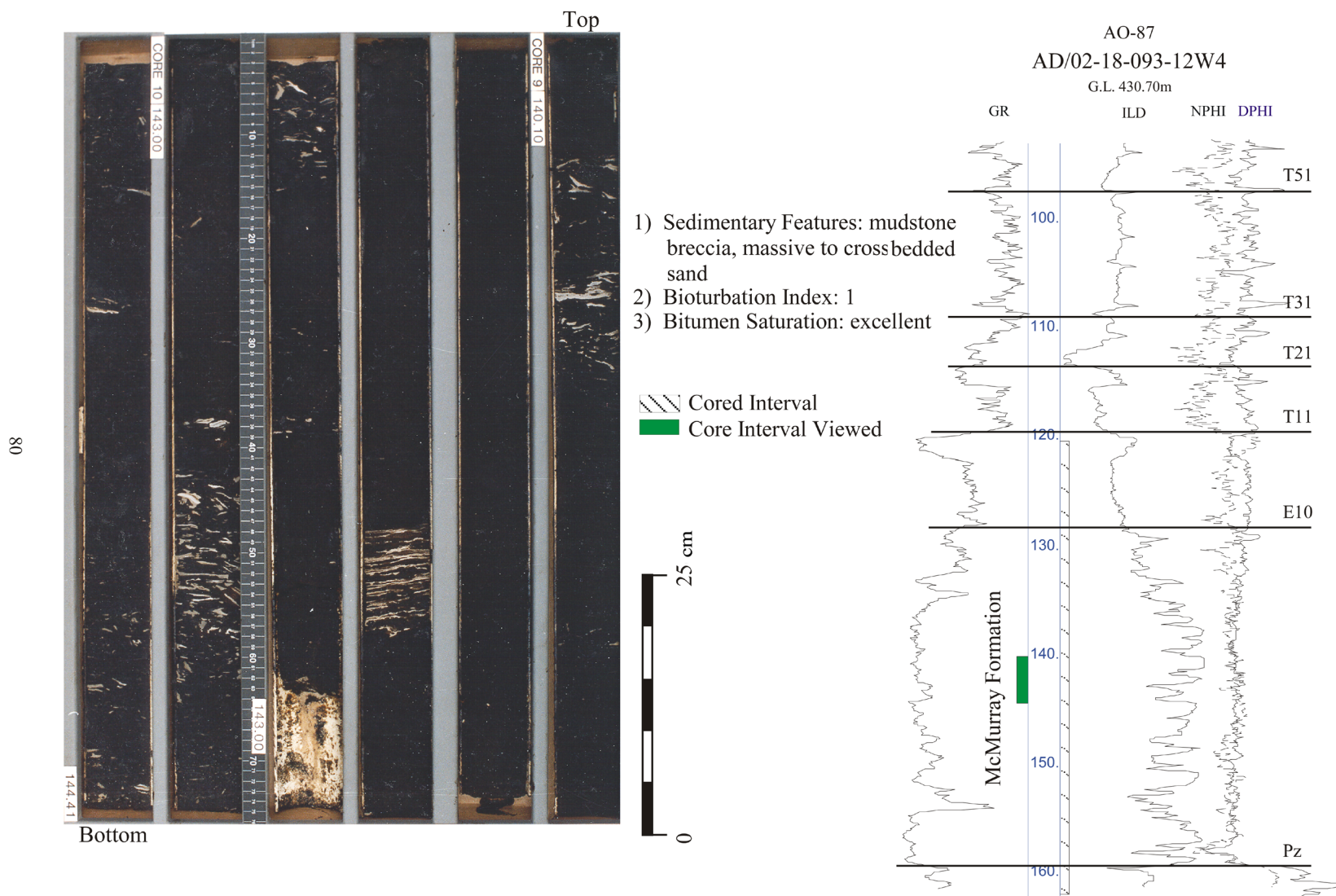


Figure 39. Core photographs and wireline logs of the UTF site AO-87, location: AD/02-18-093-12W4.

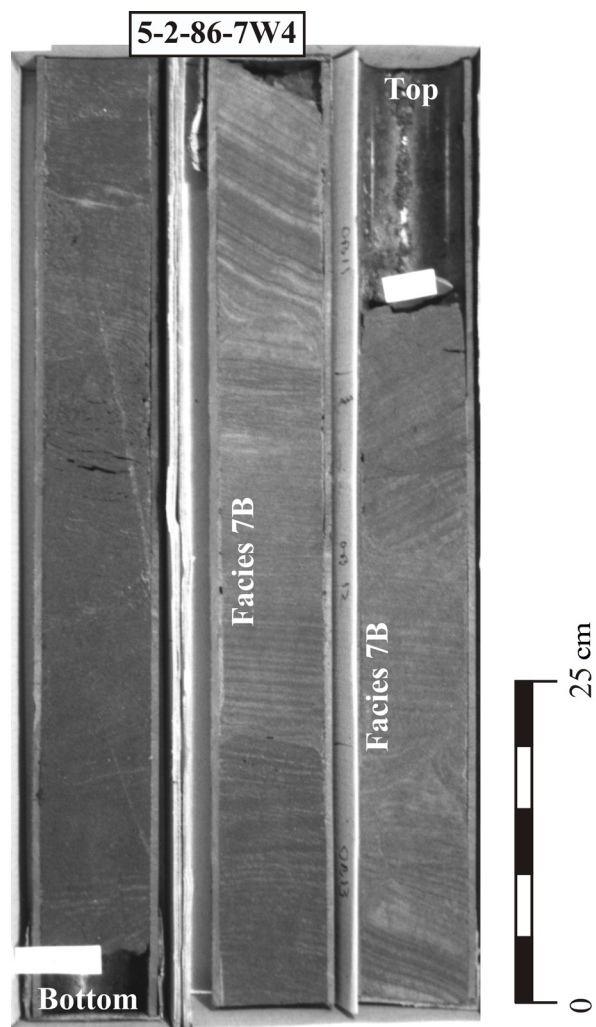


Figure 40. Core photograph of Opti/Nexen well, location: 00/05-02-086-07W4.

12 Outcrop Descriptions: Daphne Island, Day 2, Stop 6

12.1 Daphne Island West Section

Map Coordinates: 74E/5 Bitumont, Scale 1:50 000, UTM 0459640E, 6349110 N (middle of section)

Location and Access: This outcrop is about 2 km upstream from the mouth of the Ells River on the west bank of the Athabasca River, west of Daphne Island (Figures 41A and 41B). Access the section by boating downstream from Fort McMurray, the barge landing on the Athabasca River, or by gaining access to the Athabasca River from a landing at the Fort MacKay settlement. Road access is obtained by driving north of Fort MacKay on Highway 963, stopping along the road about 1 km south of the mouth of the Ells River, and hiking about 500 m through the bush to the Athabasca River.

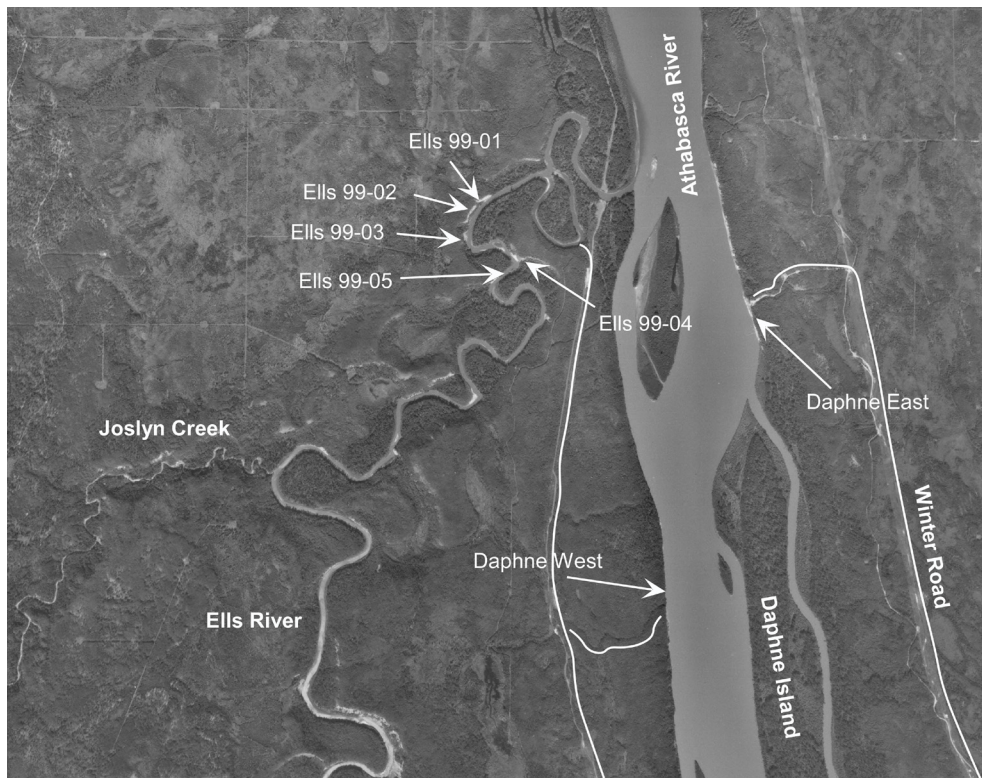


Figure 41A. Aerial photograph of the Daphne Island sections.

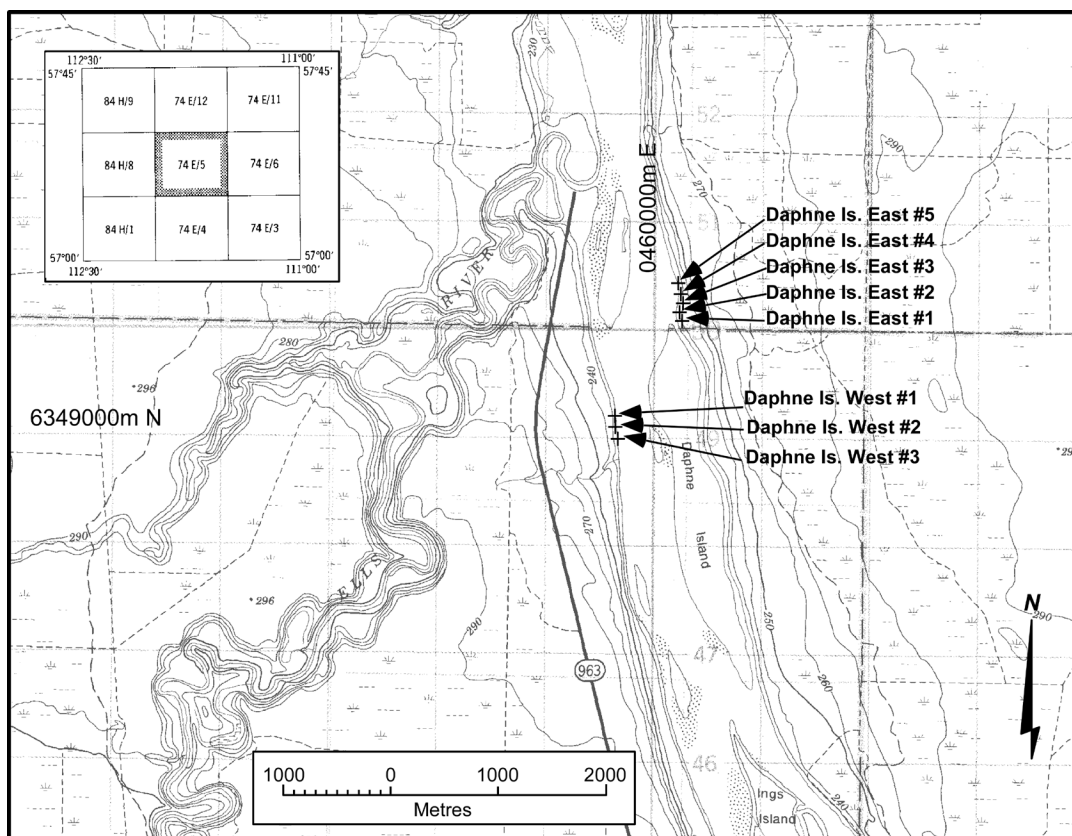


Figure 41B. Topographic map of the Daphne Island sections.

Highlights:

- Stacked and laterally interfingering fluvial, estuarine and tidal channel, and other coastal plain deposits;
- Thick, coaly mudstone in the middle part of the outcrop (Daphne Island West #2).
- Fossilized logs and abundant coal debris.

Description: Due to the significant along-strike variation in sedimentary facies at this outcrop, three vertical sections were measured, each spaced about 100 m apart going from upstream (Daphne Island West #3) to downstream near the mouth of the Ellis River (Daphne Island West #1). In the Daphne Island West #1 section (Figure 41C), a 4.5 m thick, fining-upwards succession occurs with large scale trough crossbedded pebbly sand passing upward into planar-tabular, rippled, trough and wave-rippled medium to coarse sand. This is scoured out and overlain abruptly by sandy-inclined heterolithic-stratified sand, with wave-ripples and abundant bioturbation, including *Cylindrichnus* and *Skolithos*. This rapidly passes upward into a very fine grained, even-bedded silty sand, with abundant coal interlaminae and a fossilized log. In the Daphne Island West #2 section (Figure 41D), a stacked sequence of planar-tabular, trough and wavy crossbedded sands crosscut one another with rapid along-strike and vertical facies changes. Grain-sizes range from very coarse to medium sand. Abruptly overlying the crossbedded sand unit is a very fine to fine sand that has sandy-inclined heterolithic stratification and small internal troughs that dip north. Otherwise all other paleoflow directions are toward the west-southwest. The Daphne Island #2 section is capped by a coaly mudstone in excess of 1 m thick. Daphne Island #3 section (Figure 41E), at the upstream end of the outcrop, starts with about 1 m of medium to coarse-grained, trough crossbedded and inclined heterolithic-stratified sand. This is overlain by a 1 m thick recessive and covered interval. The next unit in outcrop is a fine to very fine sand, about 2 m thick, that has southerly, paleo-landward, directed low-angle master bedding surfaces. Internally, the low-angle master bedding has trough and planar-tabular crossbeds with local *Skolithos* burrows near the top. This is scoured out by the overlying 2.3 m thick medium sand that has paleo-seaward, northward directed, low-angle master bedding, internally with planar-tabular crossbeds, horizontal lamination, abundant coal debris and rare *Skolithos* burrows. The top of the outcrop is an inaccessible 3 to 4 m thick, burrowed silty sand and mud that appears to be generally fining-upwards with an even and wavy bedding style.

Interpretation: The complex interdigitation of facies and switching paleoflow directions all indicate sedimentation within complex nearshore settings that show both fluvial domination during prograding regressive phases, and shoreline/coastal plain sedimentation during transgressive phases. In the Daphne Island West #1 section, the lowermost 2/3 of the outcrop section is interpreted as a fining-upward succession of fluvial channel sands, perhaps a remnant of the Lower McMurray succession. This is scoured out and overlain by a sandy estuarine point-bar succession and possibly a sand flat deposit of the Upper McMurray Formation. The surface of erosion between the Lower and Upper McMurray is interpreted as a transgressive surface of erosion.

In the Daphne Island #2 section the, Lower McMurray fluvial component is missing. Here, Upper McMurray comprises most of the section with stacked main estuarine channel or open estuarine sandy bay deposits and southwest-west paleo-landward directed bar and other bedforms. Possible upper shoreface sands abruptly overlie this with low-angle master bedding directed northward and paleo-seaward. The thick coaly mudstone at the top of the section is interpreted as coastal plain deposits following the initial transgression marked by the main estuarine system at the base of the Upper McMurray.

In the Daphne Island #3 section an upper McMurray tidally influenced estuarine channel succession

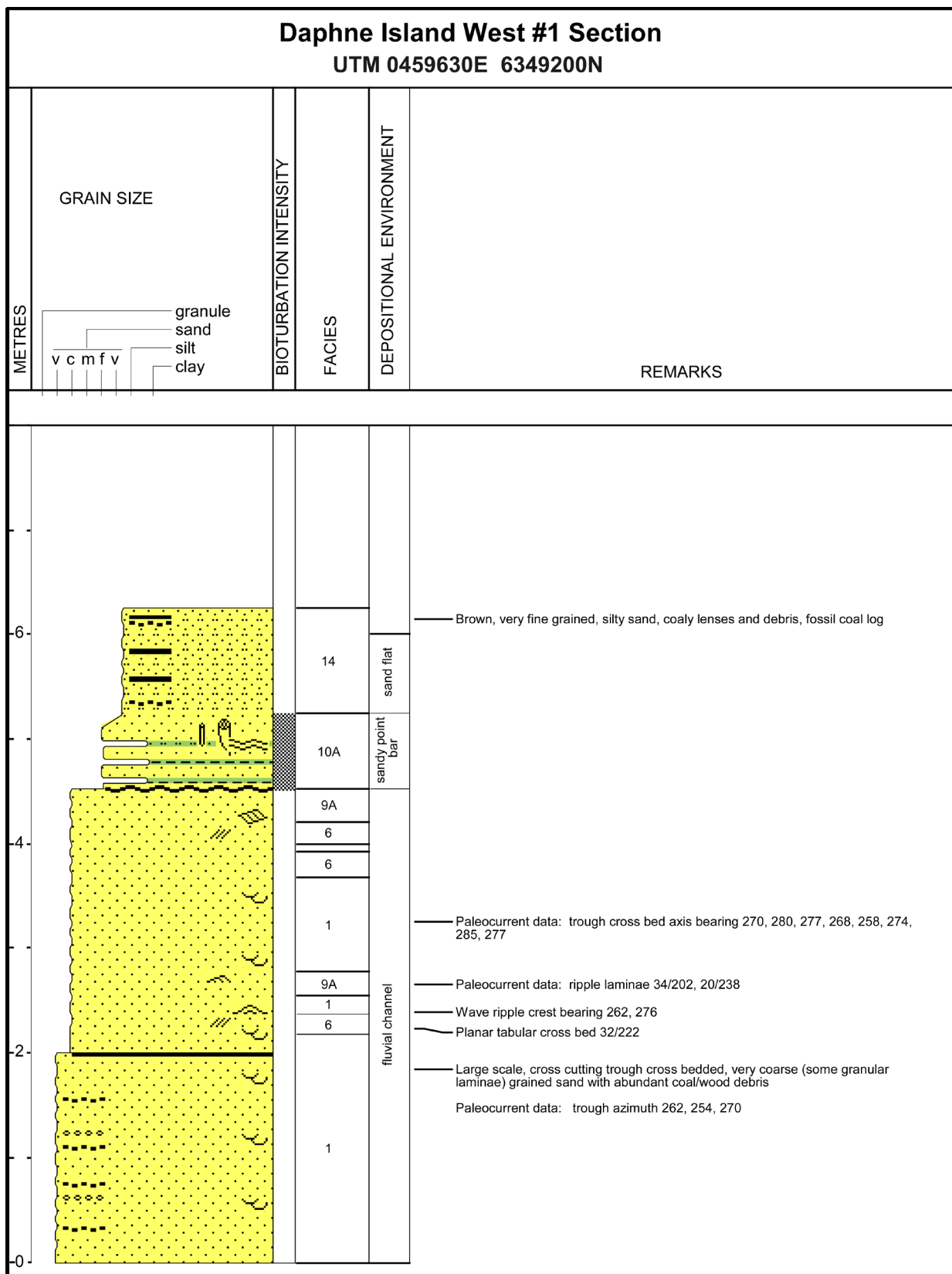


Figure 41C. Measured Daphne Island West #1 section.

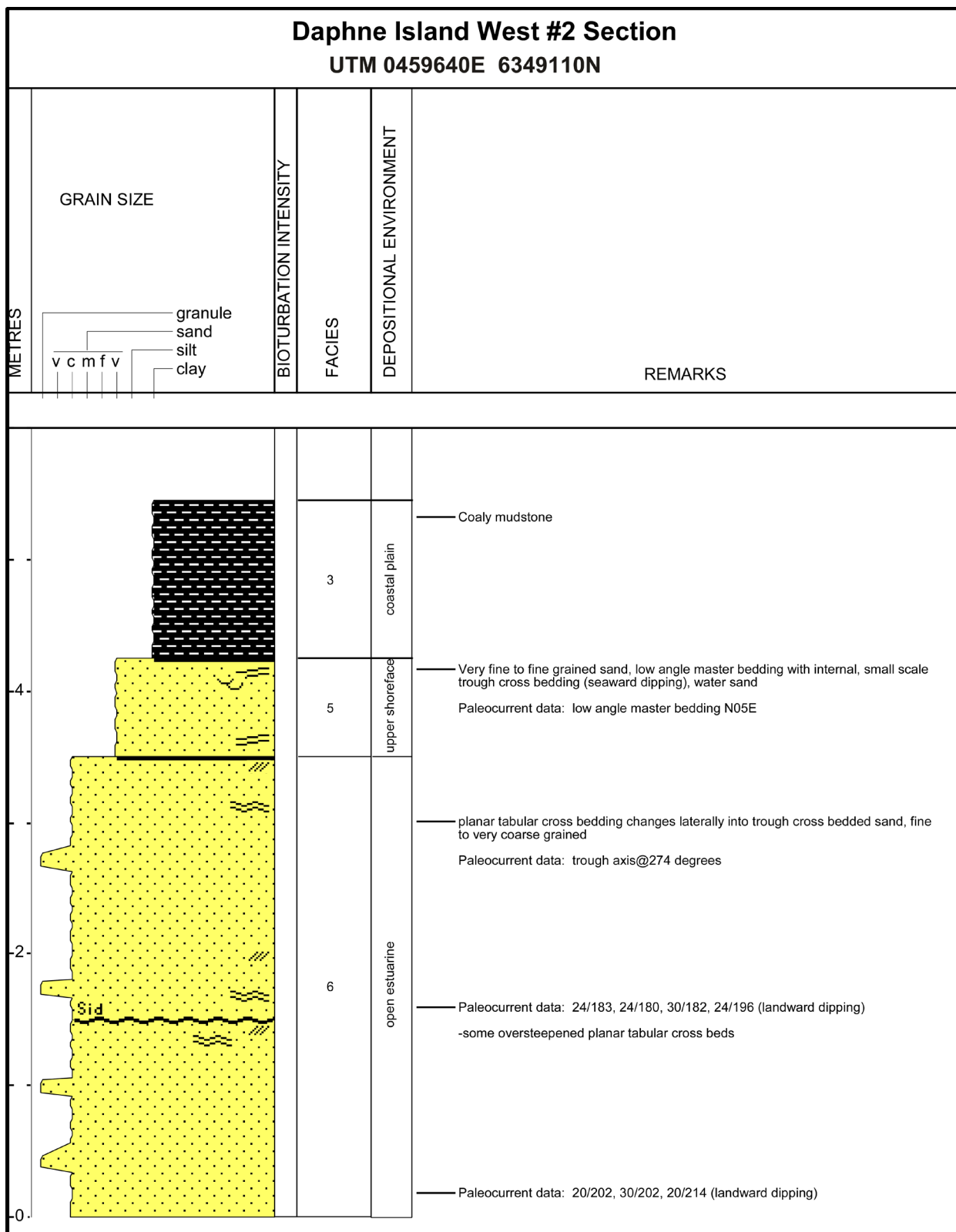


Figure 41D. Measured Daphne Island West #2 section.

UTM 0459650E 6349002N



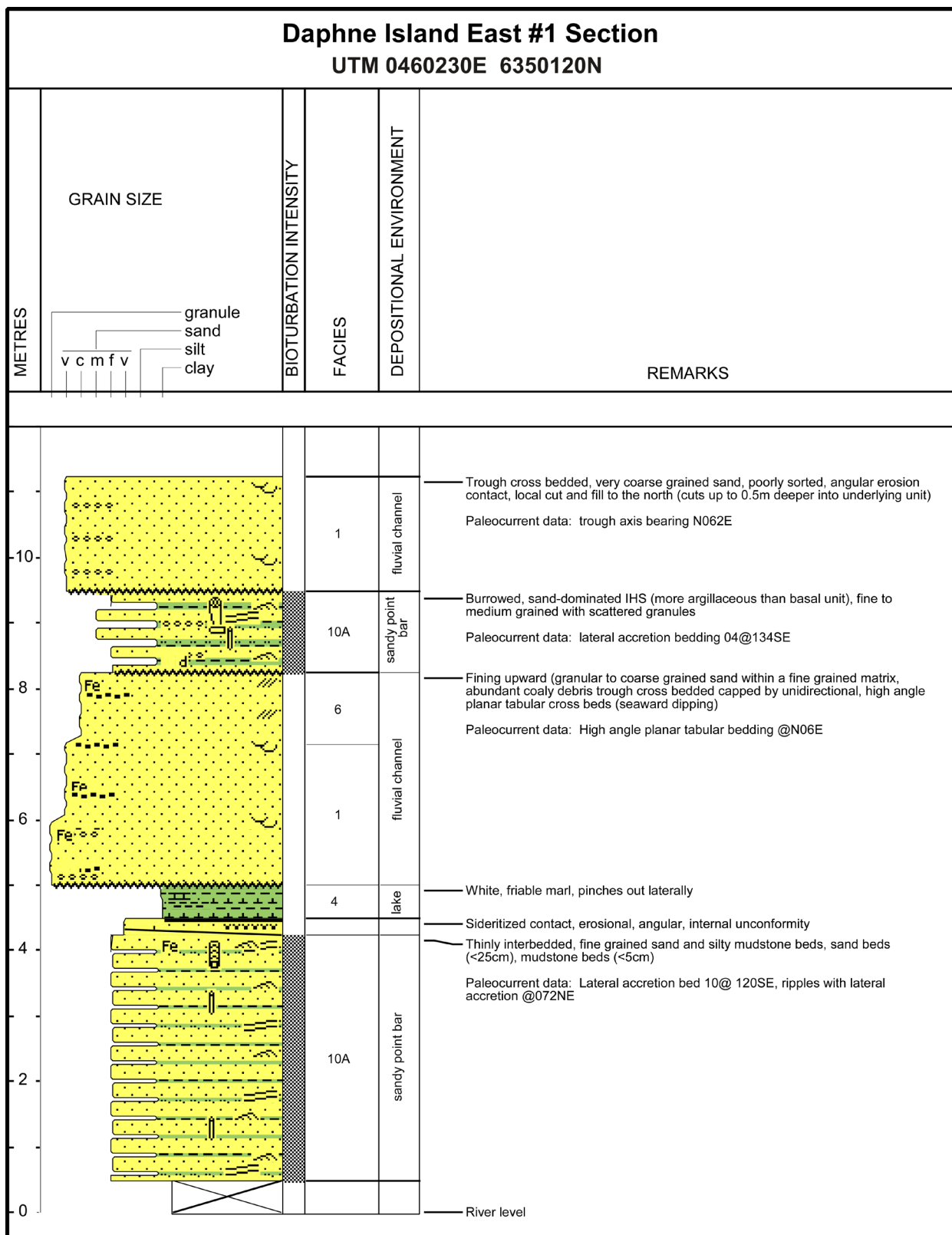


Figure 41F. Measured Daphne Island East #1 section.

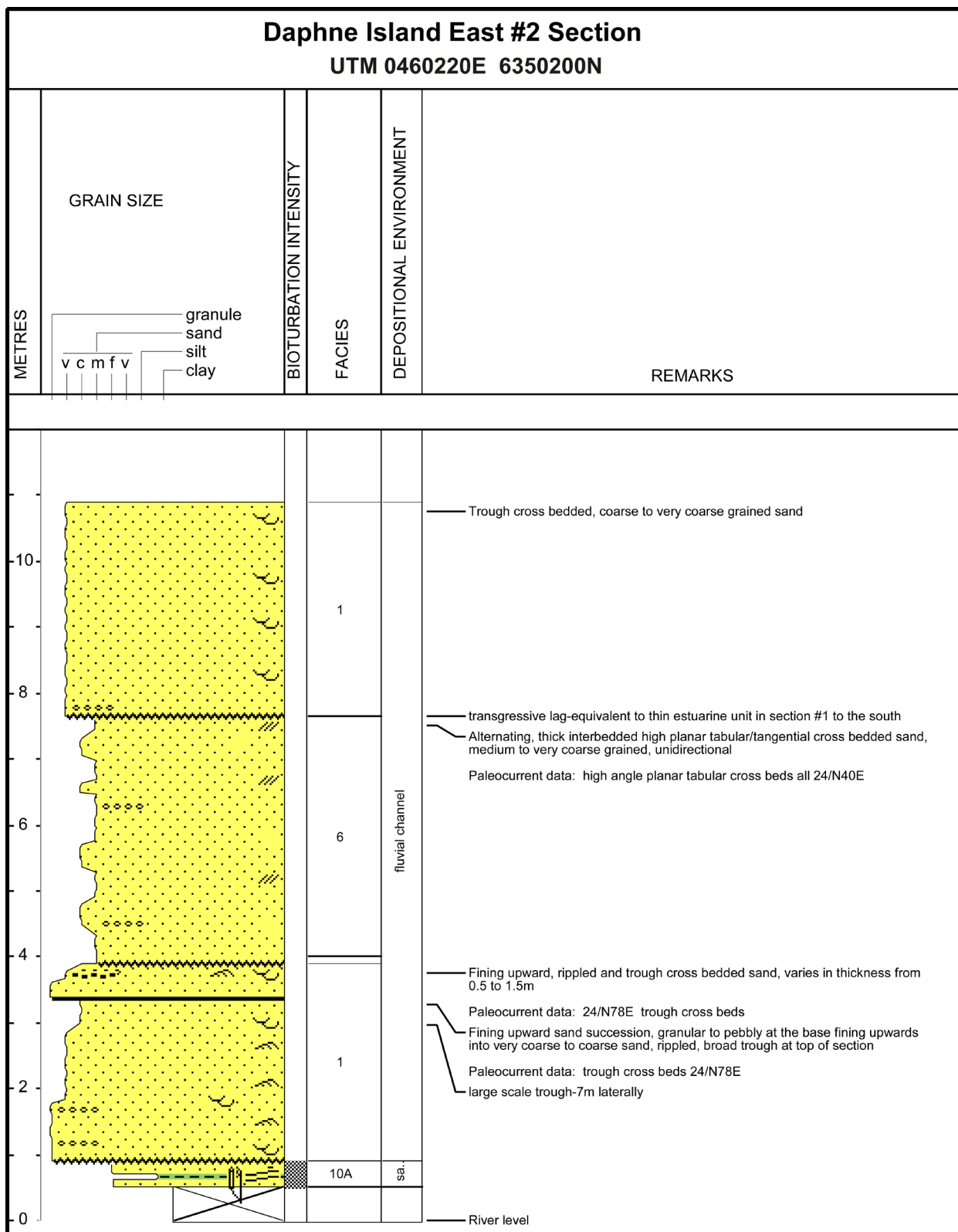


Figure 41G. Measured Daphne Island East #2 section.

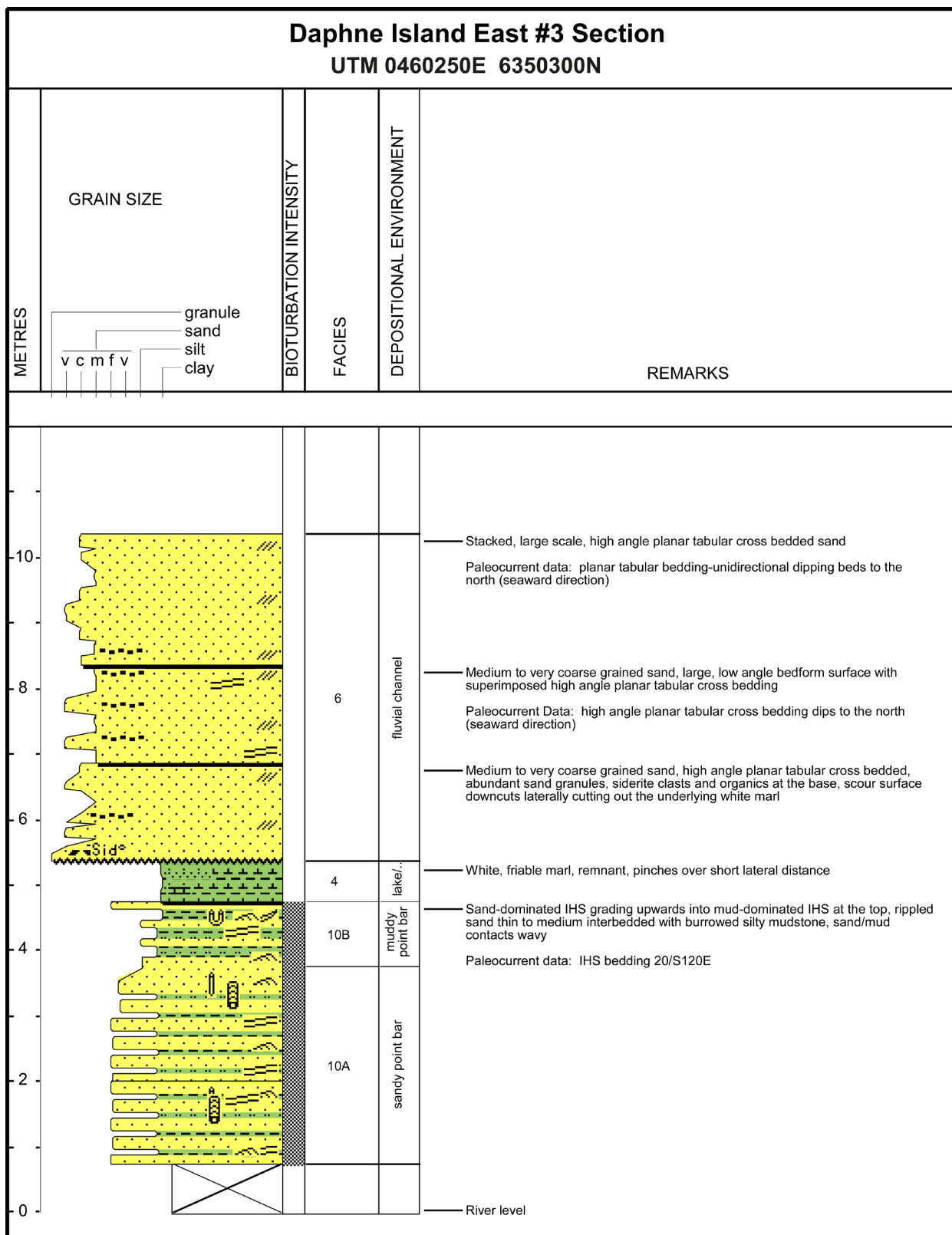


Figure 41H. Measured Daphne Island East #3 section.

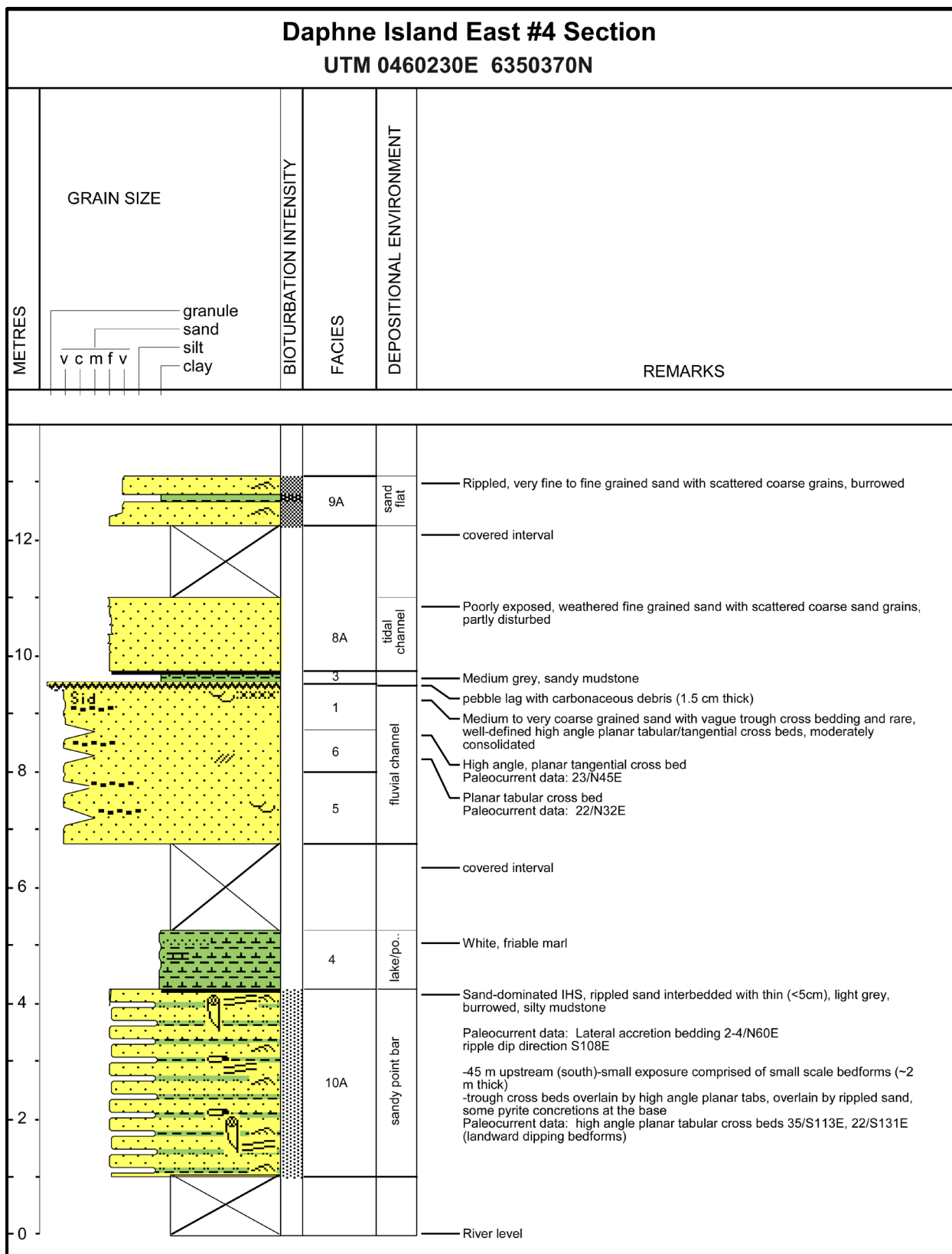


Figure 41l. Measured Daphne Island East #4 section.

UTM 0460210E 6350433N



grades up into perhaps a more open estuarine deposit. This is scoured out and abruptly overlain by upper shoreface deposits, of either a coastal plain bay or more offshore lower shoreface succession. The upper part of the outcrop is inaccessible, and from the bedding style and degree of bioturbation in the float appears to have been deposited within a nearshore, as opposed to fluvial, setting (Figure 42).

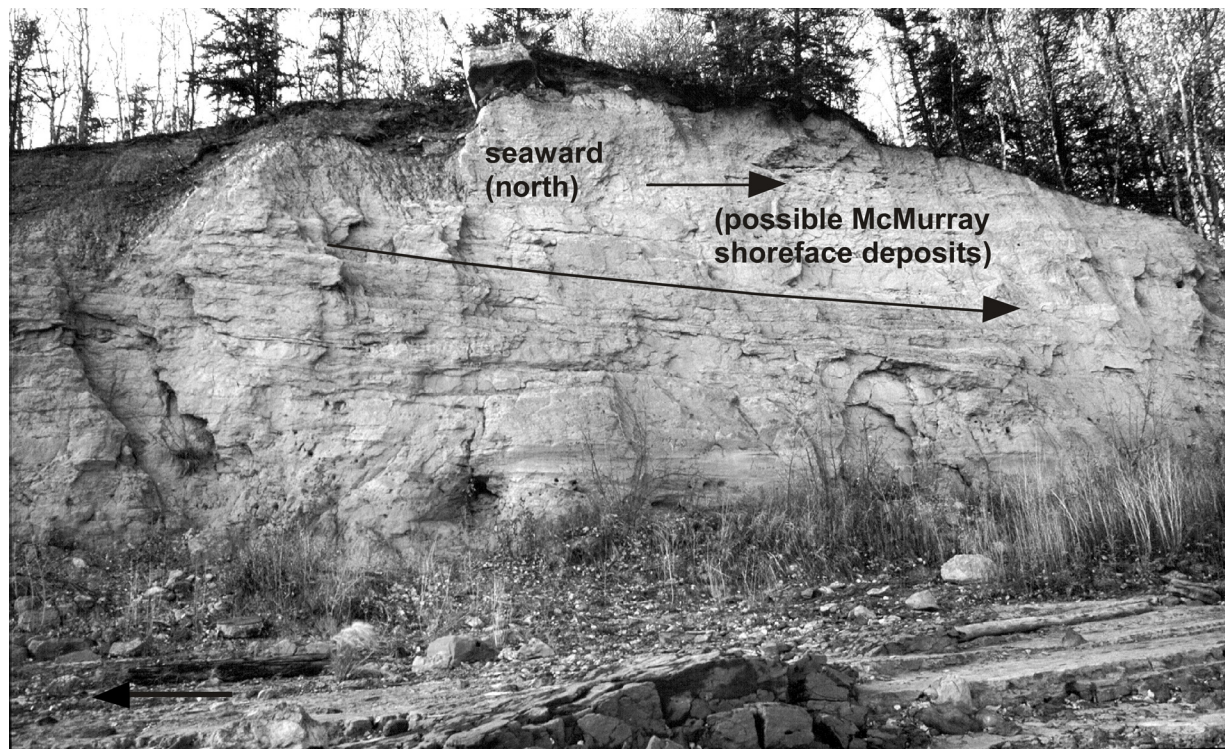


Figure 42. Clean, whitish sand (bitumen free) with northerly paleo-seaward dipping surfaces, Daphne Island #3 section (from Hein et al., 2000).

12.1 Daphne Island East Section

Map Coordinates: 74E/5 Bitumount, Scale 1:50 000, UTM 04602500E, 6350300 N (middle of section)

Location and Access: This outcrop is about 1 km upstream from the mouth of the Ells River on the east bank of the Athabasca River, at the downstream end of Daphne Island (Figures 41A and 41B). Access the section by boating downstream from Fort McMurray, the barge landing on the Athabasca River, or by gaining access to the Athabasca River from a landing at the Fort MacKay settlement. On land, access is obtained by driving to road access to the barge landing on the Athabasca River, then heading north on a winter road on the fork in the road to the barge landing, continuing about 2.5 km until the mouth of the Ells River is seen on the western bank of the Athabasca River. Park along the winter road and hike for about 500 m to the east through the bush to access the eastern bank outcrops along the Athabasca River.

Highlights:

- Stacked and laterally interfingering fluvial, marl and estuarine channel deposits.
- Thick, marl at the downstream and upstream parts of the outcrop (Daphne Island East #4, #3 and #1).
- Large fluvial channel incision in the middle part of the outcrop (Daphne Island East #2) and at the downstream end (Daphne Island East #5).

Description: Due to the significant along-strike variation in sedimentary facies at this outcrop, five vertical sections were measured, each spaced about 100 m apart going from upstream at Daphne Island East #1 to downstream at Daphne Island East #5 across from the mouth of the Ells River (Figures 41A, 41B and 43A to 43E).

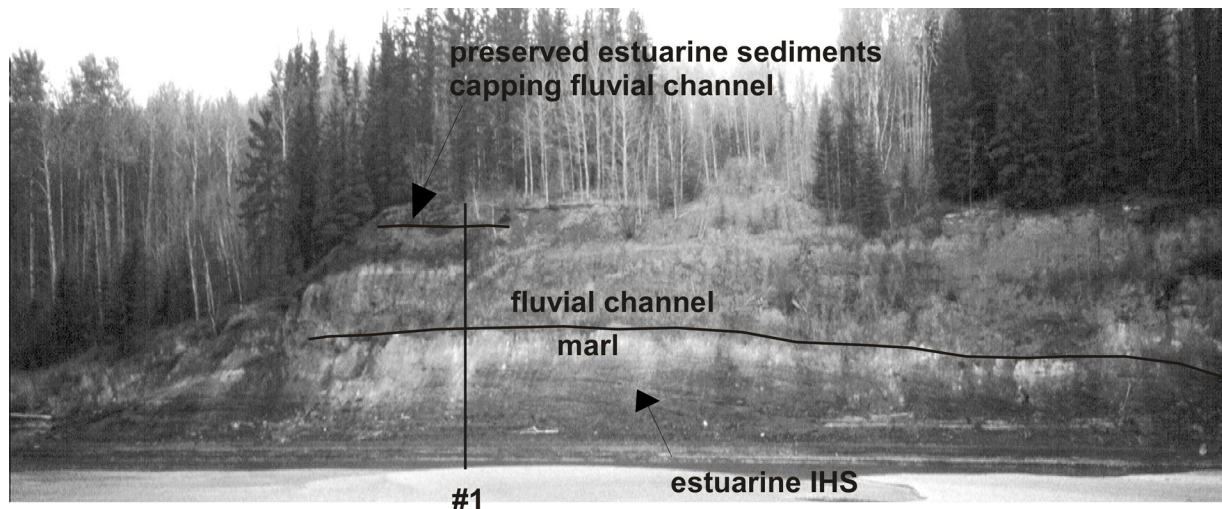


Figure 43A. Thinner, coarser-grained fluvial channel margin sand bound by finer-grained, interbedded estuarine sediments above and below, Daphne Island East #1 section.

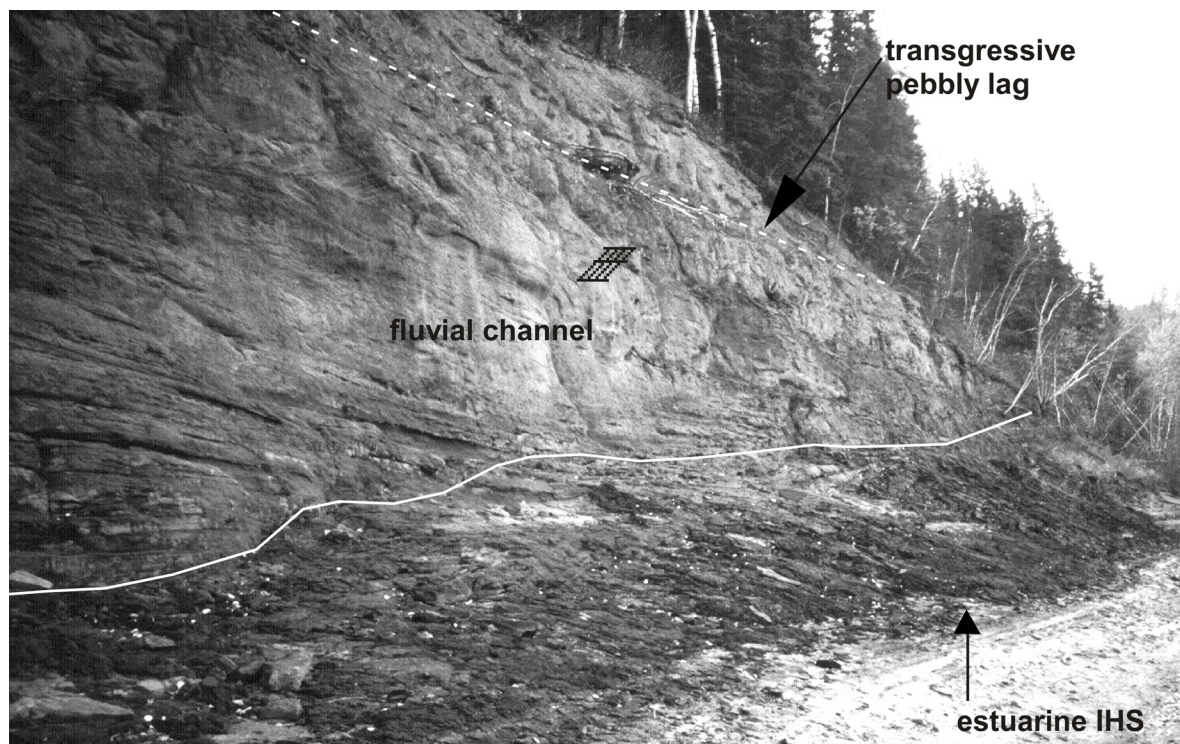


Figure 43B. Angular unconformity separating estuarine inclined-bedding from overlying fluvial channel sands, Daphne Island East #1 section.

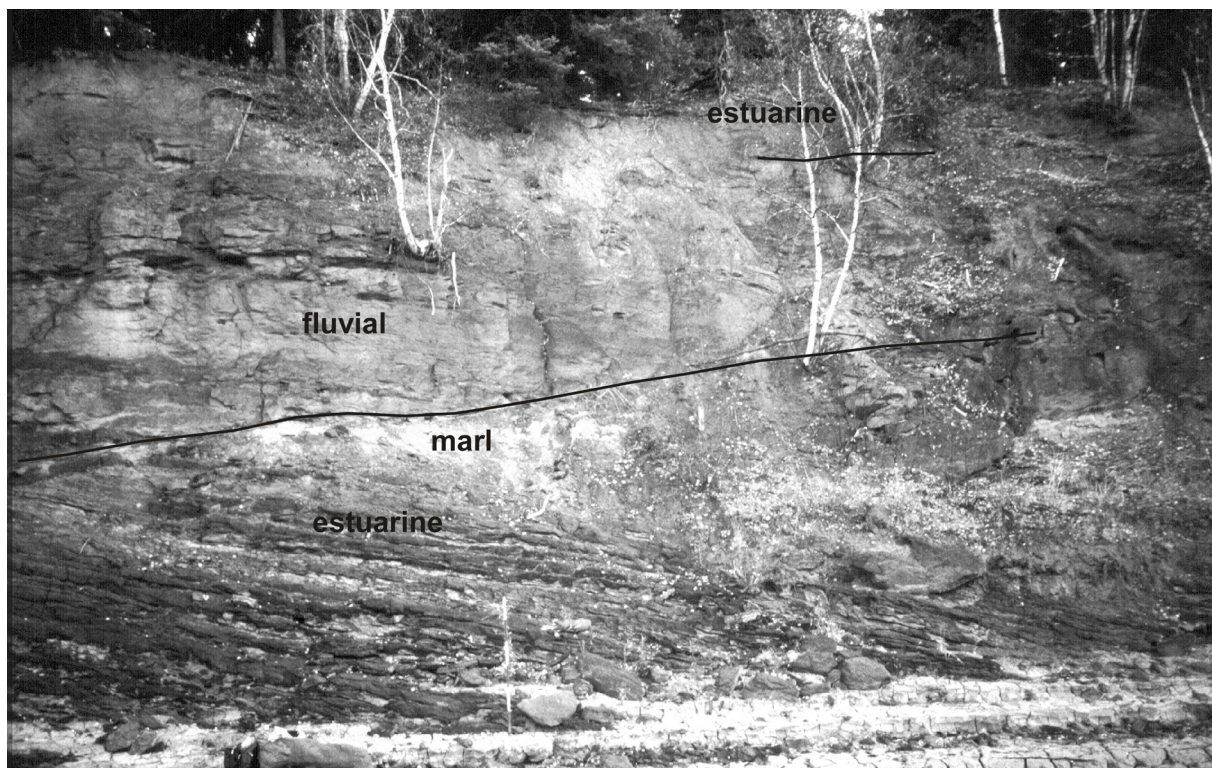


Figure 43C. Fine-grained, estuarine, lateral accretion deposits unconformably overlain by coarse-grained fluvial channel deposits, Daphne Island East #1 section.

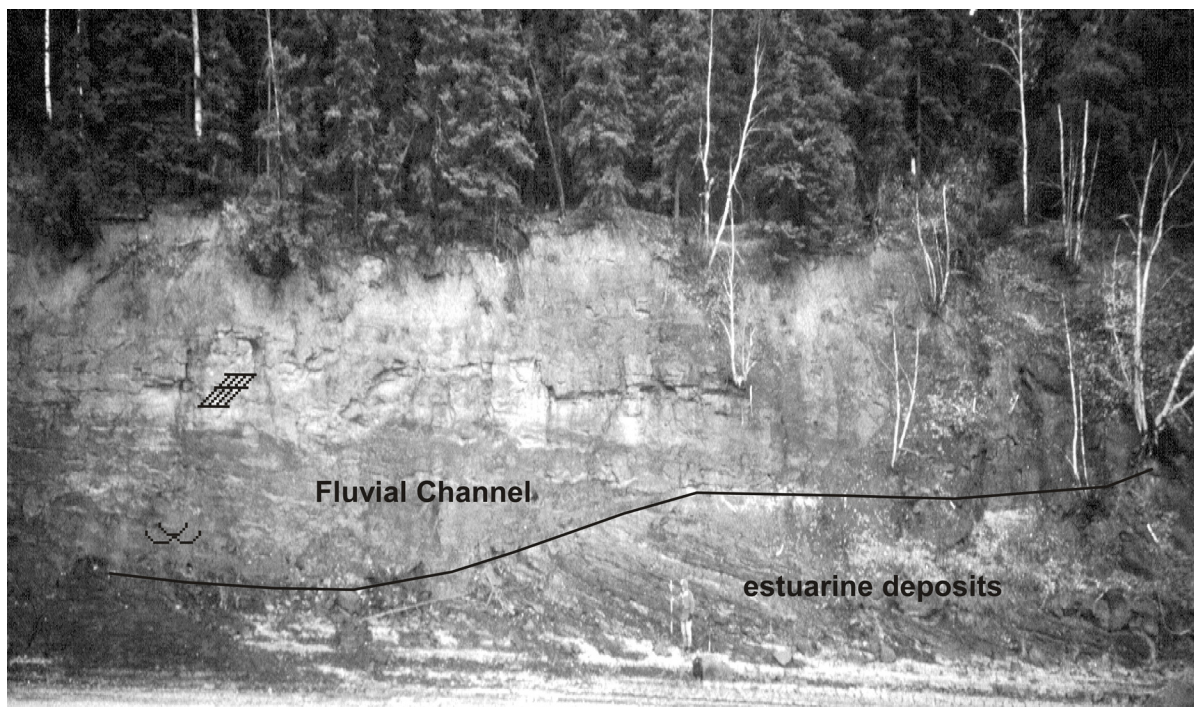


Figure 43D. Coarse-grained fluvial channel incising into underlying estuarine, low-angled, inclined bedding, Daphne Island East #1 section.

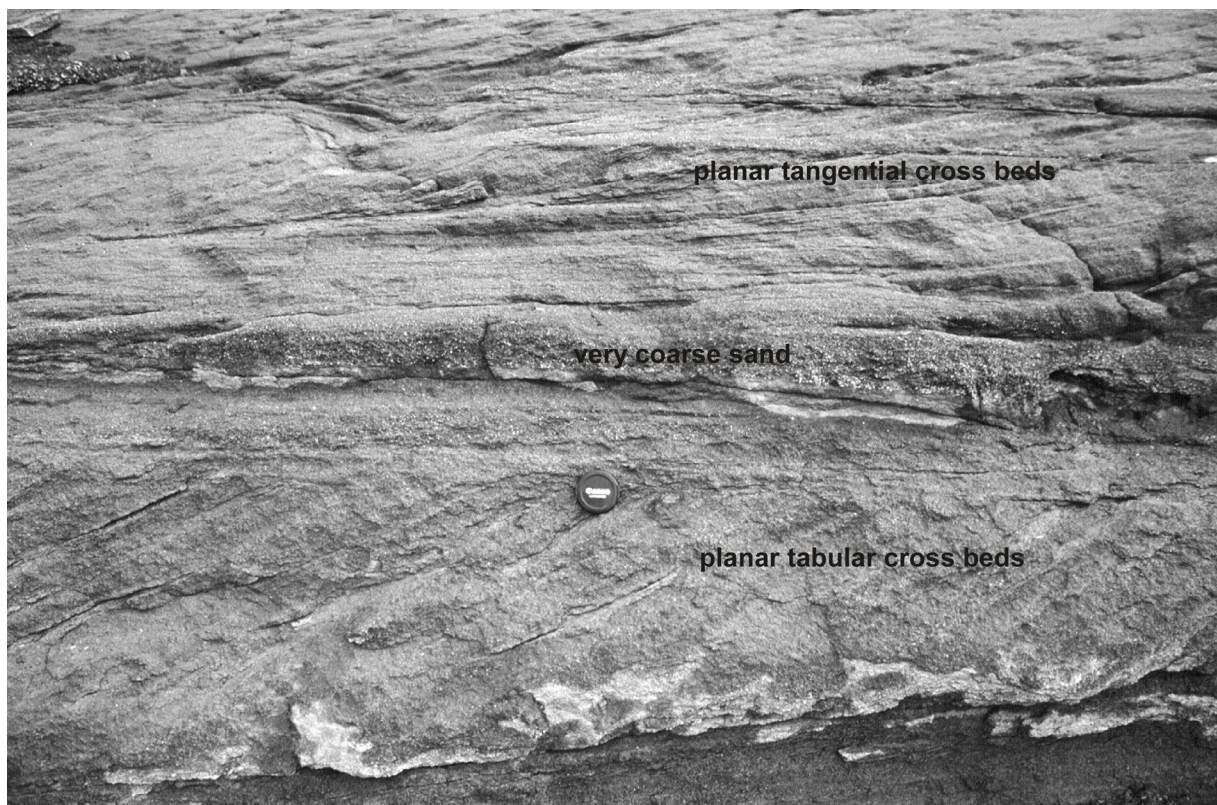


Figure 43E. North paleo-seaward dipping, medium to very coarse grained, high-angle, planar-tabular and planar-tangential crossbedded sand just above water level, Daphne Island East #5 section (from Hein et al., 2000).

In the Daphne Island East #1 section (Figure 41F), a 4 m thick, fining-upward succession occurs with large scale, sandy-inclined heterolithic stratification at the base that becomes more muddy and thinly interbedded toward the top. Internally, the inclined heterolithic-stratified sand has current ripples and minor burrowing, including *Skolithos* and *Teichichnus* within the finer upper beds at the top of the sequence. This unit is scoured out above and unconformably overlain by white friable marl, that is itself scoured out along strike. The marl is overlain, in turn, by a fining-upward succession of pebbly and coarse-grained, crossbedded sand that has abundant iron staining and siderite cement. Trough crossbeds and, to a lesser extent, planar-tabular crossbeds are unidirectional and mainly oriented toward the north paleo-seaward direction. The trough crossbedded sands are scoured out by sandy-inclined heterolithic-stratified pebbly sand that, in turn, is scoured out and replaced by trough crossbedded, very coarse-grained sand.

In the Daphne Island East #2 section (Figure 41G), a thin remnant of sandy-inclined heterolithic-stratified and burrowed sand (< 0.5 m thick) is scoured out and replaced by trough crossbedded and pebbly to coarse medium sand. This pebbly sand fines upward into medium rippled sand that is scoured out by another fining-upward, rippled and trough crossbedded sand, that varies in thickness from 0.5 to 1 m. The next 4 to 5 m is an alternating sequence of thick, interbedded planar-tabular and planar-tangential crossbedded sand, with unidirectional paleocurrents, directed in a paleoseaward direction to the north. The unit is scoured out and overlain abruptly by a thin conglomerate lag. The lag is capped by 2 to 3 m of generally inaccessible trough crossbedded coarse to very coarse sand.

In the Daphne Island East #3 section (Figure 41H), about 1 m of section is covered at river level. This is overlain by a bioturbated, inclined, heterolithic-stratified medium to fine sand that grades upward into

muddy inclined heterolithic-stratified units. Burrows occur throughout the sandy and muddy inclined heterolithic-stratified units, and include mainly *Teichichnus* and *Skolithos* with rare U-shaped burrows at the top. Internally, the low-angle, crossbedded sands and mudstones show current ripples, flaser bedding and wavy laminations. This low-angle, crossbedded sand and mudstone sequence is abruptly overlain by a white friable marl remnant that pinches out rapidly along strike. The marl, in turn, is scoured out by a succession of fining-upward sand. The sands each start off with medium to coarse-grained sand at the base, fining-upward to medium to fine sand. Internally, the sands contain sideritized mudstone intraclasts and abundant coal debris. Crossbedding is planar-tabular or, less commonly, low-angle, inclined, heterolithic stratification. Paleoflow directions are uniformly to the north in a paleoseaward direction.

In the Daphne Island East #4 section (Figure 41I), about 1 m at the base of the section is covered. This is overlain by about 3 m of sandy, inclined, heterolithic-stratified, burrowed sand and mudstone. Internally, the sand units show trough crossbeds toward the base, which are overlain by planar-tabular crossbedding and ripples. Pyrite concretions occur at the base of the section. Bioturbation increases in intensity upsection, along with a fining up of grain-size. Burrow types are dominantly *Cylindrichnus* and *Planolites*. In a lateral upstream direction the sizes of bedforms diminish, with large-scale troughs and planar-tabular crossbedded sands being replaced entirely by rippled fine to very fine sand. Abruptly overlying the low-angle, inclined heterolithic-stratified sand and mudstone is a 1 m thick marl unit that (as elsewhere along the outcrop) is white, friable and locally calcareous. The next 1 to 2 m of vertical section is covered. The next exposure is a medium to coarse sand, with trough crossbedding and less commonly planar-tabular or planar-tangential crossbeds. This unit is fairly consolidated and local siderite cement occurs at the top. Next is a medium grey, sandy mudstone, scoured out and overlain by a poorly exposed fine to pebbly sand with some herringbone crossbedding. The next 1 m or so is again covered. The top of this section consists of rippled, very fine to fine-grained, burrowed sand with scattered coarse sand grains.

The Daphne Island East #5 section (Figure 41J) is a relatively simple succession comprising stacked, trough crossbedded, very coarse to granular sand at the base, overlain by a 6 to 7 m thick, fining-upwards succession of low-angle, inclined, heterolithic-stratified sand and mudstone. Internally, the low-angle bedding is parallel laminated, rippled or locally shows small planar-tabular crossbeds. Burrows were not noted either in outcrop or in float at this section. Few reversals in paleoflow directions occur, with most of the paleoflows oriented in a northerly, paleo-seaward, dipping direction.

Interpretation: As with the Daphne Island West locality, the Daphne Island East outcrops show very complex interdigitation of facies, multiple channelling and scouring, and the occurrence of major internal erosional unconformities or disconformities (Figures 43A and 43D). In the Daphne Island East #1 section, the lowest 4 m of section is interpreted as sandy estuarine point-bar deposits that are overlain abruptly by lacustrine marl. This lacustrine unit is then cut out by prominent fluvial channel sand eroded out by an estuarine point-bar succession. Another fluvial channel succession occurs at the top of the section. The sequence at Daphne Island East #2 is much simpler, with a thin remnant of estuarine point-bar sands at the base, scoured out by the base of a fluvial channel. The fluvial succession consists of a series of crosscutting individual fluvial channel sands that show complex vertical and lateral facies changes. The Daphne Island #3 section starts with a thick sandy to muddy estuarine point-bar succession that is capped by the lacustrine marl. As in the Daphne Island East #1 section, the base of a fluvial channel cuts out this marl. The overlying fluvial succession consists of a series of interbedded channel sand and sandy point-bar deposits. A similar repetition of events occurs at the Daphne Island East #4 section, where sandy estuarine point-bar deposits are overlain by lacustrine marl. The contact with the overlying fluvial channel sand is covered. The fluvial channel sands then grade upward into tidal channel and sand flat deposits. A coarse-grained, pebbly and carbonaceous debris unit occurs just above the contact between

the fluvial and tidal channels. This is interpreted as the initial transgressive lag deposits associated with the incision and scour of the transgressive surface of erosion between the fluvial and tidal channel sands. The Daphne Island East #5 section returns to a relatively simple facies pattern, with a lower 2 m thick fluvial channel sand, overlain by a 6 m thick sandy to muddy estuarine point-bar deposit. The contact between the fluvial and estuarine units is covered.

13 Outcrop Descriptions: Eymundson Creek, Day 2, Stop 8

13.1 Eymundson Creek Mouth #1 Section

Map Coordinates: 74E/5 Bitumount, Scale 1:50 000, UTM 0465500E, 6371500N

Location and Access: This section is at the northern end of the Bitumount map area, along the west bank of the Athabasca River about 800 m upstream of the mouth of Eymundson Creek (Figures 44A and 44B), near Clauson's Landing on the Athabasca River. Access the section by boating downstream from Fort McMurray, the barge landing on the Athabasca River or by gaining access to the Athabasca River from the landing at the Fort MacKay settlement.

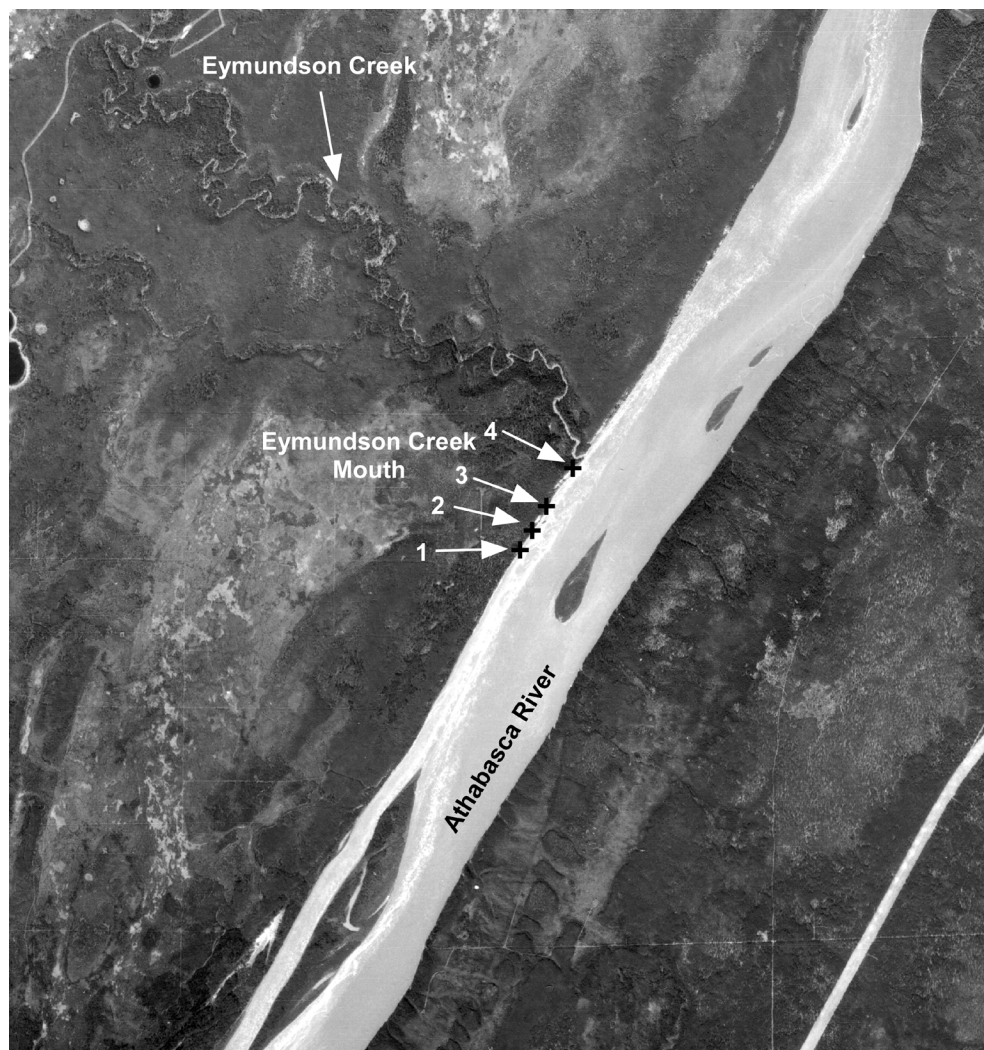


Figure 44A. Aerial photograph of the Eymundson Creek sections.

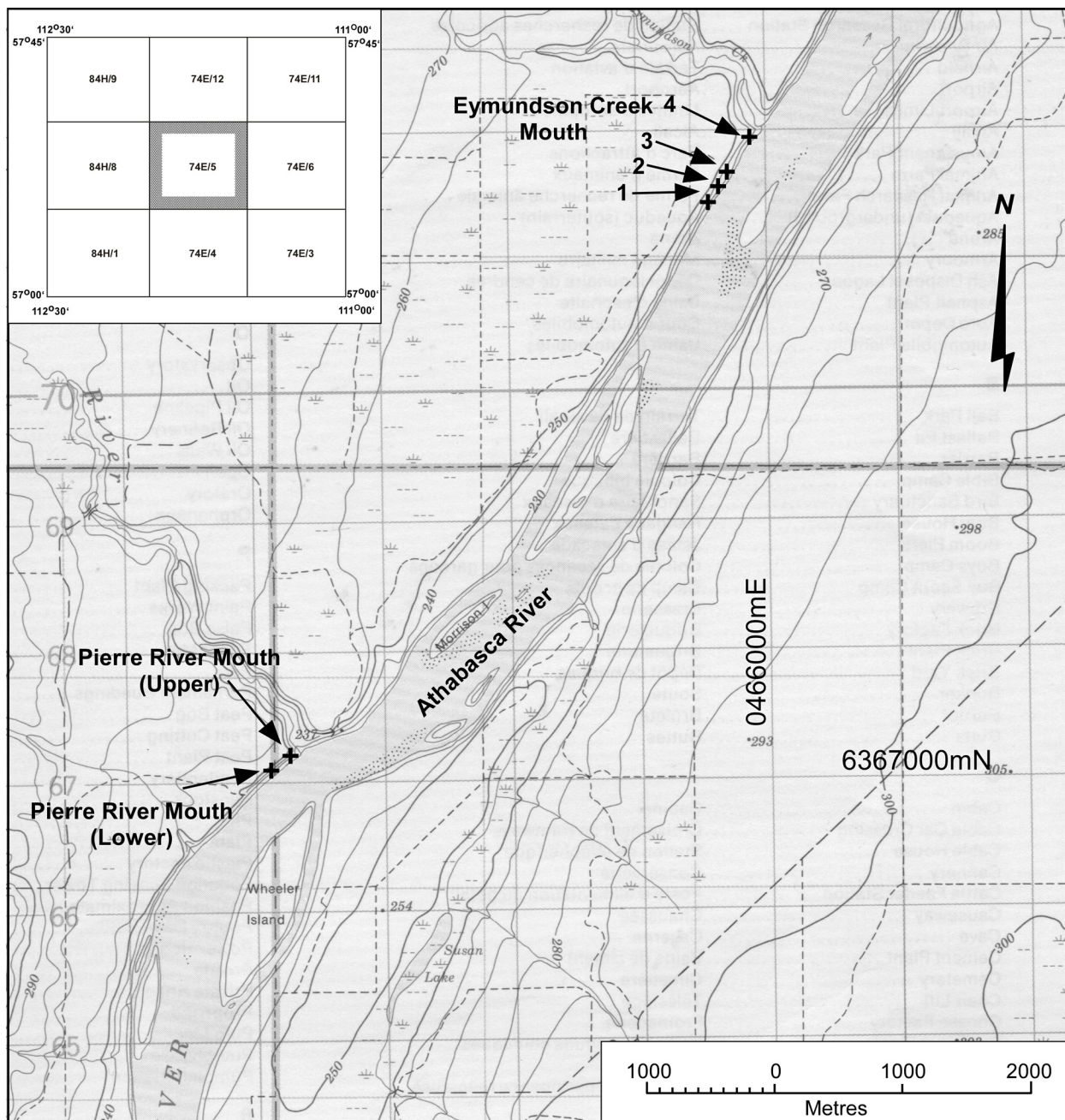


Figure 44B. Topographic map of the Eymundson Creek sections.

Highlights:

- Stacked estuarine and fluvial channel sediments.
- Rare organic mudstone interbeds.
- Thin (< 0.25 m) Quaternary loess at the top of the section.

Description: This cutbank is very well exposed and generally accessible. At the very base of the section is approximately 3 to 4 m of trough and ripple crossbedded oil sand and scattered mudstone intraclasts

(Figure 44C). A small wedge of rippled sand at the base of the section contains organic mudstone that was sampled for biostratigraphic dating. At the top of this unit is large and small-scale convolute lamination. Next are a series of stacked planar-tabular and trough crossbedded oil sands, with internal scours, dispersed mudstone intraclasts and carbonaceous debris. A 100 mm thick cap of thinly laminated shaly mudstone caps the McMurray succession. The McMurray Formation is unconformably overlain by light tan, unconsolidated silt that is interpreted as Quaternary loess.

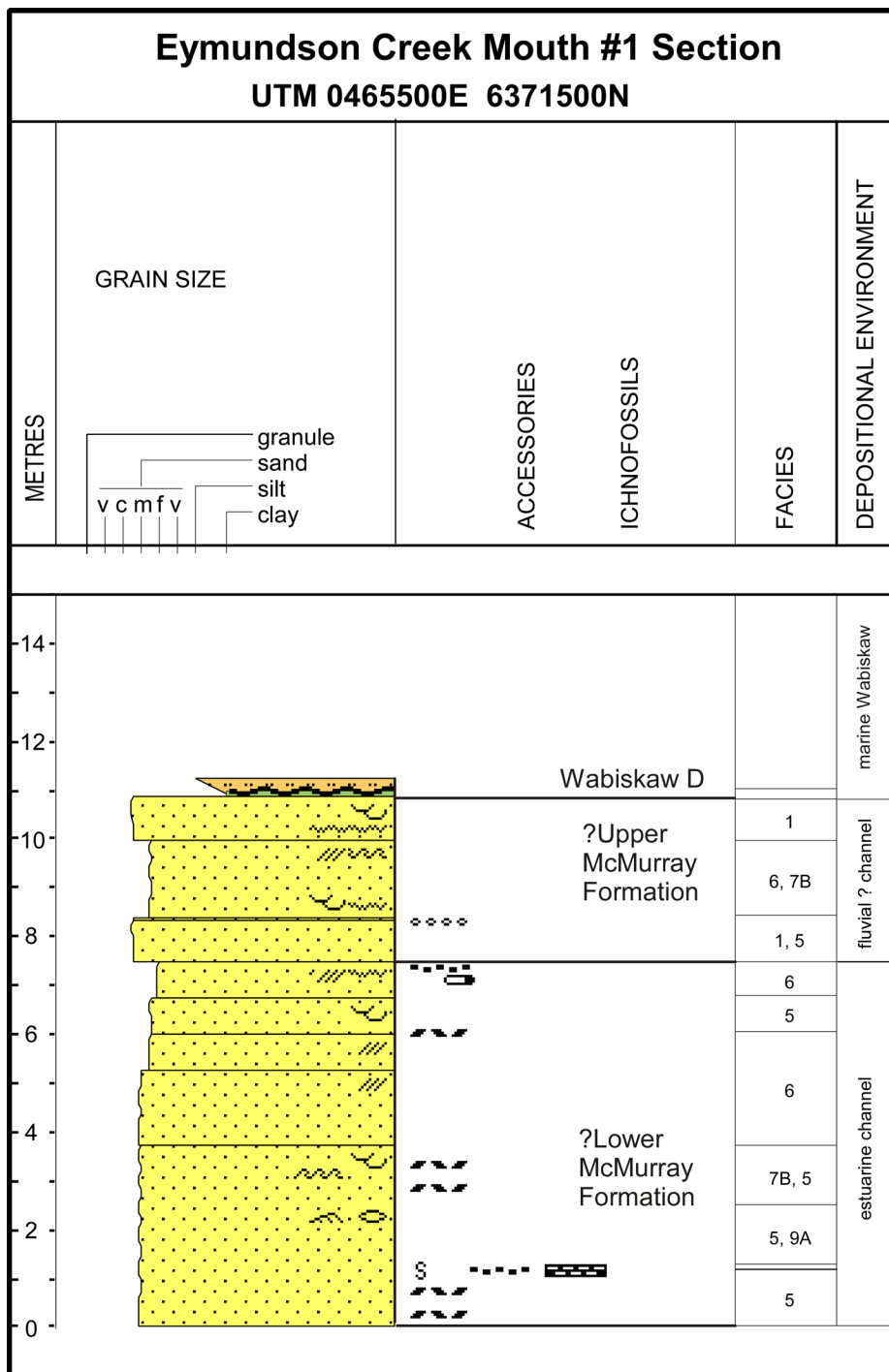


Figure 44C. Measured Eymundson Creek Mouth #1.

Interpretation: Convolute lamination and burrowing are rare, but do occur in the lower part of the section. The uppermost 2 to 3 m of McMurray succession lack any burrow structures, are coarser grained, with dispersed pebbles and granules, dominated by internal scouring, and have fills of trough and planar-tabular crossbedded sand. The lowermost 7.5 m of sediment are interpreted as estuarine channel deposits of the Upper McMurray Formation. Stacked high energy estuarine or possibly fluvial channel sediment of the Upper McMurray Formation overlies these. As with other Athabasca River sections, lateral transitions along the face of this show internal transitions between different cross-bed types and lateral cut and filling of superimposed channel units.

13.2 Eymundson Creek Mouth #2 Section

Map Coordinates: 74E/5 Bitumount, Scale 1:50 000, UTM 0465600E, 6371600N

Location and Access: This section is at the northern end of the Bitumount map area, along the west bank of the Athabasca River about 600 m upstream of the mouth of Eymundson Creek (Figures 44A and 44B), near Clauson's Landing on the Athabasca River. Access the section by boating downstream from Fort McMurray, the barge landing on the Athabasca River or by gaining access to the Athabasca River from the landing at the Fort MacKay settlement.

Highlights:

- Stacked estuarine and tidal channel sediments
- Excellent dewatering structures within large-scale convolute lamination and oversteepened crossbedding.
- Reverse-flow ripples and herringbone crossbeds on toesets of larger scale, planar-tabular and planar-tangential crossbeds.

Description: This cutbank is very well exposed and generally accessible (Figure 44D), except for the topmost 4 to m of outcrop that are too steep to climb. At the base of the section is approximately 3 to 4 m of planar-tabular and planar-tangential crossbedded oil sand, with scattered mudstone intraclasts. Reverse-flow ripples commonly occur along the toesets of the larger crossbeds. Overlying this unit with the reversing paleoflows is a 2 to 3 m thick, large scale trough crossbedded unit, which has oversteepened crossbedding, dewatering structures, including convolute lamination, dish structures and fluid escape tubes. Small-scale, planar-tabular crossbedded sands, with reverse-flow toeset ripples, locally cut into dewatering structures. These crossbedded sands become coarser grained and medium to very thick bedded. Crossbedding features are complex and change laterally along strike. Very thick bedded, planar-tabular and planar-tangential units grade into wavy-bedded sands, with reverse-flow ripples and abundant carbonaceous debris. Internal erosional surfaces are common, but it was impossible to map the geometry of these due to the steepness of the outcrop face. Near the top of the thick to very thick bedded sands is an increase in the abundance of sideritized mudstone intraclasts and a slight fining-upwards in grain-size. A 1 m thick massive sand caps the measured section.

Interpretation: The very thick bedding style, complex interfingering of different crossbedding types and the common occurrence of large-scale dewatering structures indicate very rapid and complex sedimentation patterns under high energy conditions. No burrows were noted. A fining-upward in grain-size was noted near the top of the measured section; otherwise grain-size was uniform throughout the section. Reverse-flow ripples are common on toesets of the larger scale planar-tabular/tangential features. This suite of physical sedimentary features suggests that the units at this outcrop were deposited under mainly channelled, high energy conditions, in which reversing tidal flows were common. The

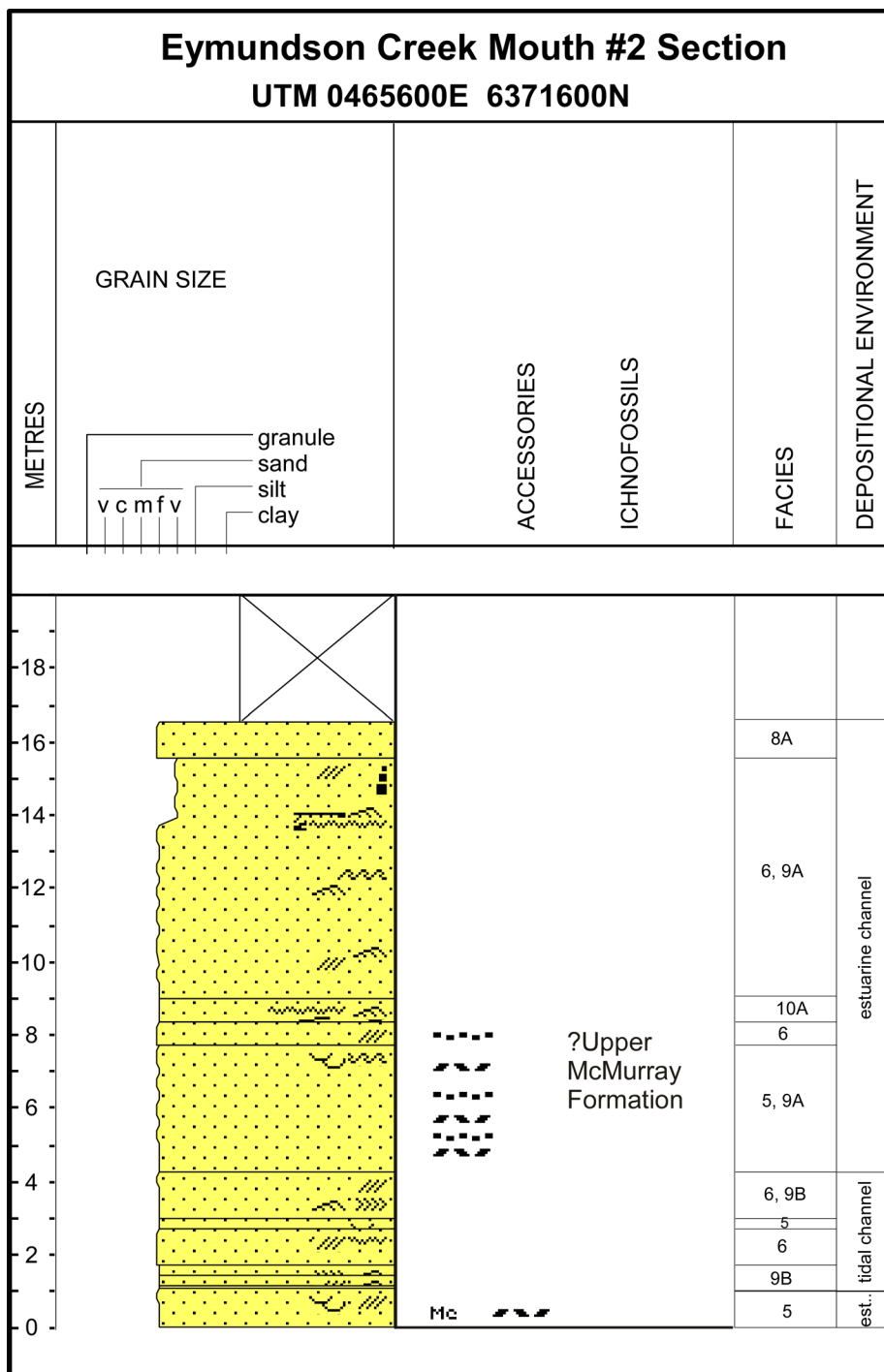


Figure 44D. Measured Eymundson Creek Mouth #2.

paleoenvironmental interpretation is that these sediments are part of a tide-dominated estuarine channel system within the Upper McMurray Formation.

13.3 Eymundson Creek Mouth #3 Section

Map Coordinates: 74E/5 Bitumount, Scale 1:50 000, UTM 0465700E, 6371800N

Location and Access: This section is at the northern end of the Bitumount map area, along the west bank of the Athabasca River about 400 m upstream of the mouth of Eymundson Creek (Figures 44A and 44B), near Clauson's Landing on the Athabasca River. Access the section by boating downstream from Fort McMurray, the barge landing on the Athabasca River, or by gaining access to the Athabasca River from the landing at the Fort MacKay settlement.

Highlights:

- Stacked estuarine and tidal channel sediments.
- Minor estuarine point-bar and crevasse splay channel deposits.
- Apparently bi-directional crossbedding (north and south directed), about midway upsection, are eastward directed planar-tabular crossbeds within a thick estuarine channel succession.

Description: This cutbank is very well exposed and easily accessible (Figure 44E). At the base of the section is approximately 1 m of trough crossbedded pebbly and coarse oil sand, with large-scale herringbone structures and scattered mudstone intraclasts. Overlying this unit with the herringbone structure, is a 4 to 5 m thick, large scale, fining-upward sequence, comprising trough to parallel and low-angle, inclined heterolithic stratification, overlain by pebbly trough and parallel laminated pebbly coarse sand, with dispersed mudstone intraclasts, organic detritus, convolute lamination and wavy bedding features. The rest of the succession consists of two very thick bedded crossbedded oil sand and with very rare mudstone or mudstone intraclasts or coaly debris. Internal erosional surfaces are common. Within the channel fills, the oil sands show most of the common crossbedding types, including convolute lamination, ripples, troughs and planar-tabular crossbedding. A slight fining up occurs toward the top of the lowermost thick sand. The upper sand does not show obvious vertical grain-size trends. Burrows are very rare, dominantly the vertical *Skolithos* types, within the finer interbeds toward the base of the outcrop.

Interpretation: The very thick bedding style, complex interfingering of different crossbedding types and the common occurrence of convolute lamination indicate very rapid and complex sedimentation patterns under high energy conditions. Rare burrows were noted. Two slightly fining-upward trends in grain-size were noted near the base and middle of the measured section; otherwise grain-size was uniform. This suite of physical sedimentary features suggests the units at this outcrop were deposited within high energy, tidal and estuarine channels. The finer interbeds toward the base of the section may be overbank and crevasse-splay deposits associated with the lower tidal and estuarine channel-fill units. All units are interpreted as part of the Upper McMurray Formation.

13.4 Eymundson Creek Mouth #4 Section

Map Coordinates: 74E/5 Bitumount, Scale 1:50 000, UTM 0465959E, 6371974N

Location and Access: This section is at the northern end of the Bitumount map area, along the west bank of the Athabasca River about 20 m upstream of the mouth of Eymundson Creek (Figures 44A and 44B), near Clauson's Landing on the Athabasca River. Access the section by boating downstream from Fort McMurray, the barge landing on the Athabasca River or by gaining access to the Athabasca River from the landing at the Fort MacKay settlement.

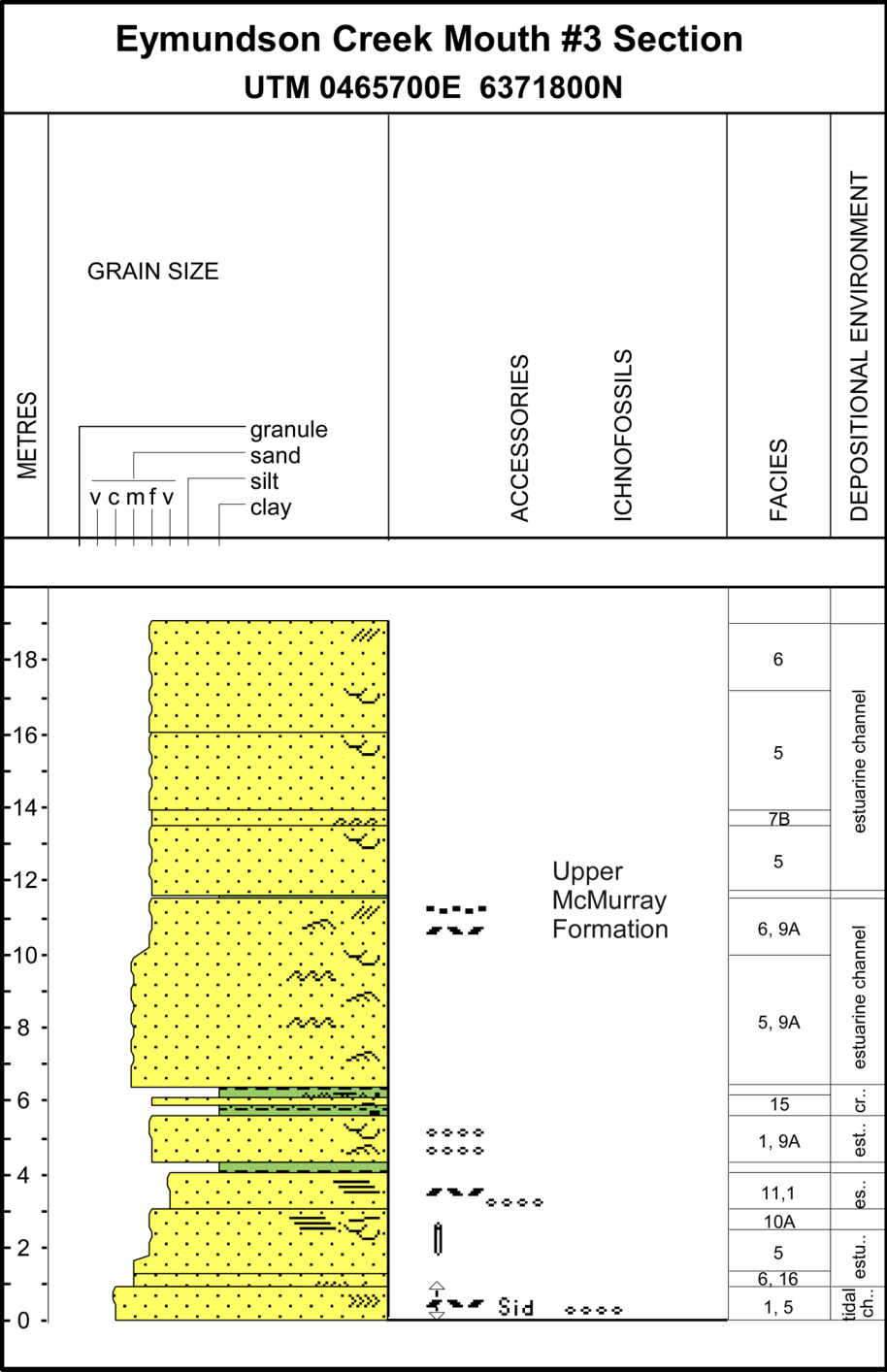


Figure 44E. Measured Eymundson Creek Mouth #3.

Highlights:

- Stacked estuarine and tidal channel sediments.
- 0.5 to 1 m thick mudstone intraclast breccia in the middle of the section.
- About a 1 m thick overbank cap to the outcrop.

Description: Recent slumping has exposed an excellent cutbank section at this site (Figure 44F). The measured section starts approximately 3 m above river level. The base of the section starts with thick to medium-bedded, trough and planar-tabular crossbedded oil sand, with common internal scours and dispersed mudstone intraclasts. A 0.5 to 1 m thick mudstone intraclast breccia overlies the crossbedded oil sand. The breccia occurs at the base of a channel-fill sand that internally has wavy, discontinuous laminations, trough crossbedding and large-scale, planar-tabular, herringbone crossbedding. Overlying channel-fill sands lack the herringbone crossbedding type, but do show good trough crossbedding and planar lamination, with internal scours. No obvious vertical grain-size trends were noted. No burrows were observed within the channel sands. The top of the succession is abruptly overlain by a thinly laminated silty mudstone and mudstone that lacks bioturbation features.

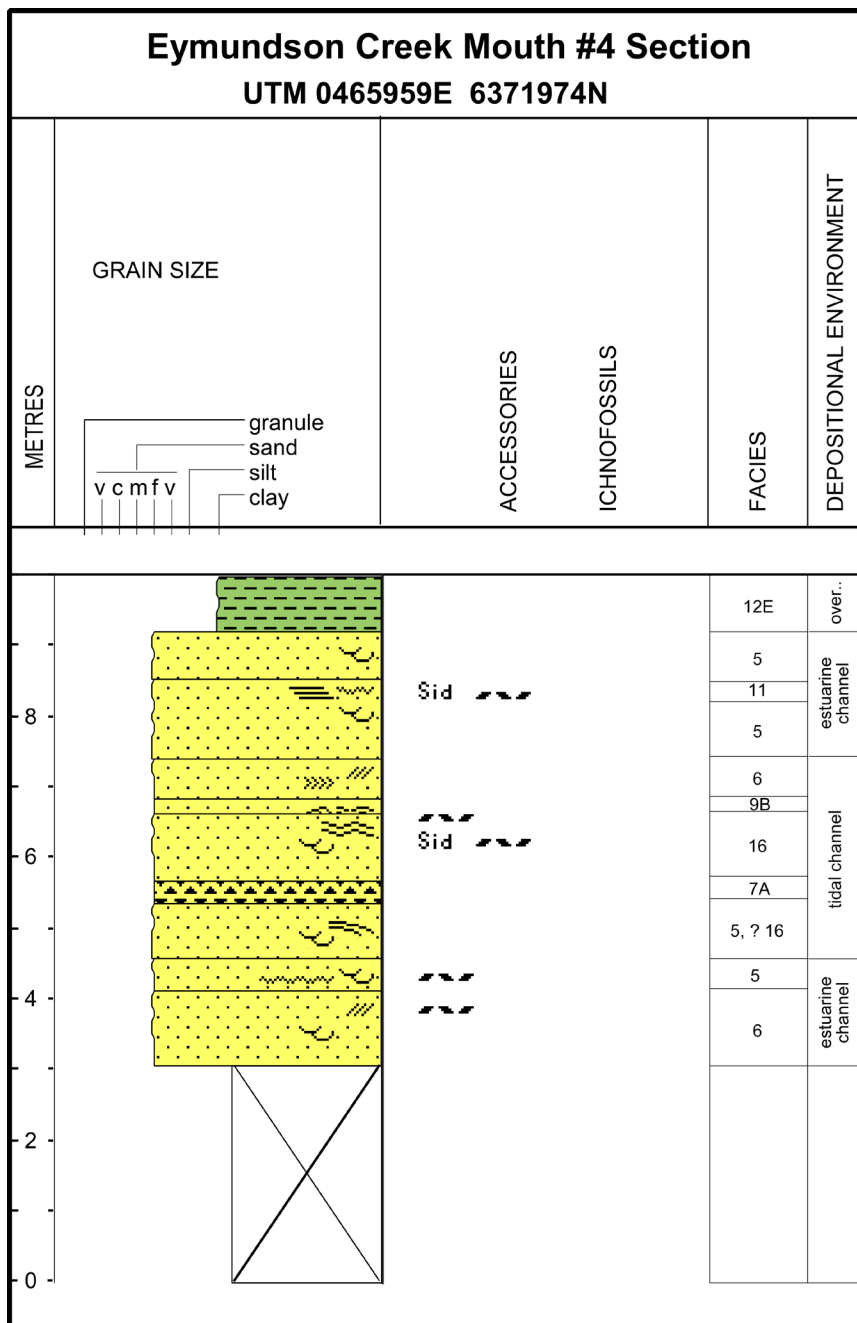


Figure 44F. Measured Eymundson Creek Mouth #4 (from Hein et al., 2000).

Interpretation: The very thick bedding style, common occurrence of internal scours, along with the predominance of trough and planar-tabular crossbedding, indicate sedimentation under high energy conditions. The middle channel fill with large-scale herringbone crossbedding and wavy bedding features indicate tidal influence. No burrows were noted. The sediments at this outcrop section are interpreted as being deposited within interfingering and stacked estuarine and tidal channels. The channels were abruptly abandoned, with only fines deposited rapidly as finely laminated, overbank siltstone and mudstone. All deposits are interpreted as belonging to the Upper McMurray Formation.

14 Outcrop Descriptions: Pierre River, Day 2, Stop 9

14.1 Pierre River Mouth (Lower)

Map Coordinates: 74E/5 Bitumount, Scale 1:50 000, UTM 0462150E, 6367150N

Location and Access: This section is at the northern end of the Bitumount map area, along the west bank of the Athabasca River just upstream from the mouth of Pierre River (Figures 45A and 45B). Access the section by boating downstream from Fort McMurray, the barge landing on the Athabasca River, or by gaining access to the Athabasca River from the landing at the Fort MacKay settlement.



Figure 45A. Aerial photograph of the Pierre River sections.

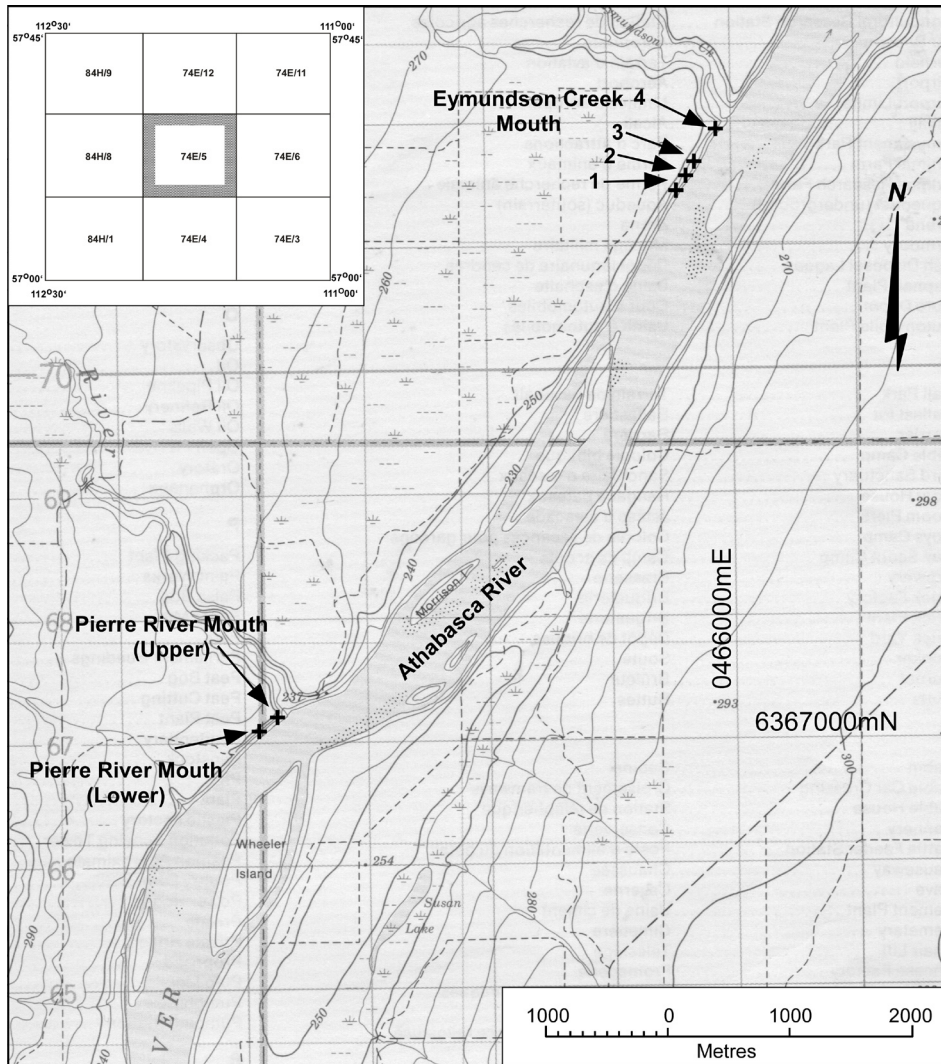


Figure 45B. Topographic map of the Pierre River sections.

Highlights:

- Stacked fluvial, estuarine and tidal channel sediments.
- Very coarse grained, conglomeratic, sideritized fluvial sediment at the base of the section near river level.
- Bay-fill, rooted and coaly coastal plain sediments at the top of the section.

Description: This cutbank is very well exposed and generally accessible (Figure 45C). At the very base of the section is approximately 3 to 4 m of conglomeratic, sideritized oil sand, with common coarse quartz granules and pebbles, many subrounded to angular. The granule to conglomeratic oil sand lacks bitumen saturation where sideritization has occurred, either as cement or replacement of mudstone intraclasts. Well developed trough crossbedding with paleoflows to the north-northeast and northwest are common. No burrows were observed in this lowermost coarse-grained unit. Overlying the sideritized base is about 9 m of pebbly to granular oil sand, alternating with fine to very coarse sand, with abundant internal scours, trough, ripple and planar-tabular, convoluted and herringbone crossbedding. Finer

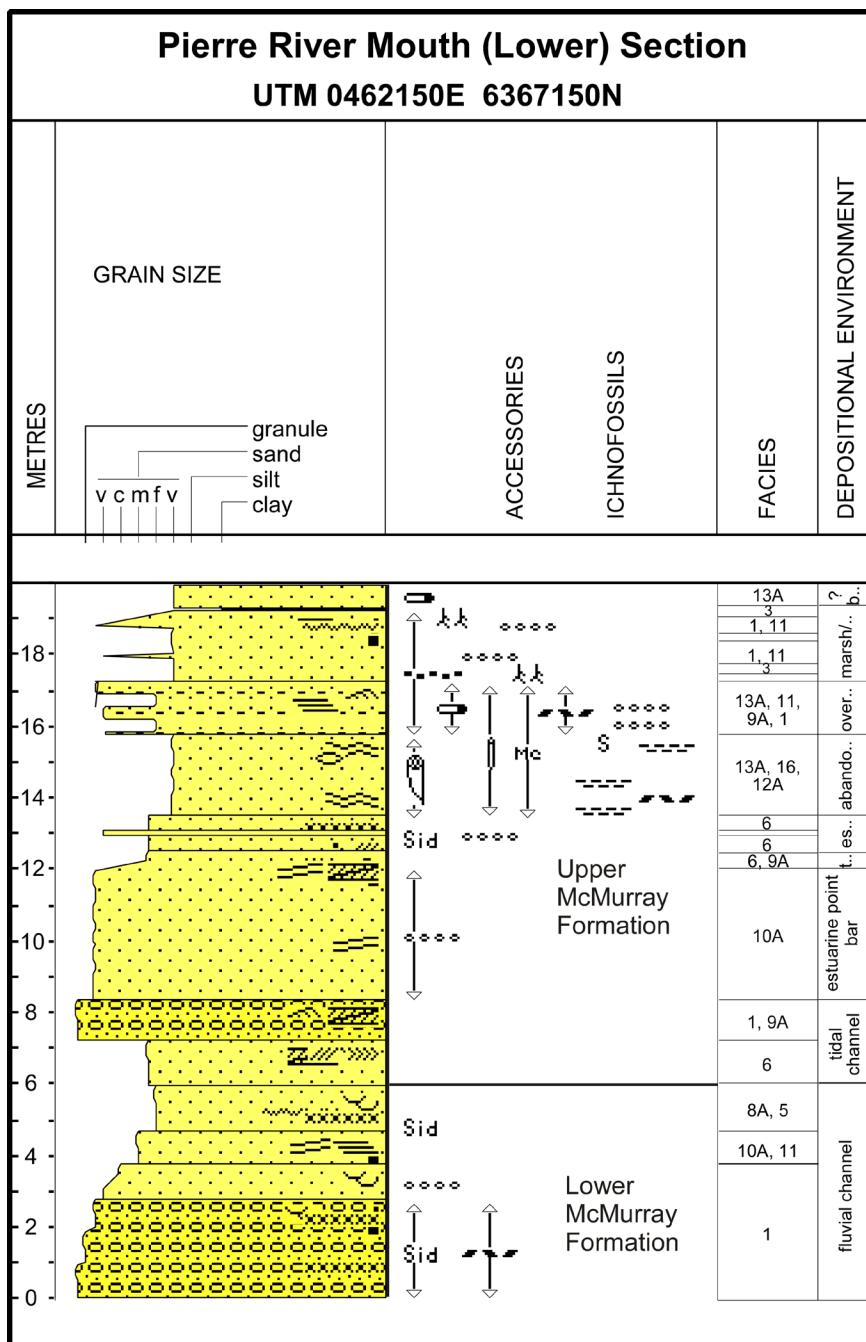


Figure 45C. Measured Pierre River Mouth (Lower).

interbeds show flaser bedding, double mud drapes and reverse-flow ripples. The uppermost 1/3 of the section is more even bedded, finer grained and has abundant *Planolites* and *Cylindrichnus* burrowed zones that alternate with coaly and rooted horizons. Carbonaceous debris is common toward the top, and much of the bedding style comprises wavy bedding, combined flow and wave ripples. The top of the McMurray succession is overlain by a thin (< 300 mm), inaccessible unconsolidated tan Quaternary sand.

Interpretation: The lowermost 6-m of sediment at the base of the succession are interpreted as fluvial channel and bar deposits of the Lower McMurray Formation. These are overlain by stacked estuarine and tidal channel sediment of the lower part of the Upper McMurray Formation. As with the Athabasca River

sinkhole sections, lateral transitions along this outcrop within the lower part of the Upper McMurray Formation show an interfingering of point-bar and channel units. The top of the succession with the wavy-bedding style, combined-flow ripples, abundant burrows, coaly interbeds and rooted horizons are interpreted as coastal plain sediments of the upper part of the Upper McMurray Formation.

14.2 Pierre River Mouth (Upper)

Map Coordinates: 74E/5 Bitumount, Scale 1:50 000, UTM 0462230E, 6367250N

Location and Access: This section is at the northern end of the Bitumount map area, along the west bank of the Athabasca River at the mouth of Pierre River (Figures 45A and 45B). Access the section by boating downstream from Fort McMurray, the barge landing on the Athabasca River or by gaining access to the Athabasca River from the landing at the Fort MacKay settlement. This section is about 100 to 200 m downstream from the Pierre River Mouth (Lower) section, and starts about 3/4 up the hillside in a small overhang-bluff section that faces the Athabasca River. A steep scree slope extends from the base of the section down to river level. The easiest access is to climb up the treed slope from the base of the Pierre River Mouth (Lower) section.

Highlights:

- Stacked, coarsening-upward successions comprising vertical accretion abandoned channel (? drowned estuary), sand flat, marine bay-fill and near shore sediments.
- Excellent trace fossils, including *Planolites*, *Skolithos*, *Gyrolithes* and *Ophiomorpha*.

Description: This cutbank is very well exposed and generally accessible, although as mentioned above the base of the section sits on a steep scree slope that extends down to river level (Figure 45D). At the base of the section is a 1 to 2 m thick, coarsening-upward, sandy mudstone to muddy sand with a high level of bioturbation. Burrows include *Planolites*, *Skolithos* and, at the northern end of the outcrop face, excellent *Ophiomorpha*. Another two coarsening-upward units of burrowed muddy siltstone/silty mudstone overlie this basal unit, each capped by rippled and trough crossbedded sand. Burrow types include escape traces, *Gyrolithes* and *Skolithos* in the sands, and the horizontal *Planolites* within the lower mudstone/siltstone of each coarsening-upward succession. At the top of the exposure is discontinuous interbedded sand and sandy mudstone, locally sideritized, capped by burrowed, rippled sand, with *Skolithos* traces. Rare wave ripples occur within laminated muddy sand at the top of the Pierre River (Upper) Section. In general, the bedding style at this outcrop is even, with little or no crosscutting relationships.

Interpretation: The coarsening-upward successions are all burrowed, and each succession is heavily bioturbated or churned towards the base. The burrow types are more diverse, including *Skolithos* and *Ophiomorpha*, generally not very common within the McMurray Formation. The occurrence of these two types of trace fossils are most characteristic of the *Cruziana* ichnofacies, that often form in subtidal, loose substrates, with moderate energy conditions in shallow water. The occurrence of stacked, coarsening-upward successions may indicate progradation within drowned estuaries, bays and lagoons. This section is interpreted as coastal plain sediments of the upper part of the Upper McMurray Formation.

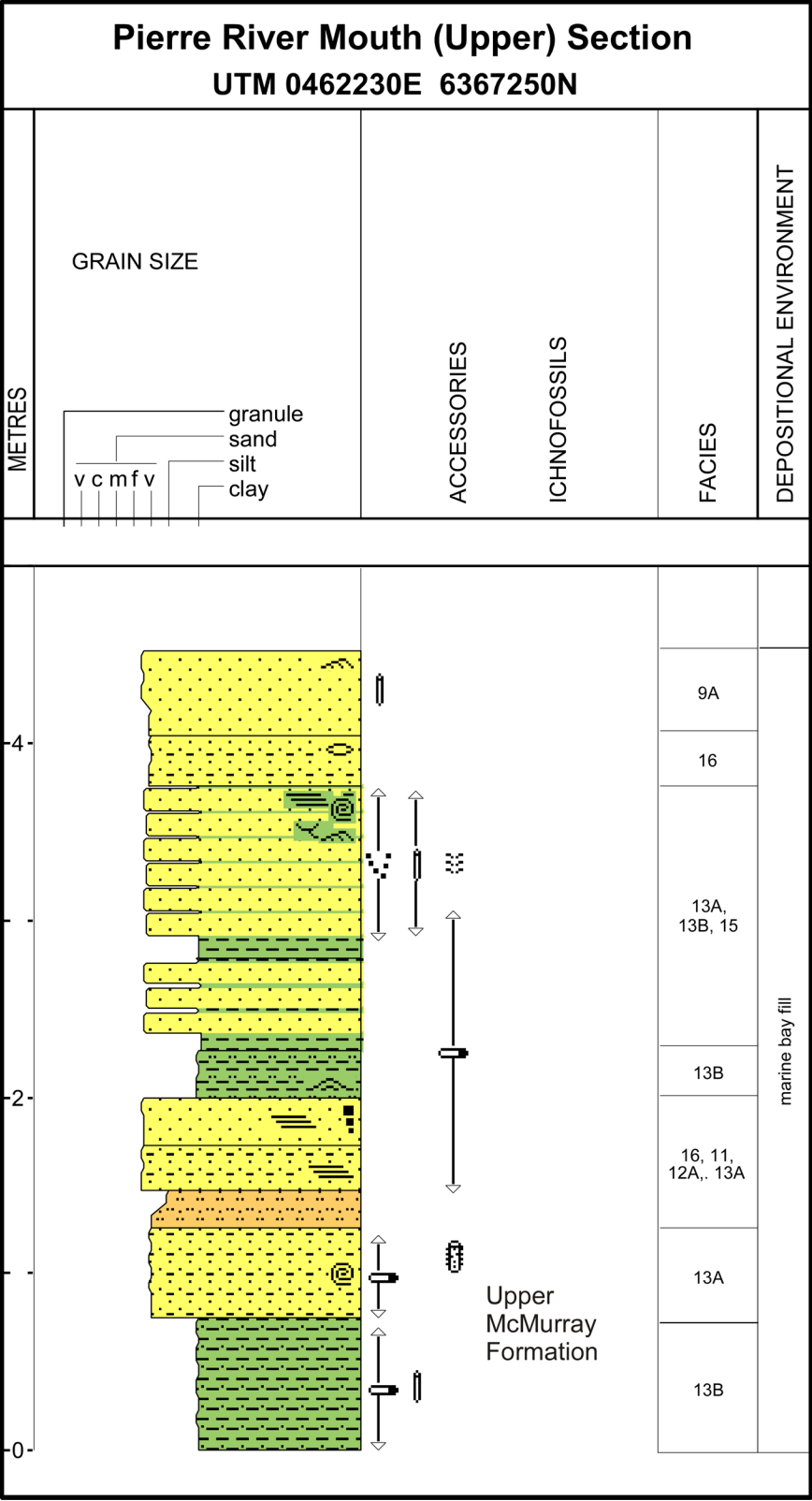


Figure 45D. Measured Pierre River Mouth (Upper) (from Hein et al. 2000).

15 Outcrop Descriptions: Oil Sands Mine Tour, Day 3, Stop 10

Guided tours to the surface mines have to be booked through the Alberta Tourism Office in Fort McMurray. Booked tours occur for the Syncrude Aurora, Syncrude north mine or Suncor Steepbank mine sites, depending upon corporate permission, availability on scheduled tours and accessibility to the mine sites. Tours include a stop at the Wood Bison Viewpoint and at the Crane Lake Nature Trail, each are reclamation sites for the Syncrude and Suncor mines. En route to the mine sites, a brief stop is usually made at the Syncrude Overview and Giants of Mining Exhibit (wood bison sculptures, see cover). Excellent examples of trace fossils occur within the sideritized oil sands used in the display. Descriptions of the mining operations and trace fossils are given in the Edmonton Geological Society Field Guide to the Oil Sands (Paulen et al., 2004).



Figure 46. Syncrude mine in the 1990s (courtesy of Mika Madunicky).



Figure 47. Suncor mine in the 1990s (courtesy of Mika Madunicky).



Figure 48. Cyclic Steam Stimulation wells at Cold Lake (courtesy of Mika Madunicky).

16 Outcrop Descriptions: Fort MacKay Area, Day 3, Stop 11

Note: Optional if low water level and the MacKay River is inaccessible by boat; stops in the Fort MacKay area will be by van and road access and will include the amphitheatre, viewpoint and Beaver River sandstone quarry sections (in lieu of the amphitheatre and karst-fill sections as originally planned by boat). For description of the MacKay River amphitheatre section see Day 1, Stop 5.

16.1 Fort MacKay Outcrops

Access: Along the MacKay River, air photo interpretation identified 68 cutbank sections with exposed outcrops. However, most of these sections are not easily accessible except those downstream near Fort MacKay. The others have to be accessed by ATVs along dirt trails into the MacKay River valley from the Dover River Project (UTF) site, or by boat upstream from the settlement of Fort MacKay, depending upon river level. Access to the outcrops around Fort MacKay is via roads, trails and creek/river courses.

Three outcrop sections in the Fort MacKay area will be visited, including the MacKay River amphitheatre section, MacKay River viewpoint section, and the Beaver River sandstone quarry section (Figures 49A and 49B).



Figure 49A. Aerial photograph of the MacKay River viewpoint section.

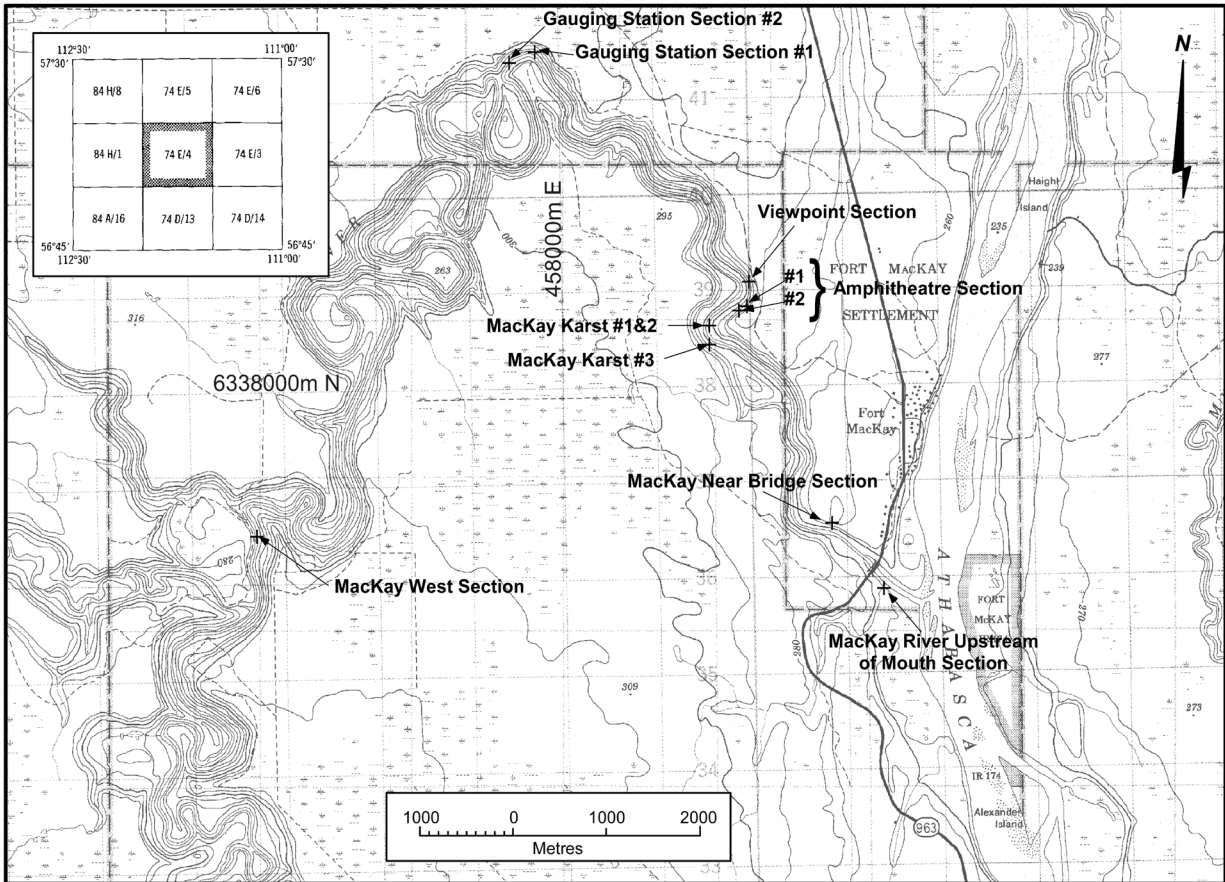


Figure 49B. Topographic map of the MacKay River viewpoint section.

16.2 MacKay River Amphitheatre Sections

Map Coordinates: 74E/4 Fort MacKay, Scale 1:50 000, UTM 0459900E, 6338820N (Section 2)

Location and Access: Drive north of Fort McMurray on Highway 63. Turn northwest (left) from Highway 63 onto the Fort MacKay access road (963 on Figure 49B), marked by a road sign, just north of the highway bridge over Beaver River. Continue on the access road to Fort MacKay, going through town to the north end where there is a fork in the road. Turn left and drive along the dirt road until you reach a fork (the right fork goes to the landfill dump). Take the left fork along the MacKay River. Stop approximately 0.5 to 0.75 km from the fork to the dump (Figures 49A and 49B). Access the trail to the west and walk for two minutes to the cutbank overview of the section at the end of the trail. Easier access down to the base of the outcrop is to the south (left) down a prominent spur that marks the downstream end of the main amphitheatre outcrop. Note: Only drive when roads are dry.

Note: See Day 1, Stop 5 for description and interpretation of amphitheatre.

16.3 Outcrop Descriptions: Fort MacKay Viewpoint, Day 3, Stop 11

16.4 MacKay River Viewpoint Section

Map Coordinates: 74E/4 Fort MacKay, Scale 1:50 000, UTM 0459990E, 6339151N

Location and Access: Go north along the dirt road past the amphitheatre outcrop, continuing until the road comes very close to the river cutbank. On the map, the access to the viewpoint outcrop is where the dirt track crosses the steep contours at the edge of the MacKay River valley (Figures 49A and 49B). Stop and access a trail to the west and walk for one minute to the overview of the valley. This section starts quite high upslope from the river level. Note: Only drive when roads are dry.

Highlights:

- Excellent *Gyrolithes* trace fossils at the top of the section.
- Thick, muddy, vertical accretion abandoned channel fill deposits.
- Estuarine channel and point-bar deposits.

Description: At the accessible portion of the viewpoint section along the MacKay River is a 19 m thick succession (Figure 49C) of well exposed Upper McMurray mudstone and siltstone interbedded with crossbedded sands that overlay a crossbedded, fine to medium-grained sand (Figure 50A). Mudstone intraclasts or reworked *Cylindrichnus* burrow-fills are scattered within the sands. Other trace fossils in the section include *Planolites*, *Skolithos* (Figure 50B) *Cylindrichnus* and *Teichichnus*, and in the top-most beds, excellent *Gyrolithes* (Figure 50C). Although the base of the section tends to be more sand dominated and lacks the *Gyrolithes* traces, no consistent overall coarsening or fining-upwards occur at this section. Overall paleoflows from the ripple and planar-tabular crossbeds are toward the northwest and north. At the top of the section the sediments have an increase in the degree of bioturbation, an increase in the diversity and abundance of trace fossils, along with a more even bedding style, rare ball-and-pillow structures and double-mud drape lamination.

Interpretation: The viewpoint section is interpreted as deposits from an estuarine system, consisting of estuarine point-bar deposits in the lowermost 8 metres, overlain by about 6 metres of estuarine channel-and-point-bar deposits. The estuarine channel sediments are capped by a thin (2 m) veneer of burrowed, vertical accretion, abandoned channel-fill (brackish-bay) deposits. Rare occurrences of double-mud drape lamination suggest there was a tidal influence during sedimentation. Facies observed in this outcrop are commonly seen in core; in some cases abundant *Gyrolithes* traces are dominant (Figure 51).

UTM 0459990E 6339151N





Figure 50A. Overview of the viewpoint section along the MacKay River.



Figure 50B. Ripple and ripple-drift crossbedded sand (Upper McMurray Formation) of the viewpoint section.

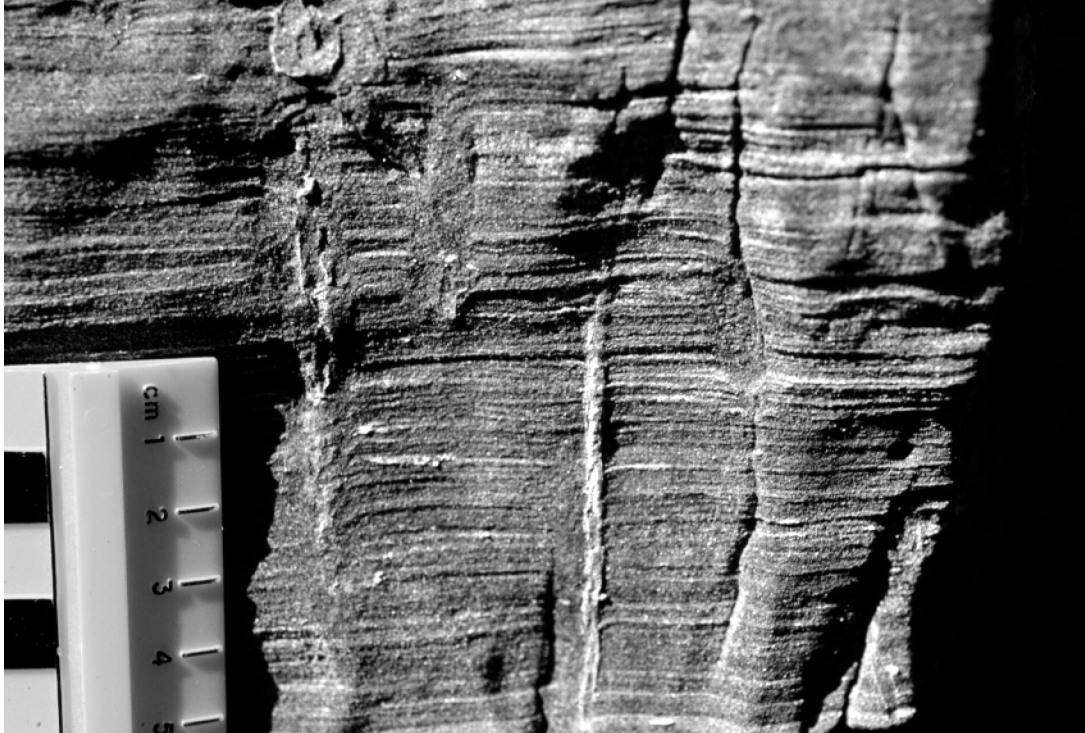


Figure 50C. *Skolithos* trace fossils within planar-laminated sand near the top of the viewpoint section.

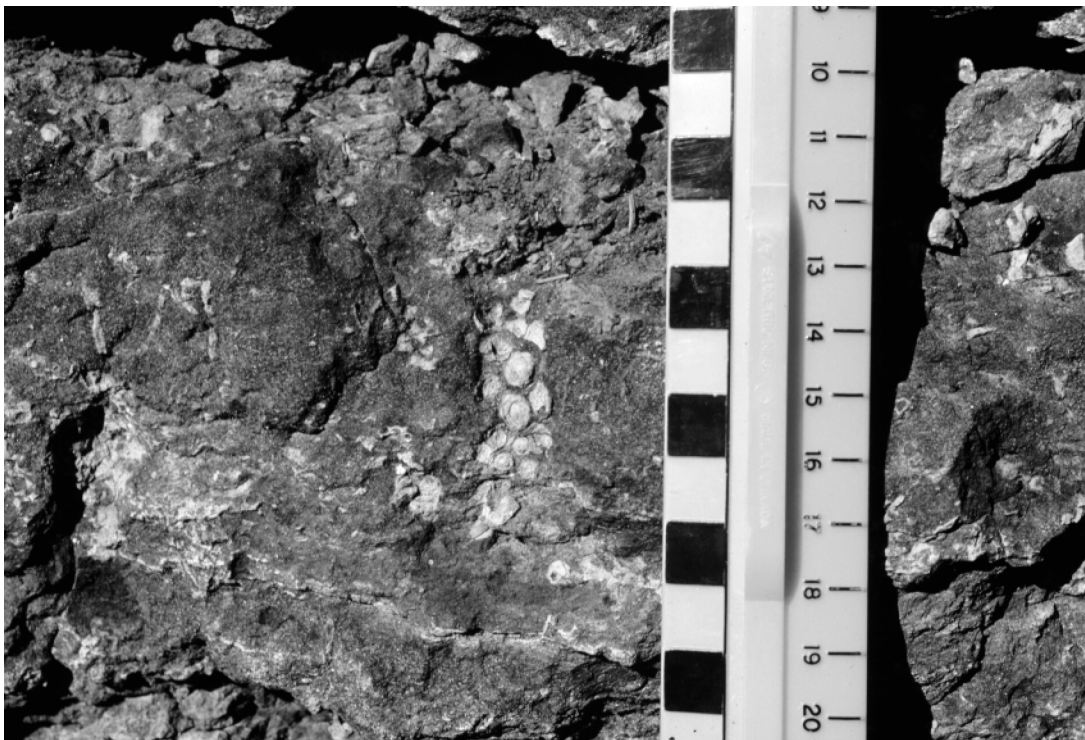


Figure 50D. Inclined and vertical *Gyrolithes* and *Cylindrichnus* traces within burrowed muddy sand (Upper McMurray Formation) of the viewpoint section.

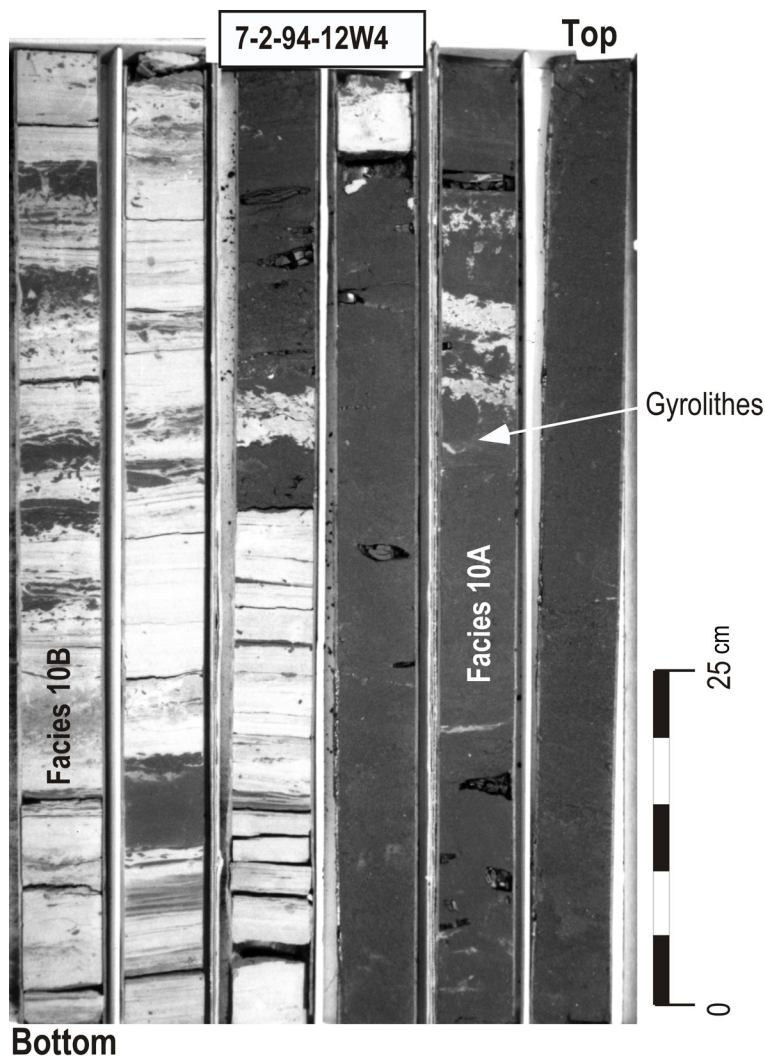


Figure 51. Core photograph of the 7-2-094-12W4 well, with inclined heterolithic stratification (IHS) and prominent *Gyrolithes* trace fossils.

17 Outcrop Descriptions: Beaver River Sandstone, Day 3, Stop 12 (optional, time permitting)

17.1 Beaver River Sandstone Quarry Section

Map Coordinates: 74E/4 Fort MacKay, Scale 1:50 000, UTM 0462350E, 6330850N

Location and Access from Fort MacKay: Travel back from the amphitheatre section through Fort MacKay to Highway 63 going south. About 500 m south of the intersection between the Fort MacKay access road and Highway 63, just north of the bridge over Beaver River (Figure 52A), is a small dirt track into the woods on the east (left) side of the highway. Turn onto the dirt track and follow to a small artificial quarry-pond.

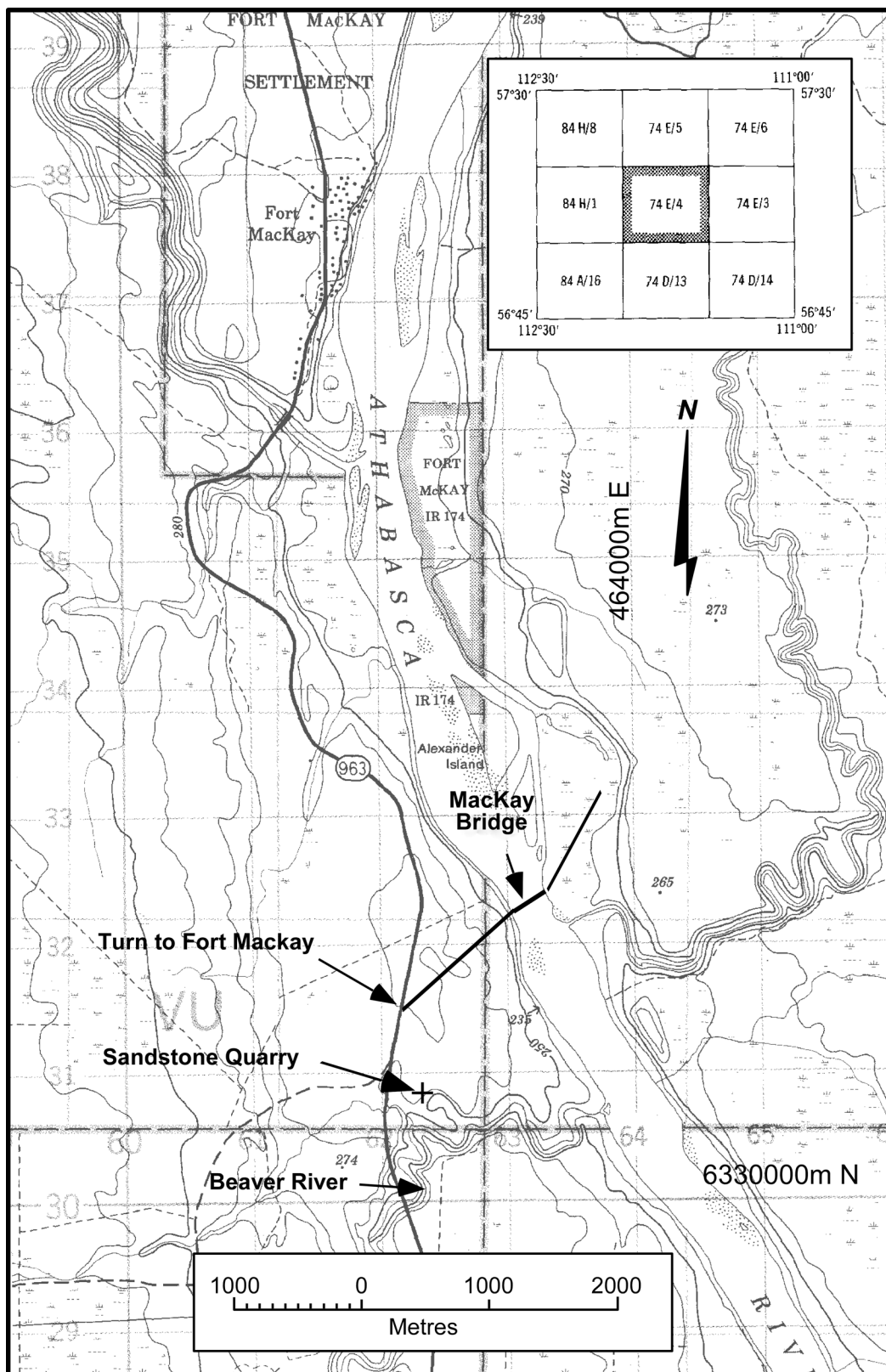


Figure 52A. Topographic map of the Beaver River sandstone quarry section.

Location and Access from Fort McMurray: Travel north on Highway 63 from Fort McMurray to about 500 m south of the access road turnoff to Fort MacKay, just north of the highway bridge over Beaver River (Figure 52A). A small dirt track is located on the east (right) side of the highway. Turn onto the dirt track and follow to the end of the track at a small, abandoned quarry.

Highlights:

- Silica-cemented sandstones within the McMurray Formation.
- Plant fossils and root traces.
- Archaeological site.

Description: Along the northern edge of the water-filled abandoned quarry are small, low and isolated outcrops of the ‘Beaver River sandstone’ (Figures 52B, 53A and 53B), a silica-cemented unit within the McMurray Formation. On bedding plane surfaces and in cross-section are root-trace imprints, some up to 1 cm in diameter. Abundant comminuted organic detritus occurs throughout the sandstone, and isolated loose organic rubble, including fossil stems and branches and coaly debris, are found as float in the area. Limited palynological dating done on a coaly fragment from the sandstone yielded a modest terrestrial assemblage of palynomorphs that appear to be Aptian-Cenomanian.

Historically, First Nation’s people quarried the silica-cemented sandstone at this site (Fenton and Ives, 1982, 1990; Ives and Fenton, 1982). Diagenesis of the Beaver River sandstone has been examined by Brian Tsang as part of his M.Sc. thesis work at the Department of Geology and Geophysics, University of Calgary (Tsang, 1998).

Interpretation: The silica cement makes the sandstone distinct lithologically from the other more typically uncemented McMurray Formation sands. The interpretation is that the silica-cemented Beaver River sandstone was within a paleolow karst feature at the time of cementation, probably associated with silica-saturated connate waters. A number of similar silica-cemented units within the Lower McMurray Formation have also been encountered in subsurface cores from the surrounding area (Figure 54). Quite commonly siderization and siderite cement is associated with the areas that have silica cement. The stratigraphic position, preliminary palynological age and lithological characteristics indicate the Beaver River sandstone at the site is part of the Lower McMurray Formation.

18 Outcrop Description: Saline Creek, Day 3, Stop 12

18.1 Saline Creek Sections

Map Coordinates: 74D/11 Fort McMurray, Scale 1:50 000 (UTM 0478740E, 6283550N, Saline Creek #3 section)

Location and Access: The Saline Creek sections are located approximately 500 m upstream from the mouth of Saline Creek, at its confluence with the Clearwater River (Figures 55A and 55B). Drive north on Highway 63 (Memorial Drive/Saskatchewan Trail) from the southern city limits of Fort McMurray, drive past the Oil Sands Interpretive Centre and the Tourist Information Centre (Port of Entry). Take the next right (east) onto Gregoire Drive. Park near the intersection of Gregoire Drive and Highway 63. Walk about 15 minutes downhill along the paved bike trail, cutting eastward to Saline Creek once you see the outcrops to the south near a major culvert.

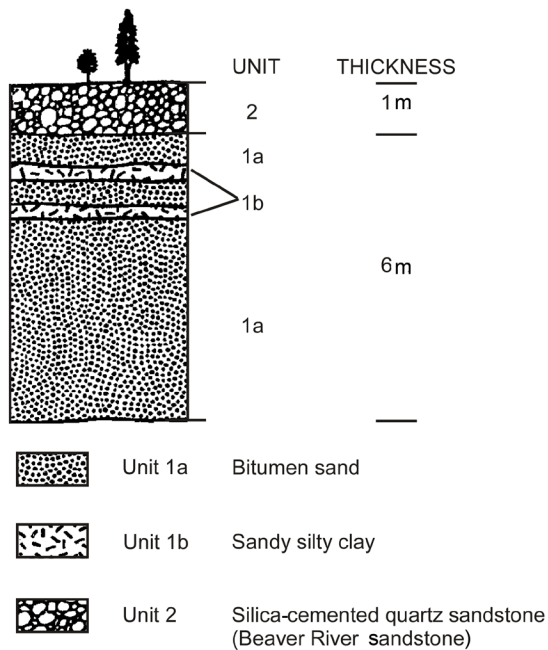
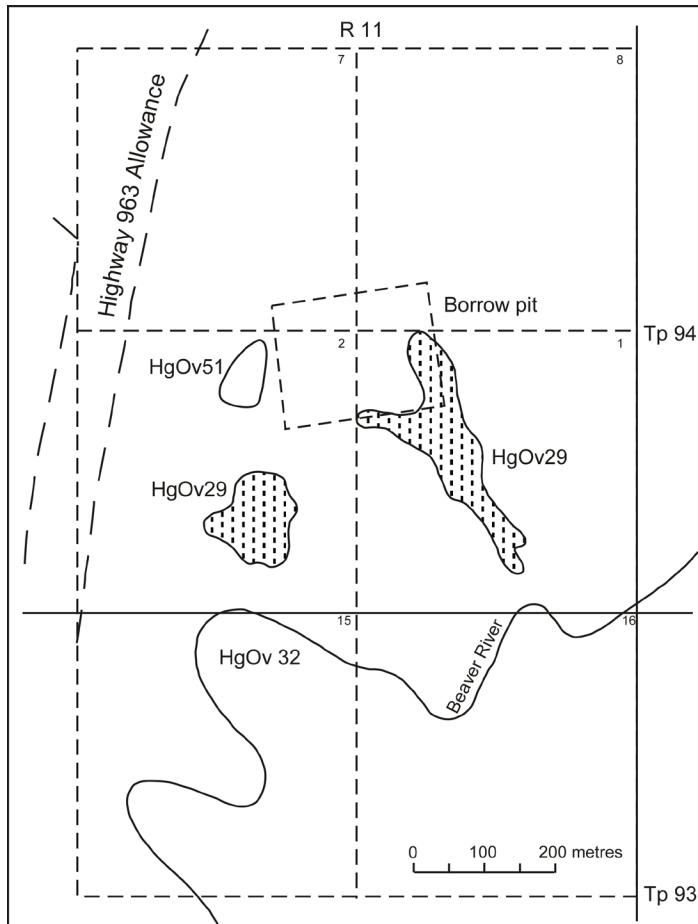


Figure 52B. Detailed map showing the Beaver River Quarry and the borrow pit in which the Beaver River sandstone is exposed, with geological section at the Beaver River quarry borrow pit (from Fenton and Ives, 1982, reprinted in Hein et al., 2000).



Figure 53A. Silicified Beaver River sandstone (Lower McMurray Formation) exposed in a quarry near the Bridge River crossing, near Fort MacKay.



Figure 53B. Clean, silicified, rooted, quartz sandstone of the Beaver River sandstone (Lower McMurray) (from Hein et al., 2000).

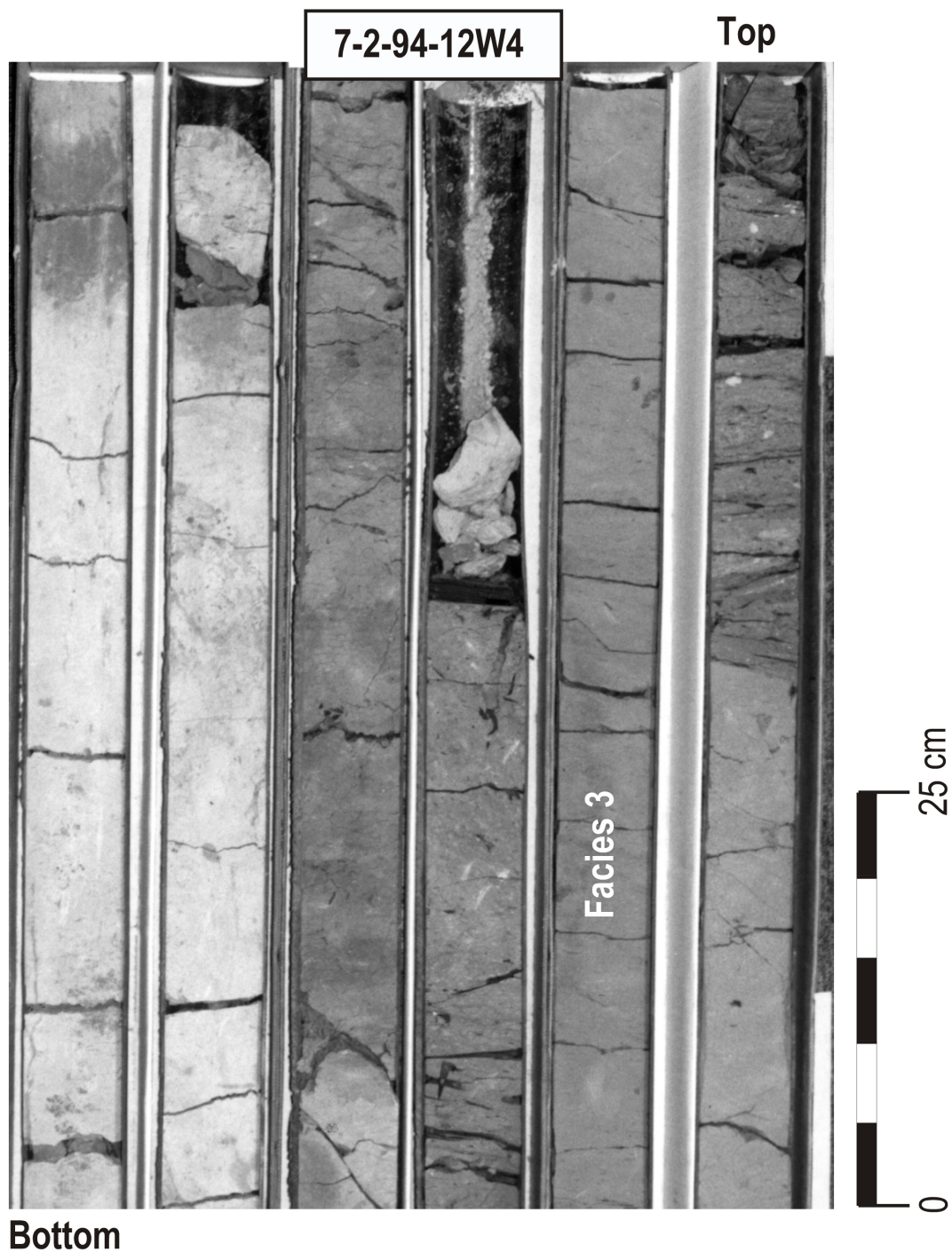


Figure 54. Core photograph of the 07-2-094-12W4 well, with indurated, argillaceous sandy siltstone, siliceous and very slightly calcareous in cemented zones, overlain by light to medium grey, carbonaceous, organic-rich, silty mudstone.



Figure 55A. Aerial photograph of the Saline Creek section.

Highlights:

- Thick, stacked, tidal channel sands.
- Excellent trough and planar-tabular, and planar-tangential crossbedding with reversing toset ripple crossbeds and tidal couplets.
- Multiple cut and fills and rapid facies changes.

Description: Along Saline Creek, medium-grained, estuarine sediments are well exposed in a series of small cutbank sections, ranging from 8 m to > 30 m high (Figures 55C to 55F). The estuarine sediment shows abundant crossbedding, including trough, high-angle planar-tabular, planar-tangential and rippled units. Rhythmic tidal couplets and reverse-flow ripples occur along some of the crossbeds. Paleoflow directions on the trough crossbeds are to the northeast; to the east-northeast for planar-tabular crossbeds; and dominantly to the north in rippled sands. Mudstone interbeds and lenses are rare. Locally, mudstone-clast breccia beds, occur ranging from 3 to 5 cm thick. Mud-lined *Cylindrichnus* burrows are rare and mainly seen as resedimented clasts within the mudstone breccia beds. Other rare occurrences of *Cylindrichnus* are in place-burrows found within trough crossbedded sands at the Saline Creek #1 section.

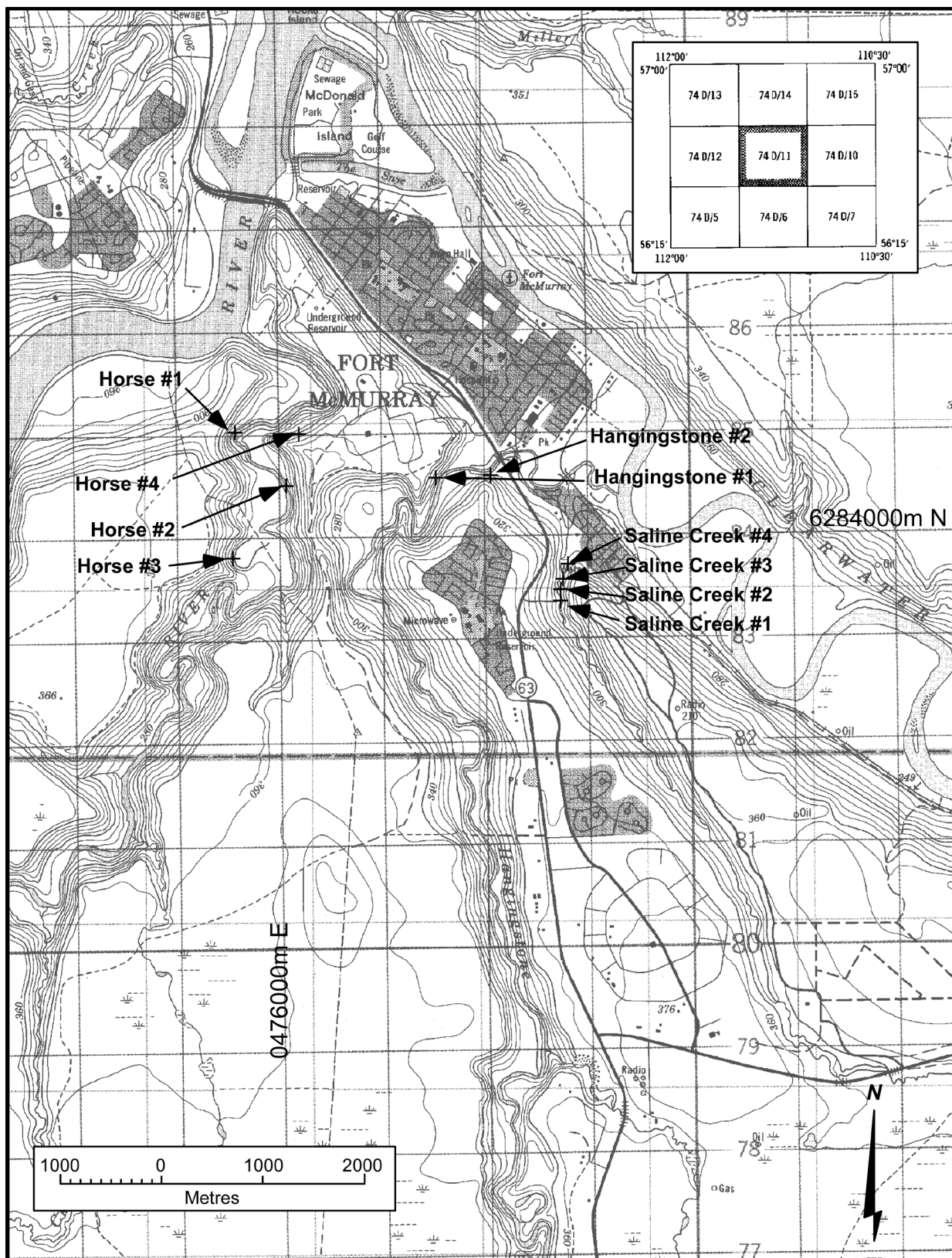


Figure 55B. Topographic map of the Saline Creek section.

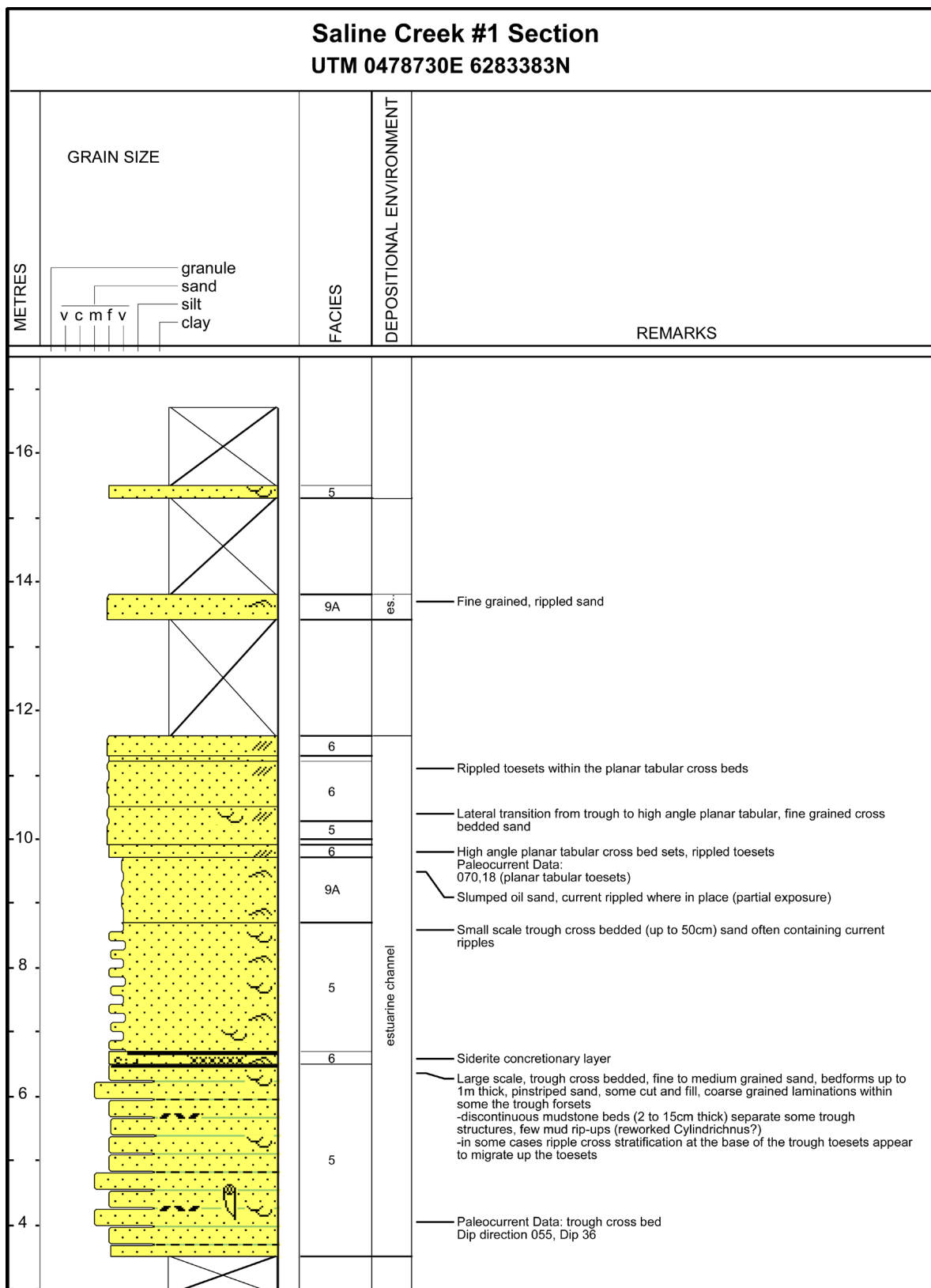


Figure 55C. Measured Saline Creek #1 section.

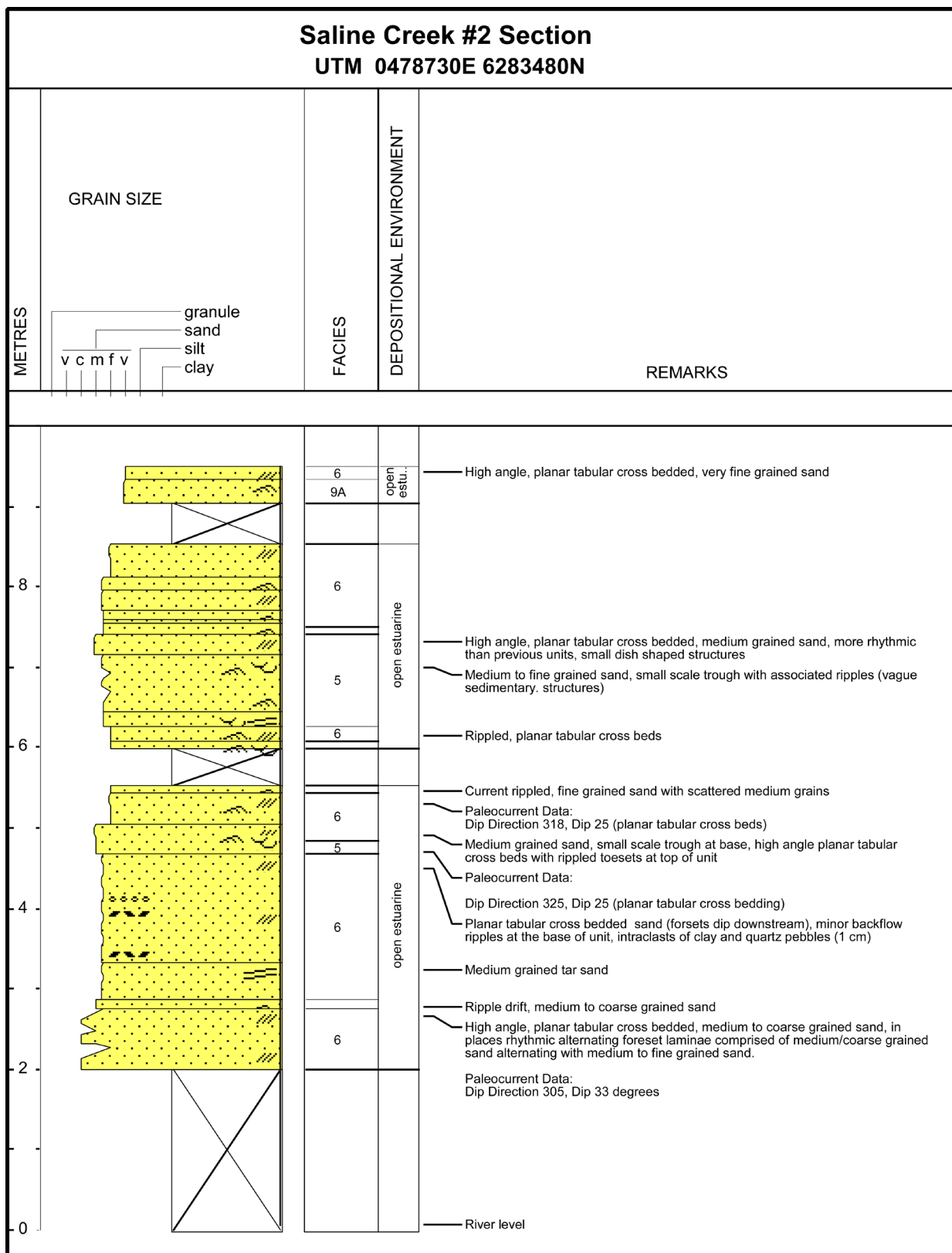


Figure 55D. Measured Saline Creek #2 section.

Saline Creek #3 Section				
UTM 0478740E 6283550N				
METRES	GRAIN SIZE	FACIES	DEPOSITIONAL ENVIRONMENT	REMARKS
	<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="text-align: center;">v</div> <div style="text-align: center;">c</div> <div style="text-align: center;">m</div> <div style="text-align: center;">f</div> <div style="text-align: center;">v</div> </div> <div style="display: flex; justify-content: flex-end; margin-top: -20px;"> <div style="text-align: right; padding-right: 10px;">granule</div> <div style="text-align: right; padding-right: 10px;">sand</div> <div style="text-align: right; padding-right: 10px;">silt</div> <div style="text-align: right;">clay</div> </div>			
24				
22				
20				
18				
16				
14				
12				
10				
8				
6				
4				
2				
0				

Figure 55E. Measured Saline Creek #3 section.

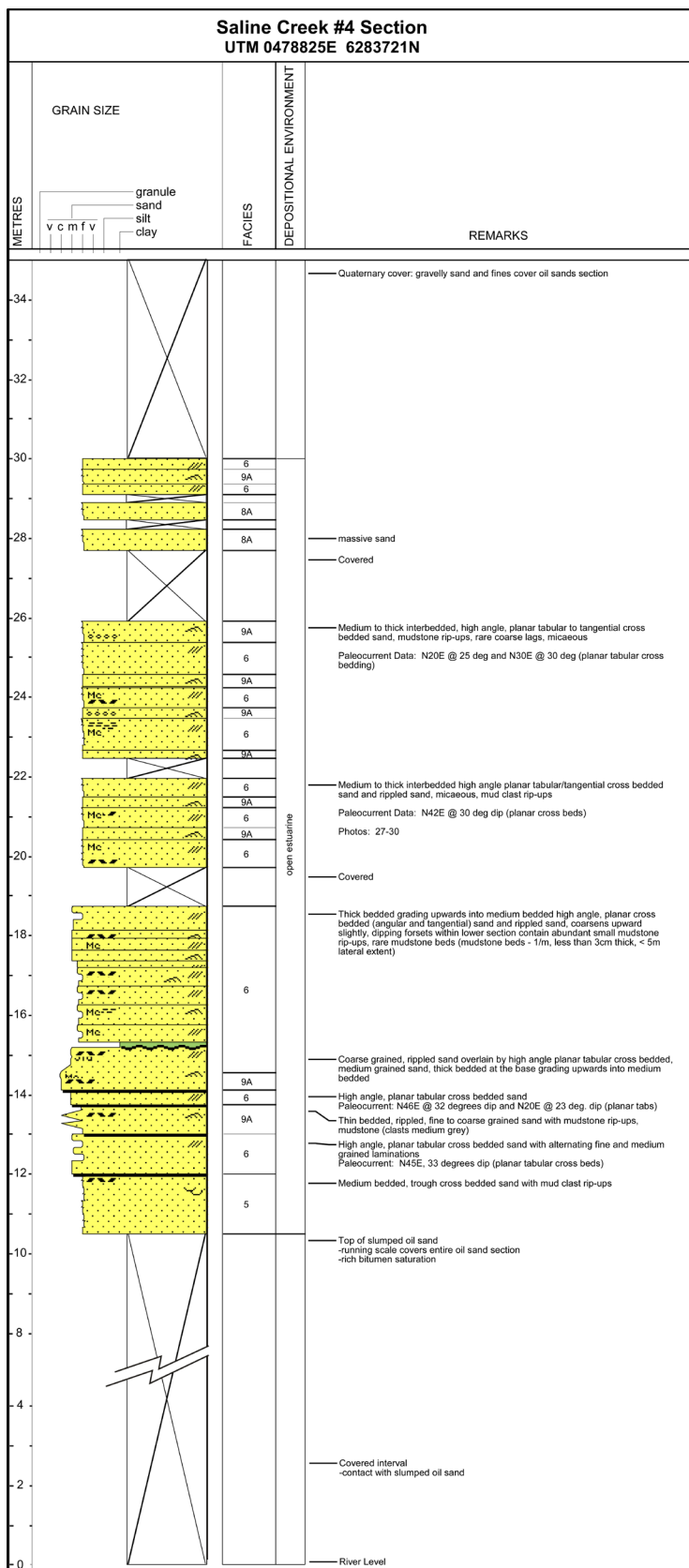


Figure 55F. Measured Saline Creek #4 section (from Hein et al., 2000).

At the top of the outcrops along Saline Creek is exposed a thin (< 1 m), bioturbated, greenish cast sandstone. This is generally inaccessible, but can be seen along the trails and within overhangs above the main outcrop sections. This is the glauconitic Wabiskaw C unit (Wabiskaw Member, Clearwater Formation) that unconformably overlies the McMurray Formation in this area.

Interpretation: The dominance of high-energy flow features, the relatively uniform paleoflow trends, along with a secondary tidal influence, indicate these sediments were deposited within high-energy estuarine channels, as bedload-dominated systems. The fine grained nature of the sediment, the occurrence of burrows (both within mudstone intraclasts and in sands), and the tidal sedimentary structures indicate the sediment does not belong to the Lower McMurray Formation, but rather represents main channel sediments of the Upper McMurray Formation.

19 Hangingstone River Outcrop Description, Day 3, Stop 13

19.1 Hangingstone River Outcrop

Map Coordinates: 74D/11 Fort McMurray, Scale 1:50 000, (Hangingstone River #1 Section UTM 0477530E, 6284570N)

Location and Access: This section is approximately 2 km upstream from the mouth of the Hangingstone River, at its confluence with the Clearwater River (Figures 56A and 56B). Drive north on Highway 63 (Memorial Drive/Saskatchewan Trail) from the southern city limits of Fort McMurray, drive past the Oil Sands Interpretive Centre and the Tourist Information Centre (Port of Entry). Take the third right (east turn) onto Hospital Street, then an immediate left onto a bridge over Highway 63 (Memorial Drive/Saskatchewan Trail). Turn left (southeast) onto Abasand Drive and continue into the Greyling Terrace Subdivision. Park at a cul-de-sac near the river (either Graham Place or Gardiner Place). At the end of each cul-de-sac is a public access gate to the trail along the north side of Hangingstone River. Walk upstream (west) along the trail for about 5 minutes to the first outcrop on the north bank.

Highlights:

- Thick mudstones at the base of the sections.
- Estuarine channel and point-bar deposits.
- Coquinas and ironstone concretions and cemented ledges, from which dinosaur, pleisiosaur and mosasaur remains have been found in float.
- Contact between the McMurray Formation and the glauconitic Wabiskaw C sand.

Description: In this thick 50 m high outcrop section, Estuarine sediment is exposed (Figure 56C). The succession at this outcrop starts with a fine-grained mudstone, mainly slumped at the base of the outcrop. This mudstone is overlain by sediment with abundant crossbedding, including trough, high-angle planar-tabular, planar-tangential, low-angle sandy and muddy inclined units (Figure 56C). Mudstone interbeds and lenses are common, with an increase in frequency and thickness going upsection. Concomitant with this increase in mudstones is also an increase in bioturbation intensity, with the most common types being *Cylindrichnus* and horizontal *Planolites* and rare vertical *Skolithos*. Thin, indurated coquina beds are in the middle and upper parts of the section.

At the top of the outcrop is exposed approximately 4.5 metres of glauconitic, bioturbated, well sorted sand. This is the Wabiskaw C unit (Wabiskaw Member, Clearwater Formation) that unconformably



Figure 56A. Aerial photograph of the Hangingstone River section.

overlies the McMurray Formation in this area. The Wabiskaw C is, in turn, unconformably overlain by Quaternary sediment.

Interpretation: The recessive basal mudstone is interpreted as an abandoned channel, vertical accretion deposit. Thick estuarine channel and point-bar sands overlie it. Coquinas are interpreted as storm-surge channel deposits. Although there is limited biostratigraphic dating from this outcrop, what is available indicates brackish water (not fluvial) settings, indicating this section is Upper McMurray.

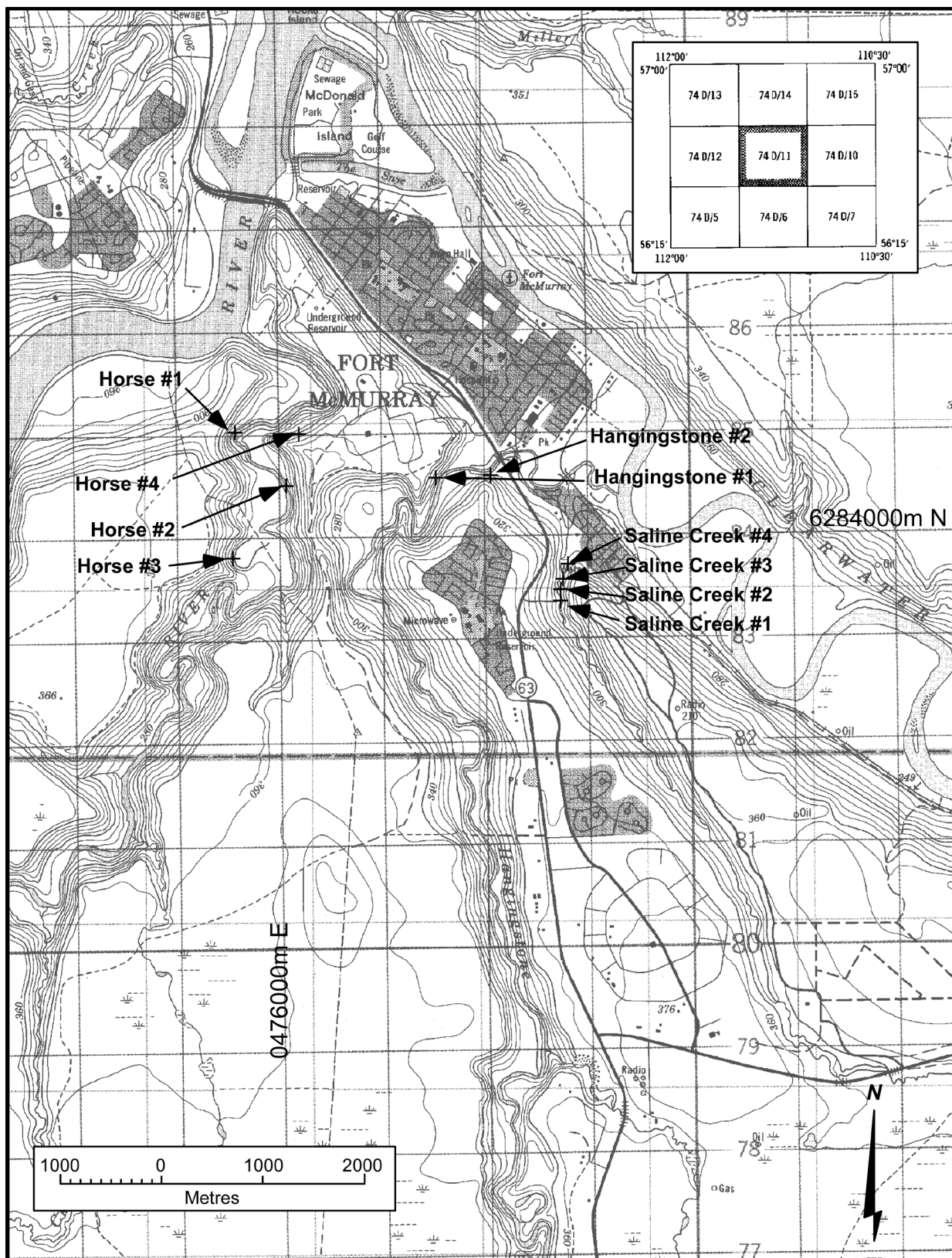


Figure 56B. Topographic map of the Hanginstone River section.

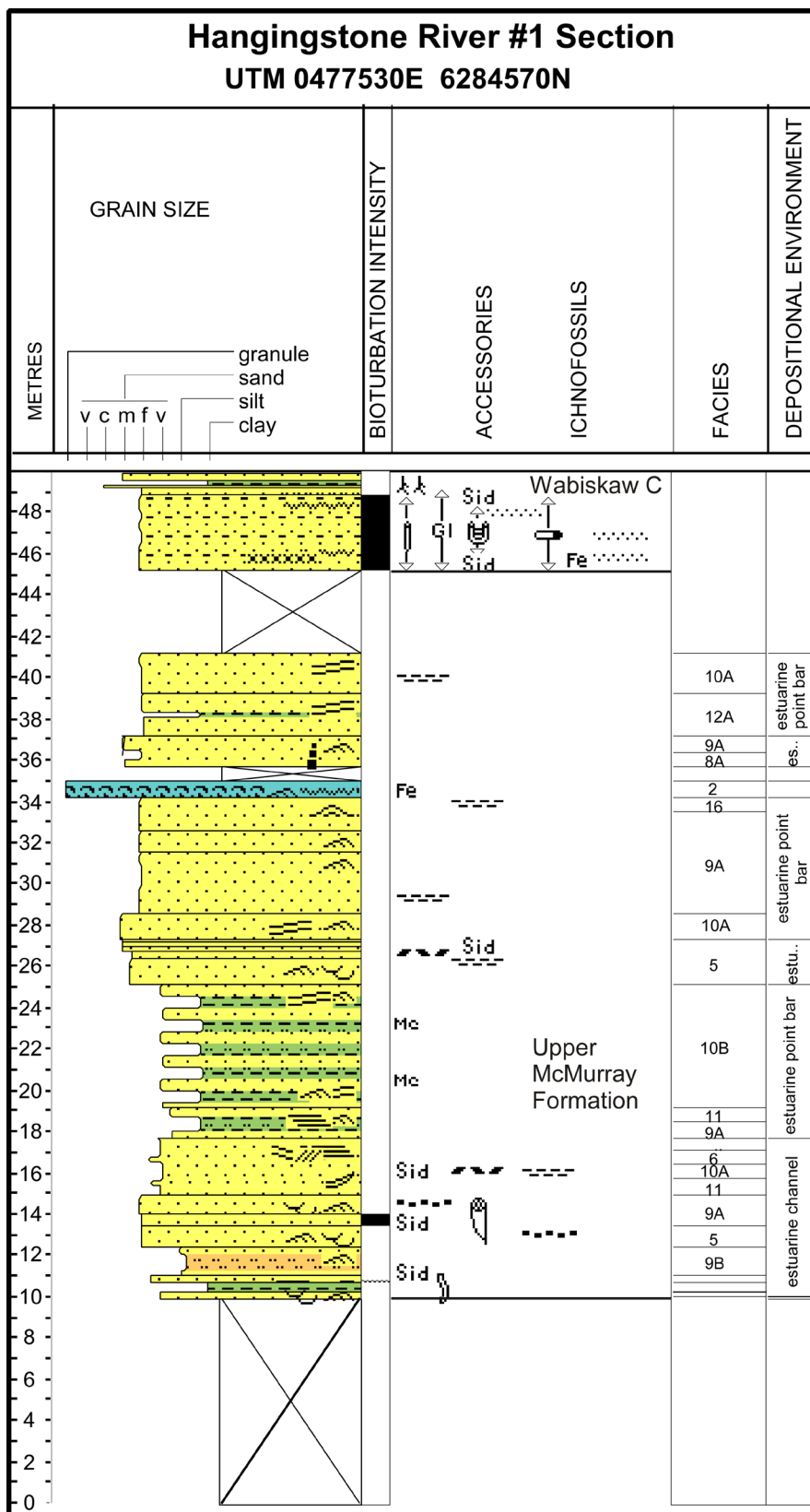


Figure 56C. Measured Hanginstone River #1 section (from Hein et al., 2000).

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Appendix 1 - Historical Development of Fort McMurray and the Oil Sands Industry

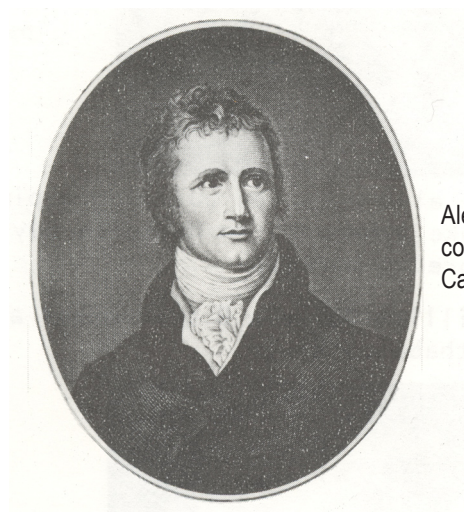
Fort McMurray was named after the Chief Factor William McMurray, who managed the trading post along the banks of the Athabasca River. This trading post served as a mainstay for many entrepreneurs involved with the development of northeast Alberta. In 1999, Fort McMurray had a population of >36 000, with about 43 000 in the regional municipality of Wood Buffalo. Studies by Statistics Canada predict that by 2005 Fort McMurray will have an urban population of 48 000.

As stated previously there has been a long (~ 90 yr) historical development of the oil sands industry in northeast Alberta. Maurice Carrigy originally compiled the history of the oil sands discovery and development in 1965. In 1989, Dr. Karl A. Clark's daughter, M.C. Sheppard, published her father's letters and notes through the University of Alberta Press. Since then, summaries of this historical overview are given by Carrigy and Kramers in 1973 (reprinted in Wightman et al., 1992) and updated by Hein in 2000. Many of the original archival photographs were published in Carrigy and Kramers' (1973) *Guide to the Athabasca Oil Sands Area*, which is now out of print. A brief overview of the Fort McMurray area and oil sands industry is summarized as follows.

1778 – Peter Pond was the first European explorer to visit the Clearwater and Athabasca rivers, noting that the local Athabasca aboriginals were using heavy tar along the outcrops in the river valleys to caulk and waterproof their canoes.

1787 – A trading post was founded, abandoned three years later.

1792 – Alexander Mackenzie traversed the Methys Portage, entering the Clearwater-Athabasca River system and described the oil sands.



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

1819 – Sir John Franklin made notes along the Athabasca River between the forks with the Clearwater and Lake Athabasca, on his ill-fated voyage to find the Northwest Passage.

1848 – Sir John Richardson, on his unsuccessful quest to find the missing Franklin Expedition, made geological notes of the oil sands and correlated them with the Devonian shales in upstate New York.

1879 – Hudson's Bay Company built a new trading post along the Athabasca River, near a present-day go-cart track.

1882 – Dr. Robert Bell of the Geological and Natural History Survey of Canada (now the Geological Survey of Canada) examined the oil sands, proposed a Devonian source of the oil, hosted within Cretaceous sands, and stated that a hot water-extraction process for bitumen recovery may be feasible.



1888 – R.G. McConnell (left) of the Geological and Natural History Survey of Canada gave the geological description of the oil sands, correlated them with the Dakota sandstone in the U.S. Western Interior Basin, and suggested that lighter oils in the same strata would occur downdip at Pelican Rapids (photo courtesy of the Geological Survey of Canada - Ottawa).



1906 – Count Alfred von Hammerstein (left) drilled for oil in Devonian limestone along the banks of the Athabasca River and discovers salt. Later, a hot-water process was used at Waterways to extract the salt, by injecting hot water down the shaft to dissolve the salt, pumping up the brine and drying it in salt pans along the river. This saltwater process had remarkable similarities to the present day Cyclic Steam Stimulation (CSS) process used to extract bitumen from depth at Cold Lake. The Waterways salt plant closed in 1950 with the opening of a new salt plat at Elk Point, Alberta. (photo courtesy of the E. Brown collection, Royal Alberta Museum, Edmonton).

1912 – Fort McMurray experienced a small economic oil boom.

1913 – Sidney Ells (right) of the Mines Branch in Ottawa began a detailed geological survey of the oil sands along the Athabasca River, hauling out over 9 tons of oil sands by backpacking and dragging scows up the Athabasca. Later, in 1915, he demonstrated potential economic benefit of the oil sands by paving streets in both Jasper and Edmonton (photo courtesy of the Royal Alberta Museum, Edmonton).



1917 – Dr. F.H. McLearn (below) of the Geological Survey of Canada described a type section for the McMurray Formation. (Photograph courtesy of the Geological Survey of Canada, Ottawa).



1920 – D. Diver was the first to use in situ methods for commercial bitumen production from the oil sands by lowering a heating unit down a well near Fort McMurray (Sec. 9, Twp. 89, Rge. 9W4th Meridian). (photo from the J.A. Allan collection, courtesy of the Alberta Research Council, Edmonton).



1921 – John Allan (right), founder of the Alberta Geological Survey, then part of the Alberta Research Council, first published on the extraction of bitumen from the Athabasca Oil Sands.

1925 – The Northern Alberta Railway was extended to Waterways to ship the salt deposits south. In 1989, Canadian National closed the railway to Waterways, but there are proposed plans (in 2004) of a new railway line being built to accommodate the rapid oil sands expansion in the area.





1925 – Dr. Karl Clark (left), at the Alberta Research Council, and Sidney Blair, at the University of Alberta, built a hot-water separation plant for bitumen extraction at the Dunvegan rail yards in Edmonton.

1926 – Sidney Ells, with support from Max Ball, drilled and cored the oil sands at Mildred Lake – Ruth Lake area, immediately west of the present Suncor and Syncrude plants, and also drilled and cored oil sands wells east of the Steepbank River, and in the Horse River areas. Today, some of these original cores are stored at the Geological Survey of Canada office in Ottawa. The Northern Alberta Railway line was finished to Waterways (right).



1936 – Max Ball built an extraction plant on the Horse River, followed in 1940 by the Abasand (short for Athabasca Sands) separation plant (above), along the Horse River, near the present subdivision of Abasand Heights in the town site of Fort McMurray. In 1941, the Abasand plant processed 19 000 tons of sand yielding 17 000 tons of bitumen. This bitumen was then reprocessed into fuel oil, diesel fuel, gasoline and coke. In 1941, the Abasand plant burnt down, rebuilt in 1942 and 1943, then destroyed again in 1945.

1942 – L.R. Champion took control of the International Bitumen Company. In 1954, it was taken over by Great Canadian Oil Sands Ltd.

1947 – Canadian Mines Branch completed its drilling and reserves estimates of the oil sands to be 1.75 billion tons of commercial grade oil sands. The richest deposit was located at Tar Island, along the Athabasca River, at the location of the present Suncor tailings pond.

1948 – Alberta Government builds the Bitumount plant and made a commercial test of Karl Clark's hot-water separation process, with the production of 500 tons per day.

1950s – Royalite (independent subsidiary of Imperial Oil Company) pioneered exploration, development and production of the Athabasca Oil Sands. In 1962, Royalite Oil Company formed a consortium with two other companies, forming the legacy of Syncrude, which was incorporated in 1964.

1951 – The first Athabasca Oil Sands Conference, sponsored by the Alberta Government, was held in Edmonton, after which the government published its leasing policy for oil sands and the first leases were issued.

1957 – Shell Oil Company began experiments on in situ steam drive and, by 1962, applied to the Alberta Oil and Gas Conservation Board (Alberta Energy and Utilities Board) to produce 130 000 barrels per day of bitumen by an in situ steam process.

1962 – Great Canadian Oil Sands Ltd. received permission from the Alberta Oil and Gas Conservation Board (Alberta Energy and Utilities Board) to produce 31 500 barrels per day from the oil sands at the Tar Island plant.

1964 – Great Canadian Oil Sands Ltd. (controlling interest by Sun Oil Company of Pennsylvania, now Suncor) began to build its first plant north of Fort McMurray. Underground pipelines were built to transport the synthetic crude oil to market in Alberta and Eastern Canada. At that time, according to the local Chamber of Commerce, Fort McMurray's slogan was "We've ships and oil and tar and brine, the port of the north at the end of the line."

1967 – Great Canadian Oil Sands Ltd. opened the first commercial oil sands plant and showed that oil sands could be commercially developed and upgraded to synthetic crude oil.

1968 – Muskeg Oil Company (Amoco) applies to the Alberta Oil and Gas Conservation Board (Alberta Energy and Utilities Board) to produce 8 000 barrels per day of bitumen by modified in situ combustion process.

1974 – Groundbreaking was done for Syncrude Canada's oil sands plant, near Mildred Lake, with the largest building boom in Alberta's history. Alberta Oil Sands Technology and Research Authority (AOSTRA) was formed to provide funding and synergies needed for research and development dedicated to bitumen extraction and upgrading.

Mid-1980s – World oil prices slumped, with recession in 1986. Alsands and OSLO oil sands plants were cancelled.

1984 – AOSTRA built the Underground Test Facility (UTF) at the present Dover River Project operated by Paramount Ltd. The UTF tested horizontal wells and Steam Assisted Gravity Drainage (SAGD). (Lee and Stroich, 2004; Rach, 2004; Ito, 1999; Komery et al., 1999; Luhning and Luhning, 1999; O'Rourke et al., 1999; Butler, 1998; Ross, 1998).

1996 – The Regional Municipality of Wood Buffalo was formed, the largest municipality in North America.

1997 – The Alberta Energy and Utilities Board held an inquiry concerning potential adverse effects of associated gas production on in situ bitumen production. This was followed with publication in 1998 of the results of the Alberta Energy and Utilities Board inquiry concerning bitumen and gas co-production in oil sands area. Following the inquiry, the Board held a number of gas-over-bitumen hearings for co-production concerns in the Athabasca area and completed a regional geological study of the Athabasca deposit. A final gas-over-bitumen hearing for the Athabasca Wabiskaw-McMurray was scheduled in 2004. For more information regarding these issues, check the following site and links: www.eub.gov.ab.ca/BBS/new/Projects/GasBitumenPolicy.htm.

1999 – The Albion Sands project was announced by Shell Canada and partners.

2003 – Syncrude opened the North mine and was working on the Aurora Mine. Suncor's new Steepbank mine went on production, and project Millennium was ongoing. Mobil Oil's Kearl Lake project was underway.

2004 – Japan Canada Oil (JACOS), CS Resources, Paramount's Dover Project, Petro-Canada's MacKay River, Deer Creek's Joslyn Project, CNRL's Ells, Suncor's Firebag, Synenco's Northern Lights, Mobil's Kearl Lake, TotalElfina-Gulf Surmont, among others, were all underway in construction, pilot projects or continued growth. According to the Oil Sands Developers of Alberta, about \$21 billion in projects were announced for the next decade in the Athabasca deposit (cf. Moritis, 2004).

Appendix 2 - Definition of Stratigraphic Markers ('picks') with Quality Codes

(modified from Wynne et al., 1994 and Hein et al., 2000)*

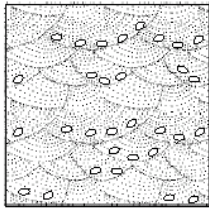
Pick	Type of Surface	Description	Quality Code**
T21	Transgressive	Wabiskaw Marker Top Wabiskaw Mbr. 'A'	Good–Very Good
T15	Transgressive	Top Wabiskaw Mbr. 'B'	Good–Very Good
E14	Major Erosion	Wabiskaw Internal Incision	Good–Very Good
T11	Transgressive	Base First Regional Marine Shale in the Clearwater Fm. Top Wabiskaw Mbr. 'C'	Very Good–Excellent
T10.5	Transgressive	Top Wabiskaw Mbr. 'D' Incised Valley-Fill Deposit	Excellent–Very Good
E10	Disconformity/ Unconformity	Top Upper McMurray Fm Major Erosion Surface	Excellent–Very Good
E5	Disconformity/ Unconformity	Top Lower McMurray Fm. Major Erosion Surface	Variable Very Poor–Fair
Sub-Cret.	Unconformity (Pal.)	Base of McMurray Fm Major Erosion Surface	Variable Very Good–Excellent (However this is sometimes difficult to pick in areas of significant clastic karst-infill, or where marl is above the sub-Cretaceous unconformity)

* Abbreviations: Group, Grp.; Formation, Fm.; Member, Mbr.

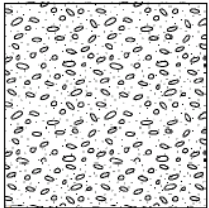
** Quality codes are relative: Excellent to Very Good, can be picked on all wireline logs and seismic; Poor to Very Poor, need to be confirmed by outcrops or core, difficult to pick on wireline logs, somewhat easier to pick on seismic.

Appendix 3 - Facies Classification Scheme with Sketch Illustrating the Dominant Sedimentary Features.

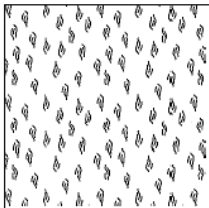
Facies 1: Coarse Grained to Pebbly, Poorly Sorted, Trough Cross Bedded Sand



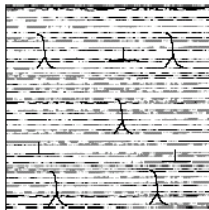
Facies 2: Very fine Grained to Pebbly, Poorly Sorted, Graded Gravel



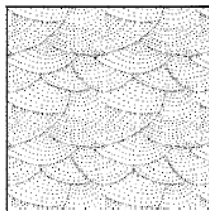
Facies 3: Carbonaceous to Coaly, Rooted Silty Mudstone



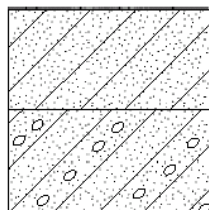
Facies 4: Mottled Argillaceous Sandy Marl



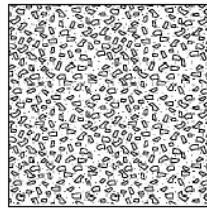
Facies 5: Fine to Medium Grained, Trough Cross Bedded Sand



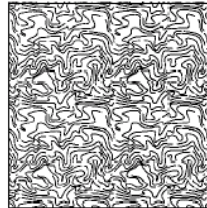
Facies 6: Fine Grained to Pebbly, Planar-Tabular Cross Bedded Sand



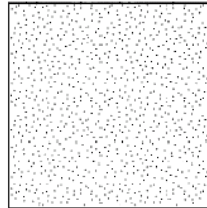
Facies 7A: Fine to Medium Grained, Poorly Sorted, Mudstone-Clast Breccia



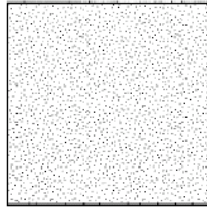
Facies 7B: Slumped Sand and Mudstone



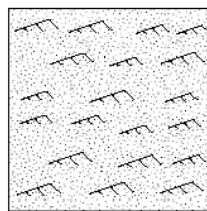
Facies 8A: Fine to Coarse Grained, Massive Sand



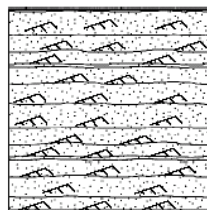
Facies 8B: Poorly to Well Sorted, Massive Sandy Silt/Silty Sand



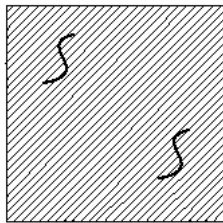
Facies 9A: Very Fine to Fine Grained, Ripple Cross Bedded Sand



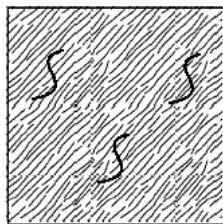
Facies 9B: Very Fine to Fine Grained, Flaser Bedded Sand and Mudstone



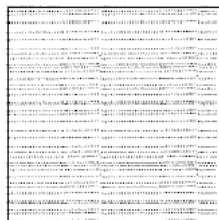
Facies 10A: Bioturbated, Inclined Heterolithic Stratified Muddy Sand



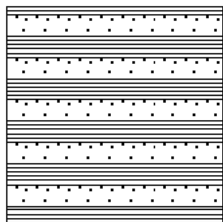
Facies 10B: Bioturbated, Inclined Heterolithic Stratified Sandy Mudstone



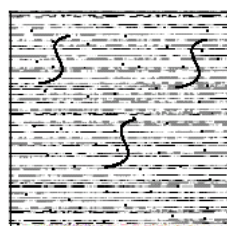
Facies 11: Very Fine to Medium Grained, Stratified Sand



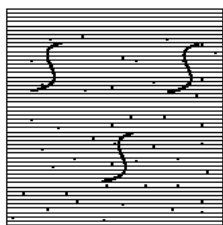
Facies 12A: Rhythmically Laminated Sand and Mudstone



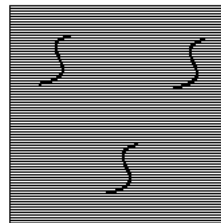
Facies 12B: Very Fine to Fine Grained, Bioturbated, Muddy Sand



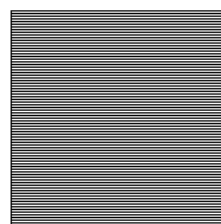
Facies 12C: Very Fine to Fine Grained, Bioturbated, Sandy Mudstone



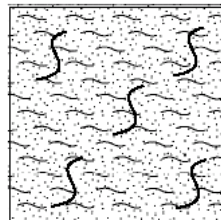
Facies 12D: Laminated to Thinly Interbedded, Bioturbated Silty mudstone



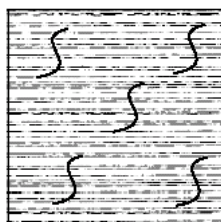
Facies 12E: Thinly Laminated Silty Mudstone/Mudstone



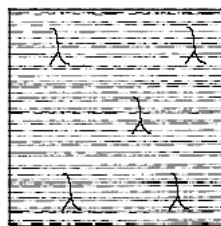
Facies 13A: Very Fine Grained, Heavily Burrowed Muddy Sand



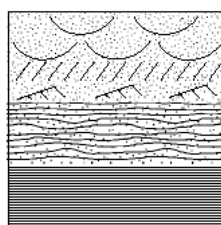
Facies 13B: Intensely Burrowed, Silty Mudstone/Muddy Silt



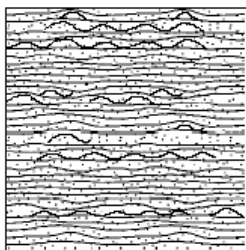
Facies 14: Coaly and/or Rooted, Sandy-Muddy Siltstone to Silty Mudstone



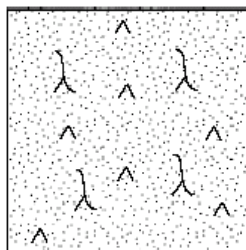
Facies 15: Coarsening-Upward Mudstone-Siltstone-Sand



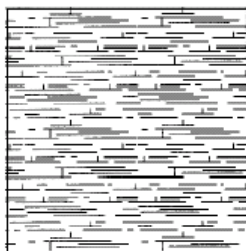
Facies 16: Very Fine to Fine Grained, Well Sorted, Wave Rippled Sand



Facies 17: Silicified Sandstone ('Beaver River Sandstone')



Facies 18: Poorly Sorted, Karstic Calci-/Siliciclastics



Appendix 4 - Oil Sands Industry Update – Alberta Department of Energy, Alberta Economic Development, March 2004 ³

What is New?

Company approvals have been given to proceed with the following oil sands projects

- Opti Canada/Nexen's Long Lake Project, a SAGD in situ facility with an integrated upgrader. The first phase is designed to produce 70 000 bpd (regulatory approval obtained in August 2003).
- ConocoPhillips' Surmont Project, a SAGD in situ facility with a design production capacity of 100 000 bpd (regulatory approval obtained in May 2003).
- Petro-Canada's Strathcona Refinery Conversion Project, designed to increase the refinery's bitumen upgrading capacity by 53 000 bpd.

Regulatory approvals have been obtained for three major developments and a new pilot project

- CNRL's Horizon Project, a mine/upgrader facility with a design capacity of 270 000 bpd.
- Shell Canada's Jackpine mine, Phase I, a mine and extraction plant with a design production capacity of 200 000 bpd.
- Suncor's Millennium Coker Unit Expansion, designed to increase the company's Fort McMurray oil sands production to 330 000 bpd by the end of 2007.
- Petrobank's Whitesands Pilot Project, the first field-scale application of the patented Toe-to-Heel Air Injection (THAI) in situ heavy oil recovery technology.

Applications for regulatory approvals have been filed for

- Suncor's South Tailings Pond, an external tailings pond located southeast of the Millennium mine.
- Devon Energy's Jackfish Project, a SAGD in situ facility with a design capacity of 35 000 bpd.

Formal public disclosures have been made for the following projects

- Husky's Sunrise Thermal Project, a SAGD in situ project with initial production of 50 000 bpd and a final design production capacity of 200 000 bpd.
- BA Energy's Alberta Heartland Upgrader, with an initial bitumen processing capacity of 50 000 bpd and an ultimate design capacity of 150 000 bpd.
- Imperial Oil has publicly announced its plan to develop the Kearl Oil Sands Project, an integrated open-pit mining/upgrader operation with an initial production capacity of 100 000 bpd and an ultimate design capacity of 200 000 bpd.

The following projects have recently been completed

- Train 2 at Syncrude's Aurora mine, which was commissioned in the fourth quarter of 2003 and is now in production.
- Phase I of Suncor's Firebag Project, which began production in January 2004.

New project construction continues on

- Suncor's Firebag Project, Phase 2.
- Syncrude's Upgrader Expansion Project I (UEI), which is now more than 35% complete.
- Deer Creek Energy's Joslyn Project, Phase I.
- CNRL's Primrose/Wolf Lake Expansion.
- Husky's Lloydminster Upgrader.

Other recent happenings that have a bearing on oil sands activity include the following

- Syncrude has announced that the completion date for Stage 3 of the Syncrude 21 expansion plan has recently been extended from mid-2005 to mid-2006. In keeping with this change in construction schedule, the cost estimate for the Stage 3 has been increased from \$5.7 billion to \$7.8 billion Cdn.
- The Province of Alberta has expressed an interest in working with industry to explore the feasibility of constructing a rail link connecting the Fort McMurray oil sands and Edmonton to potentially reduce traffic on northern highways (especially Highway 63) and move heavy equipment and construction modules more quickly and economically than by truck. The first step for the proponents of the project will be a feasibility study.

Summary

Oil sands production continues to increase, although unexpected maintenance needs and other factors have kept production below actual capacity, as reflected in the following figures from selected oil sands facilities.

- Suncor averaged daily oil sands production of approximately 217 000 bpd in 2003, up from approximately 206 000 in 2002. In January 2004, production was down to approximately 209 000 bpd due to equipment maintenance and cold weather, but the company is expecting to produce an average of 225 000 to 230 000 bpd in 2004.
- Syncrude produced an average of approximately 212 000 bpd during 2003, down from approximately 230 000 bpd in January 2002. The decline was due to unscheduled coker turnaround and extended maintenance work. Following completion of the coker turnaround, production rose to an average of 264 000 bpd in December 2003.
- The Athabasca Oil Sands Project (the Muskeg River mine, Corridor Pipeline and Scotford Upgrader) averaged production of 130 000 bpd during the fourth quarter of 2003, up from 115 000 bpd in the third quarter. Design production capacity for the project is 155 000 bpd.
- Petro-Canada produced an average of 16 000 bpd at its MacKay River In Situ Project during the fourth quarter of 2003, up from 4 500 bpd in the same period in 2002. Design capacity of the project is 30 000 bpd.
- EnCana Energy is producing about 5 300 bpd from the first phase of the Christina Lake Thermal Project, up from 3,500 bpd in September of 2003. Design capacity is 10 000 bpd. The company is also producing 30 000 bpd from its in situ Foster Creek Thermal Project.
- Imperial Oil produced an average of 130 000 bpd from its Cold Lake Production Project in 2003, up from 112 000 bpd in 2002.
- CNRL is producing 35 000 bpd from its Primrose/Wolf Lake operation.

- Suncor has completed construction of Phase 1 of its Firebag Project and has begun construction of Phase 2. The Firebag Project is an integral part of the company's Voyageur growth strategy, which is designed to increase production capacity to more than 500 000 to 550 000 bpd by 2010 to 2012.
- Deer Creek Energy is working on its Joslyn Project (Phase 1), a SAGD facility designed to produce 600 bpd.
- Husky is proceeding with the engineering of debottleneck and on-stream reliability projects designed to enhance the performance of its Lloydminster Upgrader.

Company approvals have been given to proceed with the following oil sands projects

- Opti Canada/Nexen's Long Lake Project, a SAGD in situ facility with a first phase designed to produce 700 000 bpd (regulatory approval obtained in August 2003).
- ConocoPhillips' Surmont Project, a SAGD in situ facility with a design production capacity of 100 000 bpd (regulatory approval obtained in May 2003).
- Petro-Canada's Strathcona Refinery Conversion Project, designed to increase the refinery's bitumen upgrading capacity by 53 000 bpd.

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- Imperial Oil has publically announced its plan to develop the Kearl Lake Oil Sands Project, an integrated open-pit mining/upgrader operation with an initial production capacity of 100 000 bpd and an ultimate design capacity of 150 000 bpd.

Two initiatives are exploring the use of solvents as a means of extracting in situ oil

- Devon Canada is operating the Dover Vapex Project to test the effectiveness of vaporized solvents instead of steam.
- EnCana is testing a Solvent Aided Process (SAP) that uses solvent as a supplement to steam.

The total oil sands industry investment in new and sustaining capital may reach \$93.5 billion in the 1996 to 2012 period. \$22.5 billion have already been spent on new and sustaining capital in the 1996

to 2002 period. Production levels may reach 1.8 million bpd of synthetic crude oil (SCO) by 2012, plus an additional 1.2 million bpd of bitumen. Not all projects may proceed in the timeframe or scope that companies currently indicate. The Regional Issues Working Group has devised a way of discounting project capital and production on the basis of where the project is in the regulatory and commercial approval process. Using this discounting schedule, the total construction and sustaining capital expenditure in the 1996 to 2012 period is estimated at \$65.1 billion. Production is expected to reach 1.2 million bpd of synthetic crude oil and an addition 50 000 bpd of bitumen.

Most of the oil sands industry activity remains focused on the Fort McMurray region, which is growing rapidly in response to the intensifying economic activity. The 2002 municipal census places the population of Fort McMurray at 47 420, up from 34 000 in early 1996. The population of Fort McMurray is forecast to reach 50 000 in 2005 and may exceed 70 000 before the end of this decade.