“ You don’t become great by trying to be great. You become great by wanting to do something, and then doing it so hard that you become great in the process.

- Anon

University of Alberta

SEDIMENTOLOGY, ICHNOLOGY AND STRATIGRAPHY OF THE CLEARWATER FORMATION, COLD LAKE, ALBERTA

by

CAROLYN FRANCES CURRIE

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Dedication

This thesis is dedicated to my parents, Graham and Avril. My accomplishments would not have been possible without your endless support and love. Thank you for giving me the chance to prove and improve myself through all my walks of life. Through good times and bad you have been my rock, and for that I thank you and I love you both!

ABSTRACT

The Lower Cretaceous Clearwater Formation in east-central Alberta contains the second largest oil sands deposit in Canada. In the Cold Lake area, 43 cored intervals were examined and classified based on physical and biogenic sedimentary structures. Core analysis and stratigraphic mapping determined that the Clearwater Formation consists predominantely of stacked tidally-dominated strata that prograde to the north into the Boreal Seaway. The trace fossil assemblages observed show evidence of somewhat stressed conditions, indicated by the more restricted and diminished ichnofauna. However, higher ichnodiversity, larger trace sizes and the predominance of more fully marine forms support sediment deposition in a deltaic system. The stratigraphic framework of the Clearwater Formation was redefined using allostratigraphy. Five allomembers were identified reflecting a series of transgressive-regressive cycles of relative sea-level rise and fall, retrogradation of the shoreline and progradation of tide-dominated deltaic sediments in the study area.

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LIST OF SYMBOLS AND ABBREVIATIONS

FACIES/SEDIMENTOLOGY

FA1	Facies Association 1
FA2	Facies Association 2
FA3	Facies Association 3
FA4	Facies Association 4
FA5	Facies Association 5
FA6	Facies Association 6
FA7	Facies Association 7
sy	synaeresis cracks
ri	ripples
ms	‘mantle and swirl’

ICHNOFOSSILS

As	*Asterosoma*
Ar	*Arenicolites*
Ch	*Chondrites*
Pa	*Paleophycus*
Pl	*Planolites*
Ro	*Rosselia*
Si	*Siphonichnus*
Sk	*Skolithos*
Te	*Teichichnus*
Th	*Thalassinoides*
Zo	*Zoophycus*

ICHNOFOSSIL SIZE

S	Small
M	Medium
L	Large

STRATIGRAPHY

TSE	Transgressive Surface of Erosion
SB	Sequence Boundary
FS	Flooding Surface
A1	Allomember 1
A2	Allomember 2
A3	Allomember 3
A4	Allomember 4
A5	Allomember 5

MISCELLANEOUS

WCSB	Western Canada Sedimentary Basin
CSS	Cyclic Steam Simulation
BI	Bioturbation Intensity
GR	Gamma Ray

Chapter 1
Introduction and Regional Setting

Introduction

The Cold Lake oil sands, located approximately 300km northeast of Edmonton, are the second largest deposit of bitumen-saturated sand in Canada with current extraction at around 189,000 barrels of bitumen per day (Braat, 2001). Estimated reserves of approximately 3.5 x $10^{10}m^3$ of high viscosity heavy bitumen, with API values around 10 to 12°, are found within $9000km^2$ of Lower Cretaceous Mannville Group sediments (Hutcheon *et al*., 1989) (Figure 1-1). The hydrocarbons are thought to have been generated from Jurassic, Devonian and Mississippian shales (Bachu, 1995). The hydrocarbons migrated updip through Upper Devonian aquifers into Lower Cretaceous sediments where they were subsequently trapped and underwent biodegradation (Bachu, 1995; Shuqing *et al*., 2008). The highest bitumen-saturated interval within this deposit, the Clearwater Formation, is currently being produced by a number of companies by means of in-situ cyclic steam injection (McCrimmon and Arnott, 2002). Bitumen recovery in the Clearwater Formation from steam injection methods have improved significantly with advancing technologies. Current estimates of bitumen recovery are around 35% to 40% (Lui, 2006). Some problems in production are related to a number of lithological factors associated with steam injection, such as mobile fines, swelling clays and the dissolution and precipitation of mineral phases which have all resulted in permeability reduction within the reservoir (Beckie and McIntosh, 1988). Oil being an important commodity on the Canadian and international market, development of the Cold Lake oil sands are important to the future energy needs of Alberta, Canada and the world.

Stratigraphy and General Geology

The Western Canadian Sedimentary Basin (WCSB) is bounded on the west by the Rockies of the Canadian Cordillera, on the east by the Canadian Shield, and is separated from the Williston Basin by the Sweetgrass Arch (Figure 1-2). The present configuration of this foreland basin is an asymmetrical syncline, as a result of major tectonism in the Cordillera in the west and subsequent subsidence of sediments that accumulated in the foredeep. Loading of the lithosphere

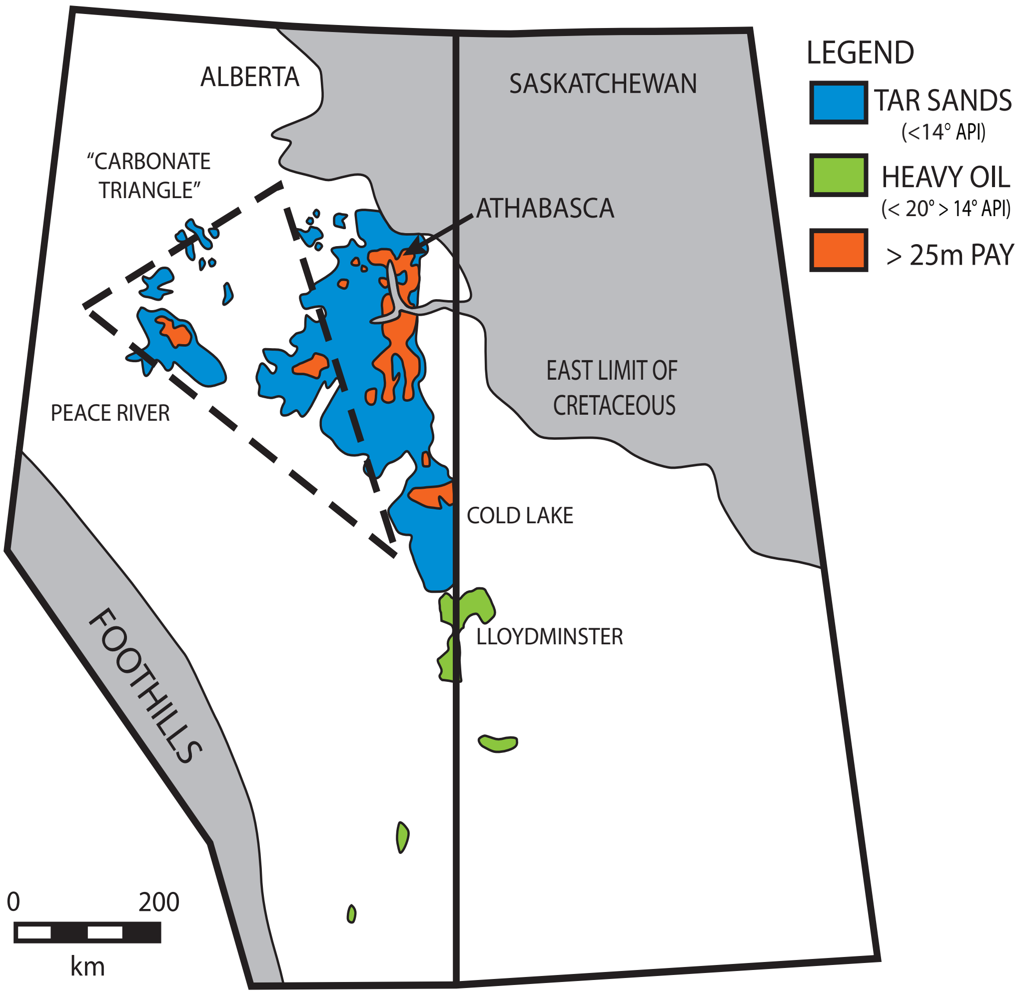

Figure 1-1: Distribution of Western Canada's tar sands and heavy oil deposits (modified from Beckie and McIntosh, 1988).

in the west and dissolution of Devonian evaporates in the east resulted in different rates of subsidence, increasing downdip to the southwest leading to the development of a foredeep trough with a distinct hingeline on its eastern flank, and axial high in the eastern portion, and an eastern regional low (Wickert, 1992).

The WCSB is composed of thick successions of Paleozoic and Tertiary strata which lie unconformably over the folded and faulted crystalline Precambrian basement. Paleozoic rocks are mainly calcareous with isolated intervals of evaporates and fine grained clastic rocks, whereas Cretaceous sequences in the Alberta basin are mainly clastic and generally lie unconformably on Jurassic clastic and Paleozoic carbonate rocks. Futhermore, the Mannville Group overlies the pre-Cretaceous unconformity in the Cold Lake area. Figure 1-3 illustrates the

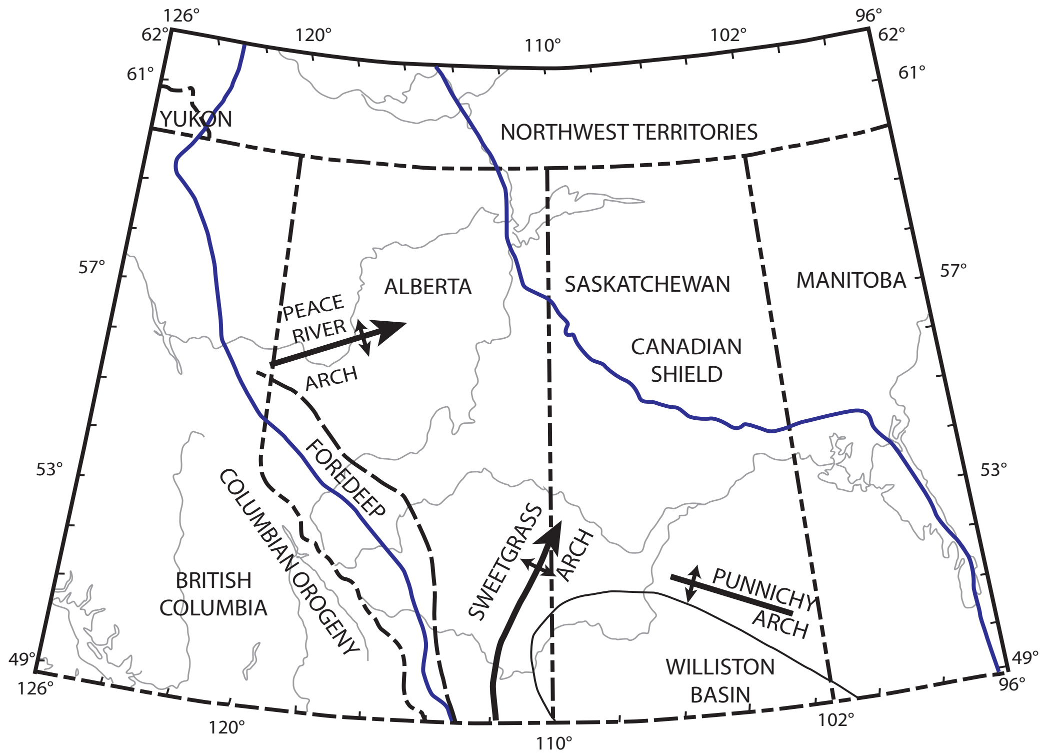

Figure 1-2: Major structural elements of the Lower Cretaceous Western Canadian Sedimentary Basin, outlined in blue (modified from Stelck, 1975).

major statigraphic units and their position within the WCSB.

In east-central Alberta, the Mannville Group is subdivided into three formations, each of which is distinct from the other in environment and resulting facies: the McMurray Formation, the Clearwater Formation and the Grand Rapids Formation (Figure 1-4). The boundary between the McMurray Formation and Clearwater Formation marks a significant change in sediment composition, from quartz arenites in the McMurray to the younger Mesozoic litharenites of the Clearwater Formation (McCrimmon and Arnott, 2002). The main structural element in east-central Alberta is the southeast plunging Athabasca Anticline, interpreted to be related to syn- and/or post-Mannville dissolution of the underlying Devonian evaporates (Wickert, 1992). Liquid hydrocarbons are thought to have accumulated below the structural high in the porous sands of the McMurray, Clearwater and Grand Rapids Formations, and subsequently degraded by meteoric-water washing and microbial activity (Wickert, 1992). Meteoric-water washing is a process by which the lighter, more soluble hydrocarbons in crude oil are removed by the flow of water undersaturated in these hydrocarbons, leaving the heavier hydrocarbons associated with oil sands deposits (Bailey *et al.*, 1973).

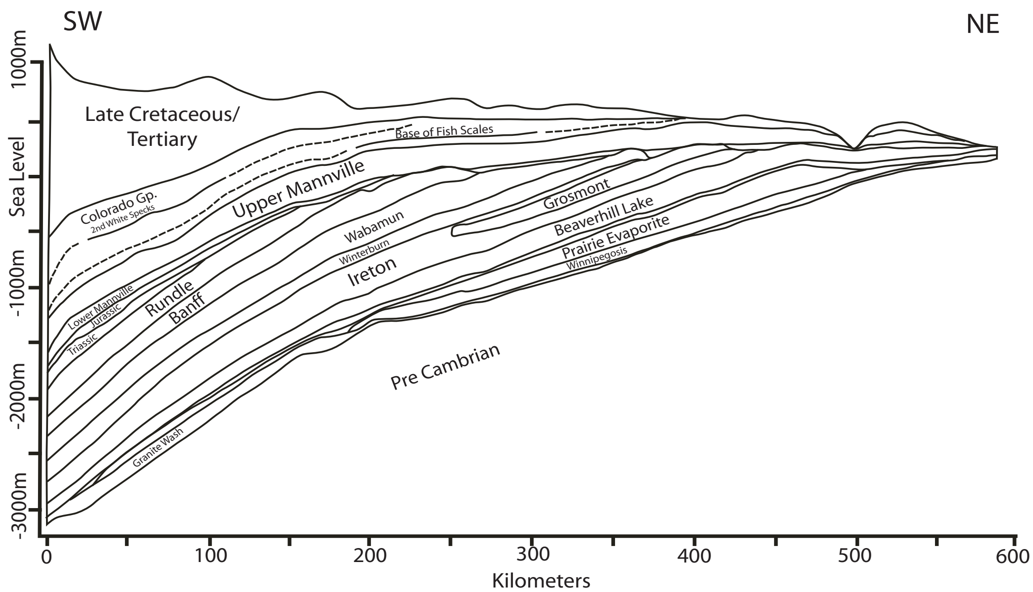

Figure 1-3: Geologic cross-section of the Western Canada Sedimentary Basin showing the major stratigraphic units and their position (from Wickert, 1992).

Microbial activity or biodegradation occurs within an area of freshwater invasion, through the introduction of bacteria. Bacteria can metabolize most types of hydrocarbons, but prefer the lighter factions, leaving behind the heavier hydrocarbons associated with the oil sands deposits (Bailey *et al.*, 1973).

Previous Work

Mineralogy and geochemical variations within a sedimentary basin is the function of numerous variables in the original depositional system as well as changes resulting from diagenetic processes. There are few detailed papers on the sedimentology, mineralogy and the diagenesis of the Clearwater Formation. Early reports on the mineralogy of the Clearwater Formation includes: Harrison et al. (1981); Putnam and Pedaskalny (1983); Hutcheon *et al*. (1989); Beckie and McIntosh (1989); and more recently McCrimmon and Arnott (2002) and Feldman *et al*. (2008). To summarize the authors, the strata within the Clearwater Formation is basically composed of marginal marine (deltaic/estuarine) and marine sediments (shoreface to offshore). The sands are predominantly composed of feldspathic litharenites. The primary lithic grains are volcanic rock fragments and chert, with considerable amounts of clastic sedimentary rock fragments and metamorphic grains also present. Diagenetic research has received much attention recently as it is proving to have a profound effect on the thermal recovery

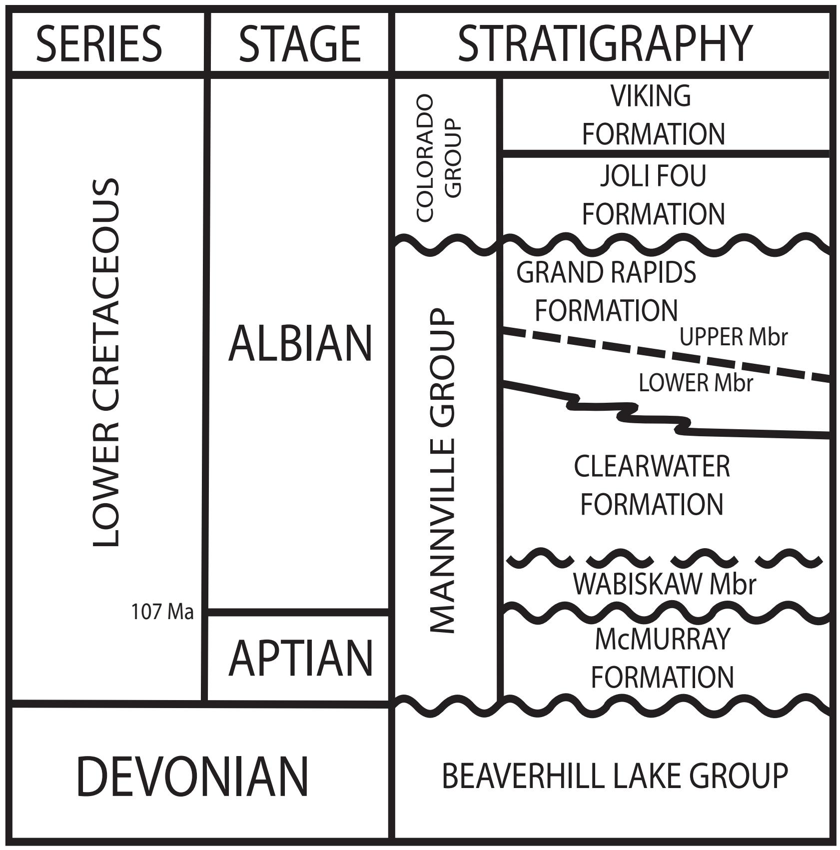

Figure 1-4: Stratigraphic nomenclature of Lower Cretaceous stratigraphy in the Cold Lake area, northeastern Alberta (McCrimmon and Arnott, 2002).

methods used to extract the bitumen. Works such as Putnam and Pedaskalny (1983); Hutcheon *et al*. (1989) and Wickert (1992) have completed a detailed analysis of the diagenetic history in the Clearwater Formation. The diagenetic history of the Clearwater Formation is complex with the precipitation and dissolution of diagenetic minerals such as pyrite, quartz, K-feldspar, albite, calcite, chlorite, siderite and smectite. The emplacement of oil hindered futher mineral diagenesis. Kaolinite and post-bitumen calcite cements were deposited after due to the introduction of meteoric waters in the Clearwater Formation.

Ichnology has been a significant contribution to the petroleum field, as it provides another 'tool' that when used with detailed sedimentological analyses, can aid in establishing depositional and stratigraphical frameworks. Within the Clearwater Formation, the trace fossil assemblage has been documented by few researchers, which include: Bradley and Pemberton (1992); and briefly by Hutcheon *et al*. (1989); Wickert (1992) and Feldman *et al*. (2008). Bradley and Pemberton (1992) identified three main trace fossil assemblages that occur in the

Clearwater Formation and Wabiskaw Member. They include (1) the *Glossifungities* ichnofacies, (2) *Zoophycos-Chondrites-Helminthopsis* assemblage, and (3) the *Chondrites-Zoophycos-Thalassinoides-Planolites* assemblage.

Posamentier *et al*. (1988) defines sequence stratigraphy as the "study of relationships within a chronostratigraphic framework wherein the succession of rocks is cyclic and is composed of genetically related stratal units (sequences and systems tracts)." The sequence stratigraphy and the depositonal history of the Clearwater Formation has been the focus of many papers, including: Hutcheon *et al*. (1989); Beckie and McIntosh (1992); Wickert (1992); McCrimmon and Arnott (2002) and Feldman *et al*. (2008). The depositional models presented by these authors vary. The models seems to have evolved through time from a basic prograding deltaic shallow marine system (Wickert, 1992) to a prograding tidal-deltaic shallow marine system cut by a number of large incised valleys (McCrimmon and Arnott, 2002). The most recent attempt at deciphering the complex history of the Clearwater sediments describes a fluvial to estuarine valley-fill model proposed by Feldman *et al*. (2008).

Methodology and Objectives

The primary objectives of the study are:

1. To define and describe/interpret facies and facies relationships;
2. Detailed analysis on the ichnology within the Clearwater Formation;
3. To determine the lateral and vertical extent of these facies;
4. To develop a depositional model and stratigraphic framework for the Clearwater Formation

In order to develop the depositional history and stratigraphic framework of the Clearwater Formation in the Cold Lake area, a multidisciplinary approach utilizing ichnology, physical sedimentology and well log analysis was employed. The objectives were accomplished by creating a database consisting of core descriptions and well logs.

(A) Core Descriptions

A total of 43 cores were described in detail to establish the depositional environment of the Clearwater Formation (Figure 1-5). All cores were accessed at the Energy Resource Conservation Board (ERCB) core research

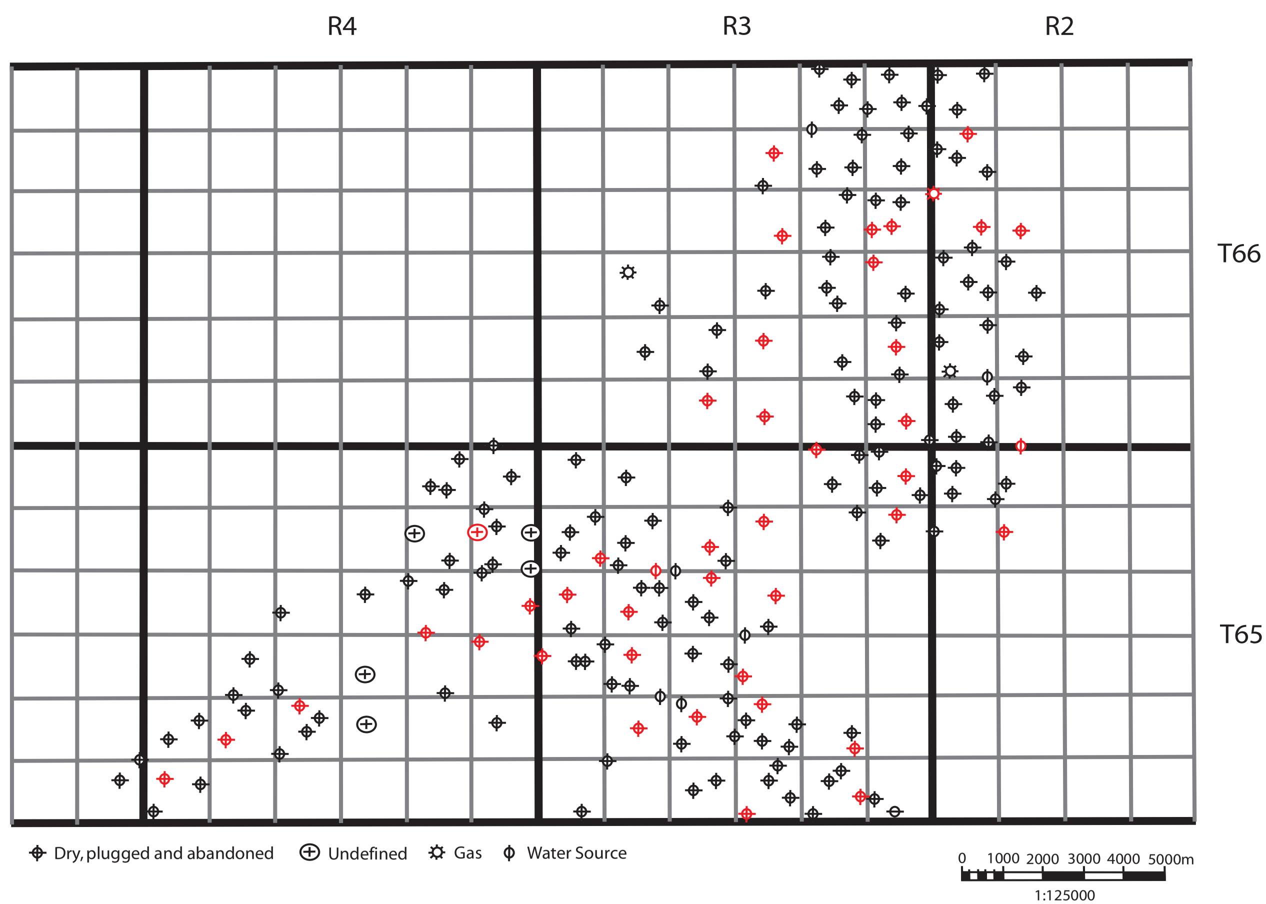

Figure 1-5: Wells utilized in the study. Total of 200, 43 of which were core logged for this study (red).

facility in Calgary, Alberta. Each core was examined with particular reference to:

1. Lithology
2. Grain size and sorting characteristics;
3. Bedding styles and bed thickness;
4. Nature of bedding contacts and bounding surfaces;
5. Biogenic and physical sedimentary structures;
6. Trace fossil identification;
7. Relative intensity of bioturbation;
8. Relative degree of bitumen saturation.

(B) Well Logs

A data base consisting of digital well logs from 200 wells (including wells core-logged) were used to supplement the information collected from the core descriptions and interpretations. Well logs were used to determine the three-dimensional distribution and connectivity of sequence boundaries and flooding surfaces recognized in the core analysis. They were also used to correlate the facies and facies associations to allow for a more cohesive depositional model.

Study Area and Well Control

The study area is located in the eastern portion of the Cold Lake oil sands area. It is bounded by township 65, ranges 2-4 and township 66, ranges 2-3 west of the Fourth Meridian, a total area of approximately 500km^2 (Figure 1-5). Forty-three cores and 157 well logs were examined to delineate facies, determine depositional processes and establish depositional environments within the Clearwater Formation.

Chapter Summary

Chapter 2 describes the facies seen in the Clearwater Formation using the criteria decribed above. These facies were then grouped into recurring packages (facies associations), where each was attributed to a specific depositional environment in a prograding, subaqueous portion of a delta. Data from the facies and facies associations were then used in a paleoenvironmental reconstruction.

Chapter 3 describes the ichnological characteristics observed in the

Clearwater Formation. Four core were chosen to represent the study area. Trace fossils were examined for abundance, diversity and relative size of burrows. This information was then compared to past research done on the Clearwater Formation and other similar depositional settings. Finally, a preliminary ichnological model/framework is presented, in which the general characteristics noted can be applied to other comparable case studies.

Chapter 4 introduces stratigraphic relationships of the Clearwater Formation to laterally adjacent and bounding strata. A brief history of previous work precedes a summary of the facies associations used in correlating. Following, an allostratigraphic analysis was based on a network of 14 cross-sections across the study area. Cross-sections were oriented based on the two main trends (NW-SE and N-S) used in industry to characterized the deposit. A number of allomembers are described and are separated by regional discontinuity bounding surfaces. This chapter concludes with a discussion on transgressive-regressive cycles affecting the deposition of the Clearwater Formation.

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Chapter 2
Facies Analysis and Paleoenvironmental Reconstruction of the Clearwater Formation, Cold Lake, Alberta, Canada

Introduction

The Lower Cretaceous Clearwater Formation in Cold Lake, Alberta is part of a discontinuous trend of heavy oil deposits extending from Peace River in north-western Alberta to Lloydminster in western Saskatchewan (Figure 1-1). The Cold Lake deposit is located 300 km northeast of Edmonton, covers an area of 9000km^2, is the second largest oil sands deposit with estimated reserves of 3.5 x 10^{10} m^3 of high viscosity, heavy bitumen (Hay, 1994). This high viscosity fluid presents a problem due to the fact that under normal reservoir conditions, it is immobile. Cyclic Steam Simulation (CSS) is the primary in situ process used which ultimately reduces the viscosity of the bitumen enabling it to be produced. The efficiency of CSS is sensitive to the lithology encountered in the reservoir. Therefore, a thorough understanding of the facies distribution, facies relationships and stratal architecture are pertinent to maximize efficiency and production. The aim of this chapter is two-fold: (1) to define and describe a set of facies seen in core and interpret the facies relationships and (2) to develop a paleoenvironmental reconstruction of the Clearwater sediments in the Cold Lake area.

Regional Geological Setting and Study Area

The Western Canada Sedimentary Basin (WCSB) contains one of the world's largest reserves of petroleum and natural gas, estimated at approximately 3.6 x 10^{12} m^3 (Hay, 1994). The WCSB was formed due to regional compressional tectonism associated with the progressive development of the Cordillera causing subsidence and flexure of the craton in the east (Figure 1-2). The WCSB forms an asymmetrical, southwest dipping trough infilled with sediments derived either from the Precambrian shield to the east or the newly formed Cordillera to the west (Figure 1-2, 3; Harrison *et al*., 1981; Wickert, 1992). Lower Mannville sediments are typically derived from eastern sources and are primarily mature quartz rich fluvial sands but gave way to more marine sediments as the Boreal Sea continued to transgress southward (Figure 2-1; Harrison *et al*., 1981; Feldman *et al*., 2008). Upper Mannville sediments are derived from western sources and are composed of immature volcanic and feldspathic sands deposited in a nearshore or deltaic/estuarine setting (Harrison *et al*., 1981; Putnam and Pedskalny, 1983; Feldman *et al*., 2008). Overlying Mannville sands, the Colorado Group marine shales mark a major transgression linking the Boreal Sea and Gulfian Sea to form the Cretaceous Interior Seaway (McCrimmon and Arnott, 2002; Feldman *et al*., 2008).

In the Cold lake area, siliciclastic sediments of the Cretaceous Mannville Group lie unconformably over folded and faulted Devonian carbonates and evaporites (Figure 1-3; McCrimmon and Arnott, 2002). In this area the Mannville Group is subdivided into three unconformity bounded formations: McMurray, Clearwater and Grand Rapids Formations (Figure 1-4; Wickert, 1992; McCrimmon and Arnott, 2002; Feldman *et al*., 2008). The boundary between the McMurray and Clearwater Formation marks a change in sediment provenance (Putnam and Pedskalny, 1983). The McMurray Formation consists of predominantly quartz arenites derived from the Precambrian shield whereas the Clearwater Formation consists primarily of litharenites derived from younger Cordilleran Mesozoic successions to the west (Hutcheon *et al*., 1989; Wickert, 1992, McCrimmon and Arnott, 2002).

Liquid hydrocarbons are thought to have accumulated and trapped below the Athabasca Anticline, a south-east plunging antiform related to syn- and/or post-Mannville dissolution of the underlying Devonian carbonates and evaporates (McCrimmon and Arnott, 2002). Subsequently the liquid hydrocarbons were degraded due to meteoric water washing and microbial activity (Bachu, 1995). This produced heavy crude bitumen common to central Alberta heavy oil and tar sands deposits along a discontinuous trend from the Lloydminster area of western Saskatchewan to the Peace River area in northern Alberta (Figure 1-1).

Clearwater Formation core and corresponding well logs examined in this study are contained within township 65, ranges 2-4 and township 66, ranges 2-3 west of the Fourth Meridian, in east-central Alberta (Figure 1-5). A total of 43 cores were described in detail along with an additional 157 infill digital log data were used to calibrate and correlate a grid of geophysical cross-sections (Appendix A).

Facies Descriptions and Interpretations

The Cold Lake area has been the subject of extensive drilling, resulting in an extensive data set for the study. Each core was examined with particular reference to the lithology, grain size and sorting characteristics, bedding styles and bed thickness, nature of bedding contacts and bounding surfaces, biogenic and physical sedimentary structures, trace fossil identification, relative intensity of bioturbation, and the relative degree of bitumen saturation. Eleven lithofacies were identified and grouped into seven facies associations, summarized in Table 2-1. Bioturbation intensity (BI) was assessed visually on a scale from one to six, one being unbioturbated sediments and six, complete obliteration of sedimentary structures due to bioturbation (Figure 2-2). In the photographs accompanying each of the facies assocations, porous sand layers are stained black due to bitumen saturation, whereas finer grained facies with lower permeability appear lighter in colour.

FACIES ASSOCIATION 1 (*Shoreface - Proximal Offshore*)

Facies 1 – Hummocky cross-stratified silt/very fine sand and mud

Description:

Facies 1 is characteristic of the McMurray Formation in the Cold Lake area. Associated deposits are common in most cores that penetrate below the Clearwater Formation. It is a light grey interbedded upper silt to very fine lower sand and 20-30% mud (Figure 2-3, A-C). The sandier interbeds tend to increase in thickness upwards with muddy interbeds (2-5cm thick) capping each of the sand interbeds. Sand/silt interbeds are typically oscillation wavy to parallel laminated with possible short wavelength hummocky-swaley cross stratification (Figure 2-3, A, C). Moving up section wave ripples, current ripples and low angle cross stratification are more prevalent. The mud interbeds may contain some minor synaeresis cracks (Figure 2-3, B). The relative degree of bioturbation is highly variable, ranging from minor to intensely bioturbated (BI 3-6); although poorly bioturbated intervals tend to predominate. This facies is characterised by a low diversity and low intensity ichnofossil assemblage dominated by *Planolites*, *Paleophycus, Phycosiphon*, minor *Chondrites* and fugichnia (Figure 2-3, C). The traces tend to be very small (<0.1cm in diameter) and dominate the muddy interbeds. For each set of interbeds (15-20 cm thick) the contact between the sand and burrowed mud above is typically gradational (Figure 2-3, A, C). Between the burrowed mud interbed and the next subsequent set of interbeds is typified by an erosional contact (Figure 2-3, A, C). Facies 1 consistently underlies Facies 2 or 4. The contact is usually sharp and erosional in nature (Figure 2-3, D). No bitumen saturation.

Interpretation:

The interbedded silt/sand and mud beds of Facies 1 are interpreted as tempestite deposits on a proximal offshore/shoreface environment. The hummocky cross stratified to oscillation wavy fine grained silt and sand interbeds indicate a high energy event (Pemberton and MacEachern, 2006). The sediment within these sand interbeds was likely deposited fairly rapidly due to the lack of bioturbation and occasional escape traces (Dott and Bourgeois, 1982). The mud interbeds gradationally overlie the sand interbeds which indicate that there is a decrease in energy, i.e. the storm is waning (Pemberton and MacEachern, 2006; Dott, 1988). The mud interbeds reflect the final fall-out of suspended sediment in fair-weather conditions (Dott and Bourgeois, 1982). An increase in bioturbation is observed within the muddier interbeds. This also reflects the reduction in the energy and causes the sediment to repopulate with mobile carnivores and deposit feeders who exploit the nutrient rich, fine grained sediments in low energy offshore environments (Pemberton and MacEachern, 2006). The top contacts of each mud interbed commonly are erosional in nature which represents the introduction of another high energy storm event in the area.

Facies 2 – Glauconitic, interbedded fine to medium sand with mud

Description:

Facies 2 is typical of the Wabiskaw Member, the basal member of the Clearwater Formation in the Cold Lake area. This facies is common in most cores that penetrate to the base of the Clearwater. Facies 2 may also be absent due to erosional processes. The Wabiskaw Member appears as a greenish-grey interbedded fine lower to medium lower sand with approximately 10-40% mud (Figure 2-3, E-G). Variable amounts of glauconite give the deposit its characteristic green colour (Figure 2-3, E-G). The mud interbeds, when distinguishable, are typically thin and lense-like (1-3 cm thick). Primary structures within this unit are typically obliterated by biogenic reworking (Figure 2-3, G). In some cases wavy bedding and low angle to parallel cross bedding is preserved (Figure 2-3, E, F). Coaly debris and other various carbonaceous materials are rarely present. The degree of bioturbation

FACIES ASSOCIATION	FACIES	GRAIN SIZE	RESERVOIR QUALITY	BIOTURBATION INDEX 0 1 2 3 4 5 6	SIZE OF TRACES S M L	ICHNOFACIES	ENVIRONMENT	FORMATION
FA1	F1 Oscillation wavy to parallel laminated silt/very fine sand and mud					Zoophycos-Cruziana	Storm-dominated shoreface/Proximal Offshore	McMurray Formation
	F2 Glauconitic, interbedded fine to medium sand and mud						Proximal Offshore	Wabiskaw Member
FA2	F3 Light grey mud with minor silt laminae					Low Diversity Cruziana	Distal Prodelta	Clearwater Formation
	F4A Highly bioturbated interbedded mud and very fine sand (5-35%)						Proximal Prodelta	
	F4B Bioturbated interbedded mud (30-60%) and very fine to fine sand						Transitional Zone	
	F5 Moderately bioturbated interbedded fine sand and mud with minor clast material						Delta Front	
FA3	F6 Fine to medium sand interbedded with minor mud and clast material						Distributary Mouth Bars	
FA4	F7 Fine to medium sand with minor mud and abundant clast material						Inter-bar channel fill	
FA5	F8 Planolites burrowed medium sand with minor mud and clast material						Sandy tidal flats	
FA6	F9 Wave reworked very fine to fine grained sand with minor mud laminae					Stressed Cruziana	Barrier Bar	
	F10 Moderately bioturbated interbedded mud (20-50%) and very fine sand						Central Basin	
FA7	F11 Dark to light grey bioturbated to parallel laminated silty mud with very minor very fine grained sand					Zoophycos-Cruziana	Distal Offshore	Grand Rapids Formation

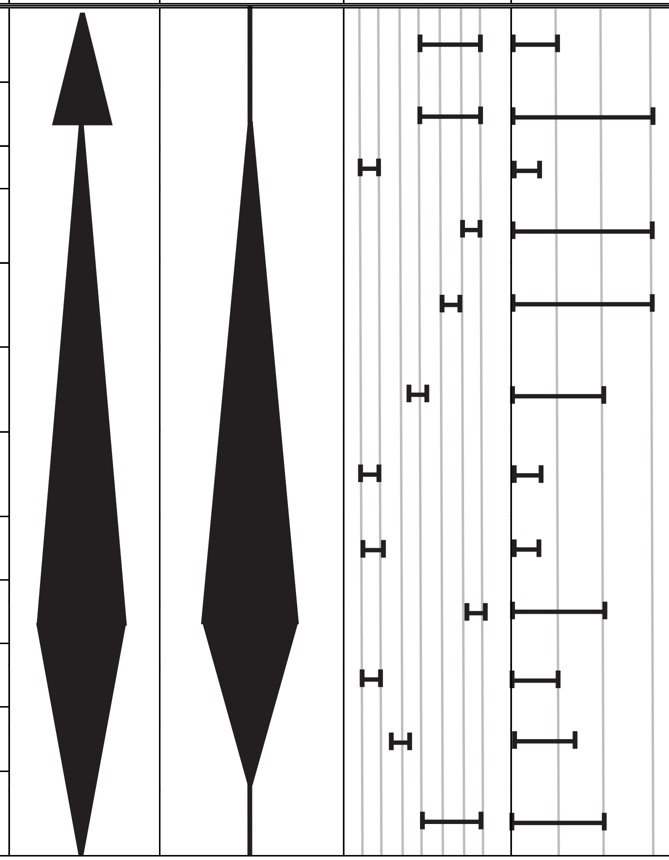


Table 2-1: Facies and Facies Associations summary chart. Bioturbation Index is quantified using Figure 7. For size of trace fossils, small (S), medium (M) and large (L) correspond to burrow diameters of less than 5mm, 5-20mm and greater than 20mm, respectively.

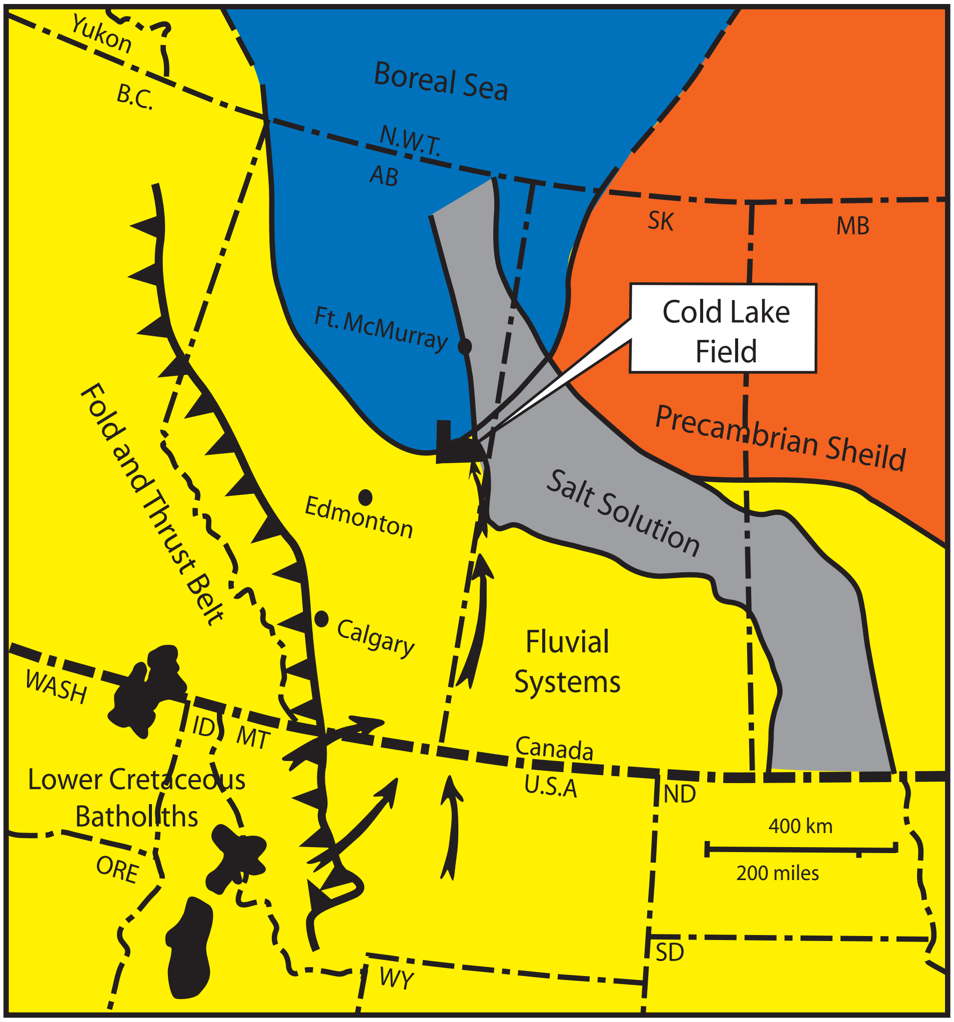


Figure 2-1: Paleogeography during the Clearwater Formation deposition. Large fluvial systems originating in the fold-and-thrust belt of the Cordillera fed immature volcanic rock fragments and deposited them in the largely transgressing Boreal Seaway to the north. Modified from Feldman et. al (2008).

in this unit is variable, ranging from minor to intensely bioturbated (BI 3-6). Typically this glauconitic unit is extensively bioturbated, sometimes making traces indistinguishable; therefore a mottled/churned texture is reported (Figure 2-3, G). In intervals where bioturbation is diminished some traces observed include *Planolites*, *Teichichnus*, *Diplocraterion*, *Siphonichnus*, *Asterosoma*, *Rhizocorallium*, *Paleophycus*, *Thalassinoides*, *Skolithos*, fugichnia, and *Chondrites* (Figure 2-3F, G). Where the Wabiskaw Member is present the basal contact with Facies 1 is sharp and the top contact commonly sharply underlies Facies 3 or Facies 4. A flooding surface commonly occurs within this facies (Figure 2-3, F). Bitumen saturation is variable, usually nil to low.

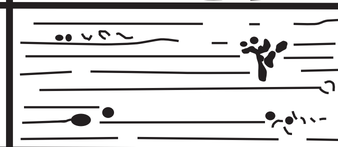
Grade	Classification	Visual Representation
0	Bioturbation absent	
1	Sparse bioturbation, bedding distinct, few discrete traces	
2	Uncommon bioturbation, bedding distinct, low trace density	
3	Moderate bioturbation, bedding boundaries sharp, traces discrete, overlap rare	
4	Common bioturbation, bedding boundaries indistinct, high trace density with overlap common	
5	Abundant bioturbation, bedding completely disturbed (just visible)	
6	Complete bioturbation, total biogenic homogenization of sediment	

Figure 2-2: Bioturbation Intensity (BI). Modified from Bann et. al. (2004).

Interpretation:

Facies 2 is interpreted as a transgressive shoreline deposit. The abundance of glauconite usually infers that the sediment was deposited on a continental marine offshore shelf with slow rates of accumulation (MacKenzie, 2005). Fully marine deposition is also supported by the diverse trace fossil assemblage present (Pemberton and MacEachern, 2006). This unit has been recognized across central and eastern Alberta and was deposited as the Boreal Sea transgressed for the final time across the region (McCrimmon and Arnott, 2002; Hubbard *et al.,* 1999; Hein and Cotterill, 2006).

FACIES ASSOCIATION 2 (*Prodelta to delta front*)

Facies 3 – Light grey mud with minor silt laminae

Description:

Facies 3 is fairly rare throughout the core and is typically seen in the northern part of the study area. Facies 3 is characterized as a grey laminated and lenticular mud with thin lenses of light grey silt or very fine sand (3-5%) (Figure 2-4, A, B). Sand lenses display symmetrical small-scale cross bedding and the mud is typically thinly laminated (Figure 2-4, B). Soft sediment deformation structures are also observed. Proportion of sand increases slightly upwards and may contain minor shell fragments and siderite. The relative degree of bioturbation is very low, low intensity and low diversity (BI 0-1). The assemblage is dominated by small *Planolites* and minor *Chondrites* (Figure 2-4, A, B). The basal contact of Facies 3 is consistently sharp and often erosional with Facies 1 and 2. The top contact is typically gradational with Facies 5. Nil to minor bitumen saturation.

Interpretation:

Facies 3 is interpreted as distal prodelta sediments deposited on the shelf where they are typically unaffected by both tidal and wave processes. The primary structures observed from the core indicate a low energy environment where fine muds and silts are allowed to settle out of suspension (Pemberton and MacEachern, 2006). The low degree of biotubation indicates that the bottom waters fluctuate between anoxic and aerobic conditions, high sedimentation rates, soupy substrates and sporadic deposition (Pemberton and MacEachern, 2006; Carmona *et al*., 2009). Soft sediment deformation structures are also common in prodeltaic sediments due to mass movements higher up in the delta front region (Carmona *et al*., 2009).

Subfacies 4A – Highly bioturbated interbedded mud and very fine sand (5-35%)

Description:

Subfacies 4A consists of light grey, intensely bioturbated mud with very fine lower to very fine upper sand (5-35%) (Figure 2-4, C, D). Subfacies 4A is fairly common throughout the core. Due to the degree of bioturbation, primary structures have been obliterated; although locally minor hummocky

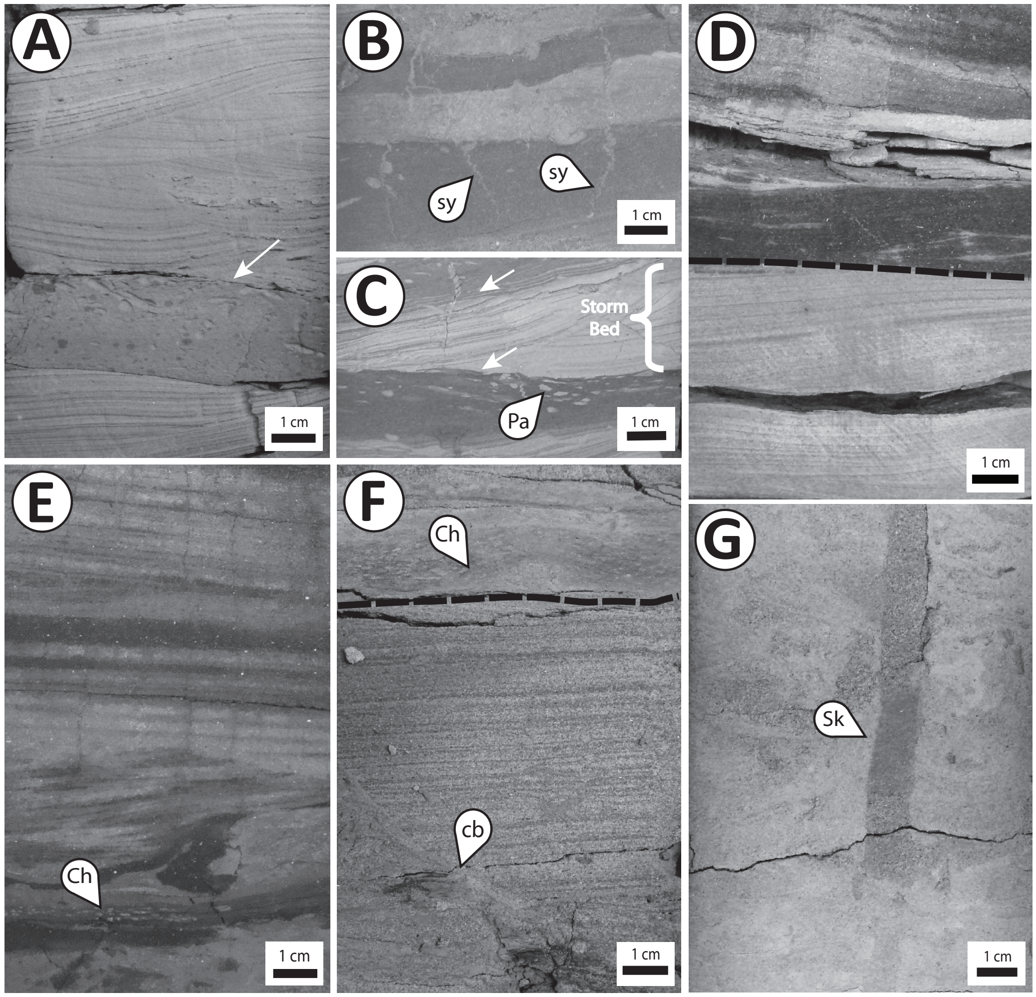


Figure 2-3: Facies Association 1 – Shoreface-Proximal Offshore. (A) Example of hummocky and swaley cross-stratification within silty/very fine sand interbeds. White arrow points to erosional contact between events. Well 1-30-065-03W4, 464.28m. (B) Rare synaeresis cracks (sy) show subaqueous shrinkage in the muddy interbeds. Well 6-20-065-03W4, 460.69m. (C) A series of storm events. The hummocky cross stratified fine grained silt and sand interbeds indicate the high energy storm events. Mud interbeds that gradationally overlie the sand interbeds indicate that there is a decrease in energy and reflect the final fall-out of suspended sediment in fair-weather conditions. Note the bioturbation within the mud beds, predominately Paleophycus (Pa). The mud interbed is capped by an erosive contact as a subsequent storm event begins. White arrows point to erosional tops. Well 8-24-065-04W4, 465.94m. (D) Sharp erosional contact between Facies 1 and Facies 2 (dashed black line). Well 06-03-065-03W4, 474.30m. (E) Oil saturated, relatively undisturbed low angle to parallel laminated glaucontic (green) medium lower grained sand with minor mud layers. Note that lower muddy layer contains Chondrites (Ch) burrows. Well 12-25-065-04W4, 462.88m. (F) Minimal oil saturation, low angle to parallel laminated glaucontic (green colour) medium grained sand containing minor carbonaceous material (cb). Photograph contains a flooding surface (dashed black line). Well 04-03-065-03W4, 525.67m. (G) Typical Wabiskaw Member. Highly bioturbated glauconitic fine to medium grained sand. Sedimentary structures are obliterated due to bioturbation. Note the large robust Skolithos (Sk) burrow indicative of the Wabiskaw Member. Well 10-27-066-03W4, 511.76m.

cross stratification and wave ripples are preserved (Figure 2-4, C, D). Contains minor soft sediments deformation structures, rip-up clast material and shell fragments. The sandier interbeds thicken stratigraphically upward. The relative degree of bioturbation is pervasive, high intensity and moderate diversity of ichnofossils (BI 5-6; Figure 2-4, C, D). The assemblage includes *Planolites*, *Zoophycos*, *Chondrites*, *Asterosoma*, *Paleophycus*, *Skolithos*, *Teichichnus*, *Thalassinoides*, *Siphonichus*, *Scolica* and *Rhizocorallium*. Size of traces tends to be average to large, ranging from 3-30mm in diameter. Both contacts above and below, are typically gradational. Bitumen saturation is variable from low to moderate and generally increases upwards.

Subfacies 4B – Bioturbated interbedded mud (30-60%) and very fine to fine sand

Description:

Subfacies 4B appears as a transitional facies between Facies 3/4A and Facies 5, and is fairly common in most cores. Subfacies 4B is characterized as interbedded very fine upper to fine upper sand with moderately to intensely bioturbated mud (30-60%) (Figure 2-4, E, F). Primary structures observed include planar to wavy bedding with low angle cross-bedding and current/ wave ripples, although maybe masked due to higher degrees of bioturbation (Figure 2-4, E, F). Also observed were some soft sediment deformation structures, minor rip-up clast material, carbonaceous material and calcite nodules. The relative degree of bioturbation is moderate to high, with the intensity generally decreasing significantly upwards (BI 4-5; Figure 2-4, E, F). Similar to Subfacies 4A the assemblage includes *Planolites*, *Zoophycos*, *Chondrites*, *Asterosoma*, *Paleophycus*, *Skolithos*, *Teichichnus*, *Thalassinoides*, *Siphonichus*, *Scolica* and *Rhizocorallium*. The bioturbated mud interbeds generally decrease up section. Contacts above and below are gradational. Bitumen saturation is variable from low to moderate, which generally increases upwards.

Interpretation:

Subfacies 4A is interpreted to be proximal prodelta sediments, whereas Subfacies 4B is interpreted as a transitional facies between the proximal prodelta sediments and delta front sediments of Facies 5. Sedimentation rates still remain low in Subfacies 4A due to the high amounts of mud and silt allowed to settle out of the water column, but sedimentation rates increase slightly moving into the transitional Subfacies 4B (Carmona *et al*., 2009). Primary structures in Subfacies 4B observed locally indicate that tidal/wave processes are minor (Carmona *et al*., 2009). Indicated by the degree of bioturbation, both Subfacies 4A and Subfacies 4B are in fully aerobic waters where organisms can flourish (McIllroy, 2007). Proximal prodelta (Subfacies 5A) is still heavily influenced by normal marine salinities and is validated by the highly pervasive bioturbation (McIllroy, 2007). In the transitional facies (Subfacies 4B) salinity mixing becomes more prevalent as the intensity and diversity of ichnofossils decrease significantly upward (Buatois *et al*., 2003).

Facies 5 – Moderately bioturbated interbedded fine sand and mud with minor clast material

Description:

Facies 5 consists of fine lower to fine upper sand interbedded with grey to brown bioturbated mud (15-30%) and minor rip-up clast material (<5%) (Figure 2-4, G, H). Sand beds typically thicken stratigraphically upward and the mud beds become thinner and less abundant (Figure 2-4, H). Thin mud drapes occur rarely. Sand beds are generally well sorted and consist of low angle cross bedding and small scale structures such as current ripples and climbing ripples (Figure 2-4, H). Interbeds of sand and mud also contain carbonaceous material and calcite nodules. Mud interbeds are moderately bioturbated with moderate intensity and diversity of ichnofossils (BI 3; Figure 2-4, G). Ichnogenera within these mud interbeds are moderate to large in size and fairly robust, but become more sporadic up section. Traces fossils observed include *Planolites*, *Thalassinoides*, *Siphonichnus*, *Arenicolites*, *Rhizocorallium*, *Teichichnus*, *Asterosoma*, and *Rosselia* (Figure 2-4, G). Burrows generally decrease in size and intensity stratigraphically upward (Figure 2-4, H). Contacts above and below commonly are gradational. Degree of bitumen saturation is moderate to high and increases upwards.

Interpretation:

Facies 5 fine grained sediments are interpreted to be delta front deposits. The overall coarsening upward trend in grain size indicates a prograding system. Futhermore, the moderately diverse assemblage characterized by larger traces suggest episodes of normal marine ecological conditions (Buatois *et al*., 2008). During high energy events thicker beds of parallel to low angle to hummocky cross stratified sand is deposited (Walker and Plint, 1992; Hill *et al*., 2003). Between storm events, periods of suspension deposition of mud would have occurred in the distal regions of the delta front, hence an increase in mud interbeds stratigraphically lower in Facies 5 (Pemberton and MacEachern, 2006). An increase in the appearance of mud drapes higher up in the sequence implies an increase in the influence of tides (Klein, 1977; Carmona *et al*., 2009). A strong tidal influence can potentially bring an influx of normal marine salinity episodically making conditions more hospitable (though sporadic) for colonization of marine traces (Buatois *et al*., 2008).

FACIES ASSOCIATION 3 (*Distributary Mouth-Bars*)

Facies 6 – Fine to medium sand interbedded with minor mud and clast material

Description:

Facies 6 consists of fine upper to medium lower sand interbedded with thin and often discontinuous fluid mud/laminae (1-15%) and 1-5% mud rip-up clasts (Figure 2-5, A-D). Sand beds are 1-35cm thick and mud layer (0.5-1 cm thick) often appear in couplets that appear to drape over the trough cross stratification in the sandier units. Moving up-section sand beds coarsen upwards and are typically massive looking with large scale low angle cross bedding and range from 1 to 5m thick (Figure 2-5, D). Primary structures observed include large scale low angle to trough cross stratification and small scale features such as current ripples and climbing ripples (Figure 2-5, A-D). Also observed are calcite nodules, carbonaceous material, and lean zones (reducing bitumen saturation locally). Within the mud laminae, a low abundance and low diversity assemblage dominated by small *Planolites* is observed (BI 0-1; Figure 2-5, C). Contacts above and below are commonly gradational, but locally a sharp basal contact is observed. Bitumen saturation is typically very high within this facies and usually occurs in conjunction with Facies 7.

Interpretation:

Facies 6 sediments are interpreted as distributary mouth-bar sands deposited above the delta front region. Fluid muds are deposited from suspension during periods of slack water and appears to ‘drape’ over the

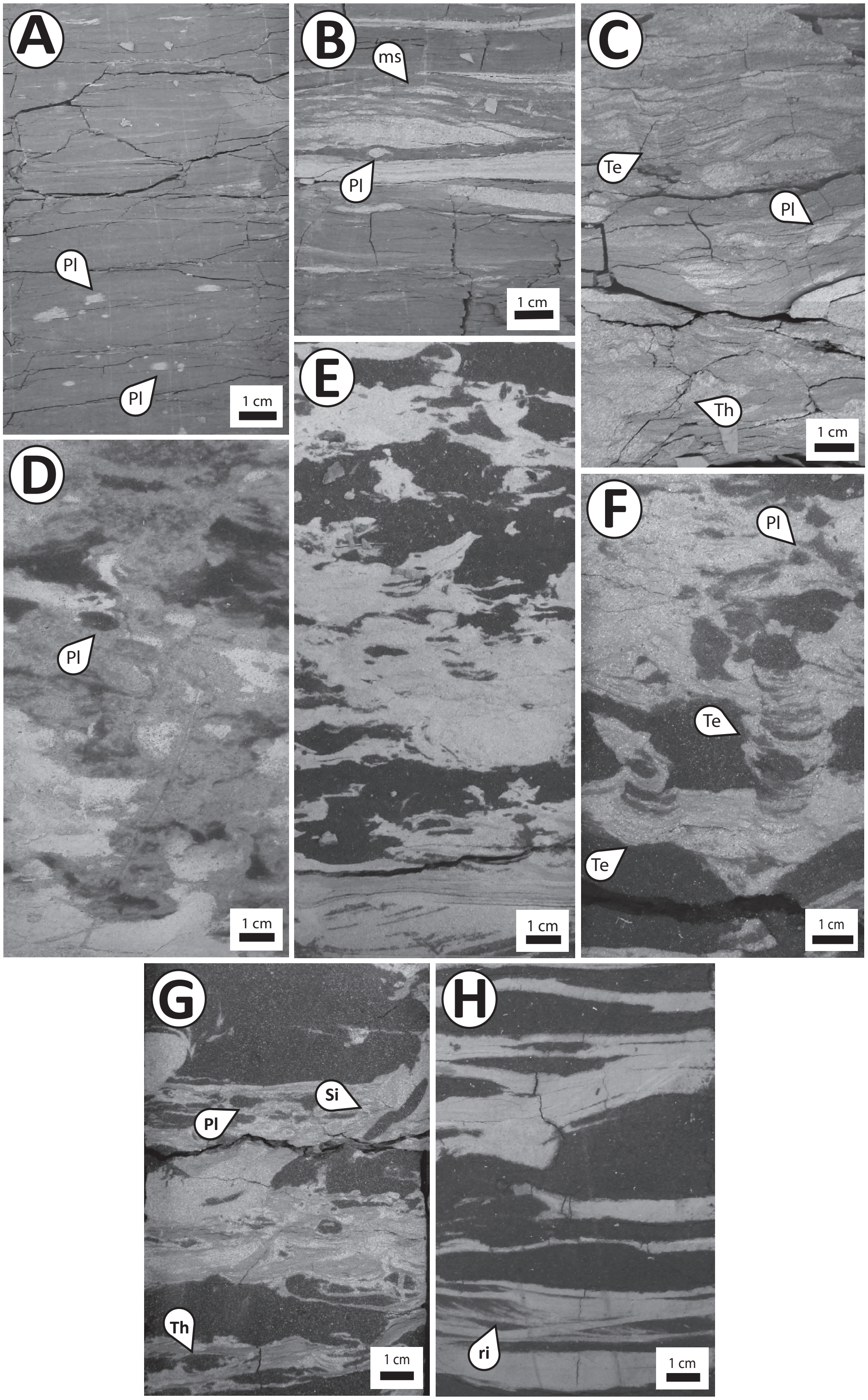


Figure 2-4: Facies Association 2 – Prodelta – delta front. (A) Distal prodelta muds (Facies 4) and

Figure 2-4 continued: slope deposits, most likely produced by a slumping action downslope due to the massive nature. Bioturbation is minimal with a few Planolites (Pl) burrows highlighted by the lighter silty material. Well 11-06-065-04W4, 481.91m. (B) Typical flaser bedded distal prodelta muds and siltstones (Facies 4) with minor bioturbation reflected in the silty layers, mainly Planolites (Pl). Some evidence of soft sediment deformation (flame structures) and lateral disruption of silty layers may represent "mantle and swirl" (ms) structures, indicating a soupy, soft substrate. Well 07-22-066-03W4, 485.85m. (C) Typical pervasively bioturbated mud and sandy silt of the proximal prodelta sediments (Facies 5A). All sedimentary structures are destroyed due to the intensity of the bioturbation. Traces seen include Teichichnus (Te), Planolites (Pl) and Thalassinoides (Th). Well 05-24-066-03W4, 470.90m. (D) Proximal prodelta sediments with minor oil saturation (Facies 5A). The brighter white areas are calcite cemented. Well 06-03-066-03W4, 470.91m. (E) Transitional facies between the proximal prodelta and lower delta front deposits showing an increase in the proportion of oil saturated sand. Sedimentary structures, as in the proximal prodelta deposits are for the most part destroyed by pervasive bioturbation, where traces are often difficult to distinguish. Well 10-27-066-03W4, 503.70m. (F) Transitional proximal prodelta-delta front deposits showing well defined Teichichnus (Te) burrows as well as some Planolites (Pl). Well 08-19-066-02W4, 470.32m. (G) Typical bioturbated section of sand and mud from a more distal portion of the lower delta front. Again in muddier sections, sedimentary structures are destroyed by bioturbation. Traces seen include Siphonichnus (Si), Planolites (Pl), and Thalassinoides (Th). Well 14-25-065-03W4, 460.17m. (H) An example from a more proximal position on the delta front. Some ripple laminations (ri) are seen near the bottom of the picture Note the drastic decrease in bioturbation. Well 06-20-065-03W4, 454.77m.

large scale cross stratification features in the sand beds (Nio and Yang, 1989; Dalyrmple *et al.*, 2003). The upward decrease in abundance and thickness of mud drapes implies that they were formed by the deposition from fluid muds in the bottom of a channel between bars (Dalyrmple *et al.*, 2003). Fluid muds tend to dominate lower lying or more distal portions due to higher amounts of suspended sediment. However, moving up-section tidal/wave action frequently inhibits the deposition of these muds or resuspends it during periods of slack water (Dalyrmple *et al.*, 2003).

Also commonly observed in mouth-bar deposits are the small scale structures, such as the current/climbing ripples and the restricted trace fossil assemblage seen in the core (Dalrymple *et al*., 2003; Buatois *et al*., 2005). Lean zones are the result of authigenic berthierine cement commonly seen in many coastal plain and shallow marine types of sediment with a brackish pore water composition (Hornibrook and Longstaffe, 1996). Rare to absent bioturbation suggests brackish water conditions indicative of tidal environments where salinity mixing is common (Buatois *et al*., 2005). Facies 6 mouth sand bars usually are interrelated with inter-bar channel deposits (Facies 7) and are seen frequently above bioturbated delta front deposits (Facies 5) (Dalryrmple *et al.*, 2003).

FACIES ASSOCIATION 4 (*Subaqueous Inter-bar Channel Fill*)

Facies 7 – Fine to medium sand with minor mud and abundant clast material

Description:

Facies 7 sediments consist of lower fine to lower medium sand with minor thin, often discontinuous mud drapes (<5%) interbedded with layers containing abundant poorly sorted angular to rounded mud clasts (Figure 2-6, A-C). Clast beds range from 15cm to over 1 meter thick and generally thin upwards, with clast material also decreasing upwards (Figure 2-6, B). Primary structures include large-scale low angle to trough cross stratification and locally current ripples are preserved. Some soft sediment deformation structures are observed as well as calcite nodules. Mud drapes are minor and occur usually in couplets. Mud clasts are generally aligned sub-parallel to the cross stratification, and locally make up 50-60% of the bed volume (Figure 2-6, A, B). The clasts are moderately uniform in shape and range from a few millimetres (usually angular in shape) to over 15cm in diameter (usually rounded and armoured) (Figure 2-6, A-C). No bioturbation was observed in the sand, although low abundance and low diversity ichnofossil assemblage dominated by small *Planolites* occurs within some of the mud clasts and mud drapes (BI 0-1). The basal contact is commonly erosive and found in proximity to Facies 6 but locally may be erosive with lower facies with a rounded chert pebble lag deposit observed in some core. Upper contacts are commonly gradational. Bitumen saturation is fairly high within the unconsolidated sand.

Interpretation:

Facies 7 is interpreted as inter-bar channel fill. Facies 7 is closely associated with the mouth bar deposits of Facies 6 and delta front Facies 5. The abundance of mud clasts are interpreted to have been eroded from muddy upper delta plain deposits and heterolithic lower delta front strata (Facies 5) (Feldman *et al*., 2008). The presence of armoured clasts suggests that the channel is also tidal in origin. These clasts are commonly formed by the rolling back and forth wave action in the intertidal zone (Chun *et al.*, 2002), and were subsequently transported into the subtidal zone as a result of increased seasonal discharge. Fluid muds with minor burrows, common in most tidal environments, are a minor constituent within this facies, thus are

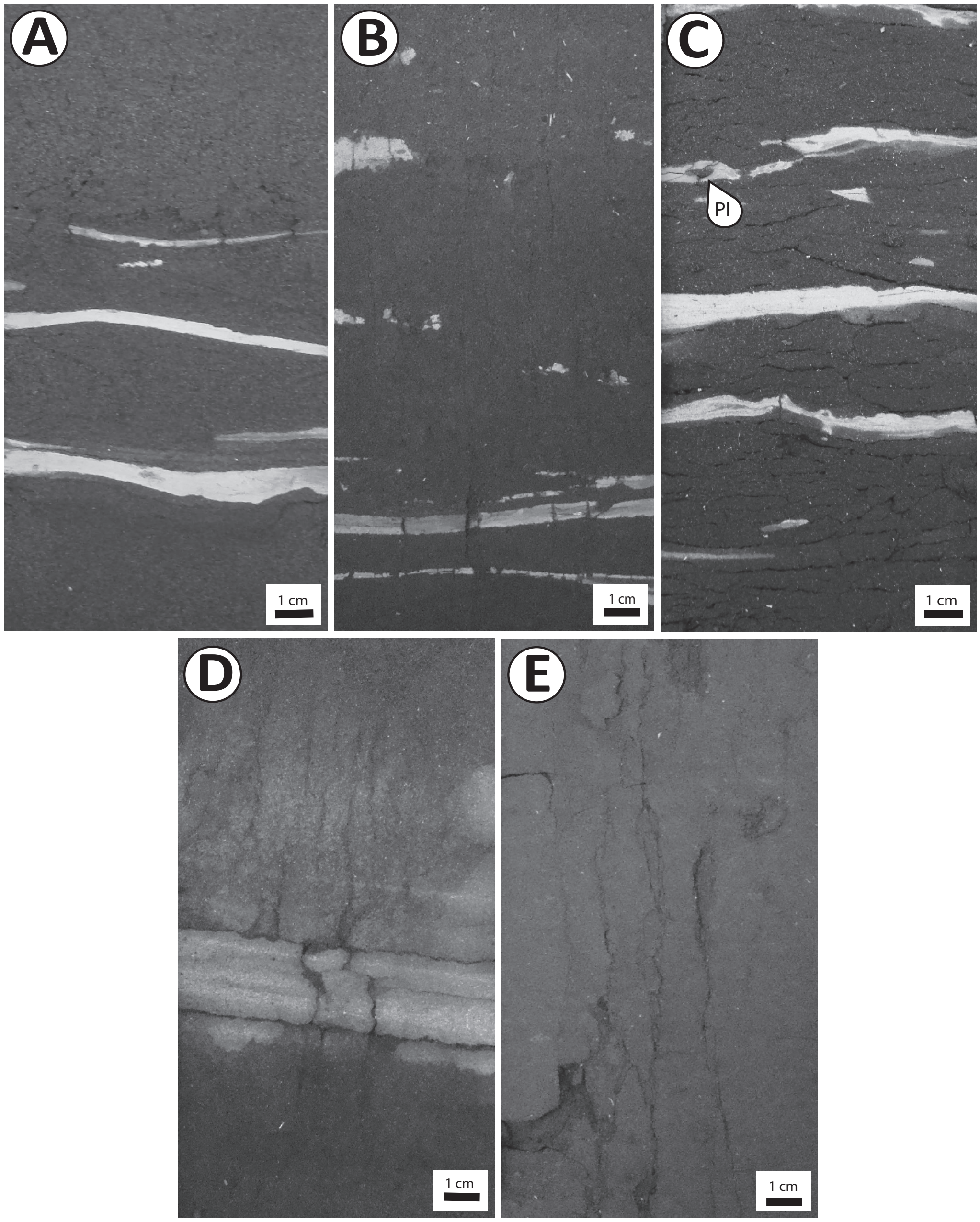


Figure 2-5: Facies Association 3 – Distributary Mouth Bars. (A) An example of distributary mouth bars. A fine upper to medium lower oil saturated sand interbedded with thin and often discontinuous fluid muds/laminae and appear to drape over the trough cross bedding seen in the sandier units. Well 04-03-065-03W4, 484.20m. (B) This facies is also characterized by minor muddy rip up clast material. Well 04-15-065-03W4, 437.74m. (C) Fine upper to medium lower oil saturated, trough cross bedded sand interbedded with thin fluid muds. Note the significant decrease in bioturbation in this facies. Planolites (Pl). Well 05-24-066-03W4, 459.50m. (D) Proximal expression of distributary mouth bars. Typical medium grained low angle cross bedded oil saturated sand (Facies 7B). Note the complete lack of mud that was present in previous facies. Appearance of the berthierine cement (lighter coloured sand) accents the large scale low angle cross bedding and creates lean zones within this facies. Well 08-02-065-03W4, 445.49m. (E) An example of the sometimes massive nature of this facies, representing the best reservoir material within the Clearwater Formation. Well 07-22-066-03W4, 475.18m.

interpreted to have been eroded away by higher tidal/wave action moving up-section (Arnott and Hand, 1989). Furthermore, the low abundance, low diversity ichnofossil assemblage is due in part to the constant shifting of the substrate which softground burrowers would have found inhospitable (Pemberton *et al*., 2001; Pemberton and MacEachern, 2006).

FACIES ASSOCIATION 5 (*Tidal Flats*)

Facies 8 – Planolites burrowed medium sand with minor mud and clast material

Description:

Facies 8 consists of medium lower sand with very minor mud and rip-up clast material (Figure 2-7, A-C). Primary structures have been completely obliterated by intense bioturbation, although locally and very rarely small scale current ripples, planar laminations and carbonaceous material are observed (Figure 2-7, A, C). These structures typically occur in a 5-10 cm thick bed that seem to cap the intensely bioturbated sand (Figure 2-7, C). The relative degree of bioturbation is very intense but diversity is very low (BI 5-6). The ichnofossil assemblage is dominated by large *Planolites*, ranging from 1-2 cm in diameter (Figure 2-7, D). Contact above and below are commonly gradational with Facies 6 and 7. Bitumen saturation is reduced in this facies due to pervasive berthierine cement accentuated by the intense burrowing action.

Interpretation:

Facies 8 sediments are interpreted as sandy tidal flat deposits. The abundance of sand indicates that there is a strong tidal influence, not conducive to the suspension deposition of mud (Arnott and Hand, 1989). The berthierine cement (common in most deltaic environments) indicates a shallow marine environment where the pore water composition is brackish, which is also reflected in the impoverished trace fossil suite (Hornibrook and Longstaffe, 1996). Unbioturbated sections, characterized by ripples and planar laminations, that caps the intensely bioturbated sand is interpreted as the top of the sand flat that is periodically subaerially exposed to the air during low tide. Whereas the extensively bioturbated sections, exclusively by Planolites, reflect deposit-feeding infaunal polychaetes or worm-like

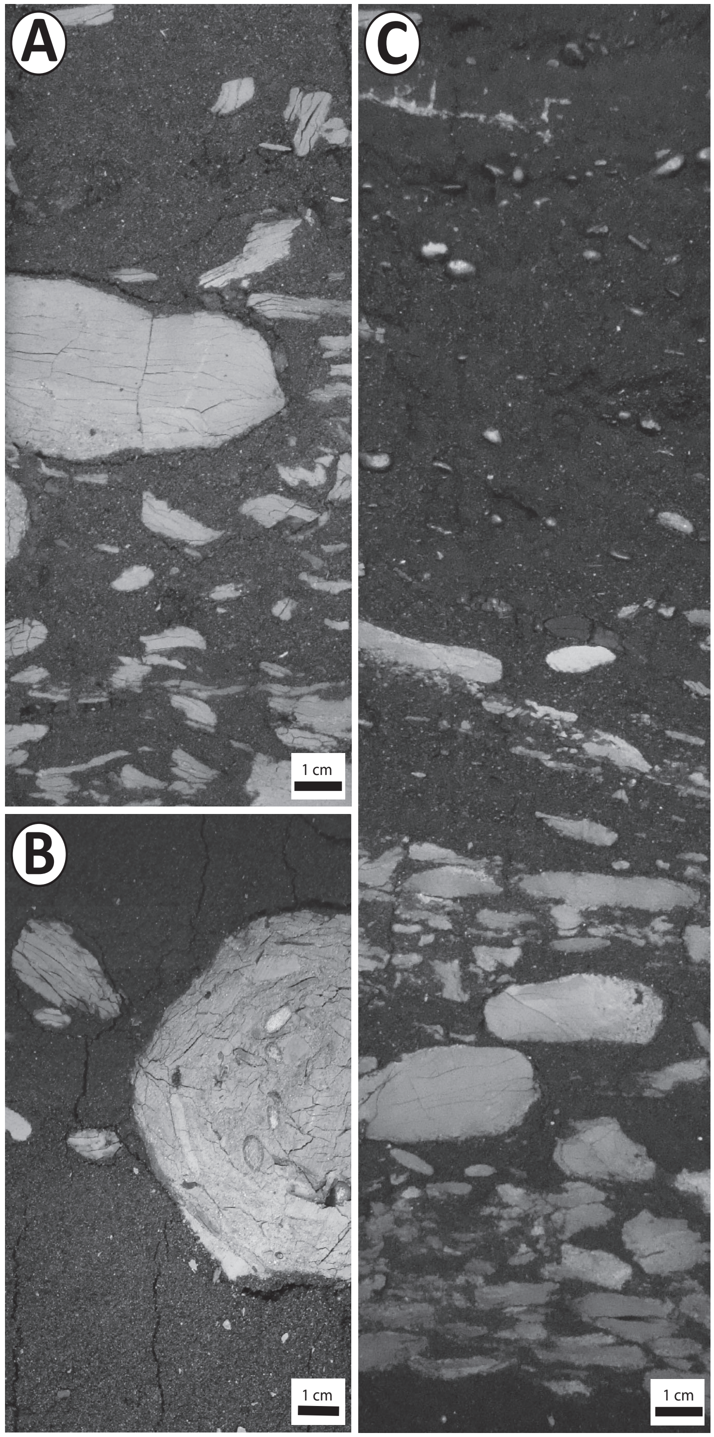


Figure 2-6: Facies Association 4 – Inter-bar Channel Fill. (A) Typical example of this clast rich facies in a matrix of fine to medium grained oil saturated sand. Note the muddy clasts are very poorly sorted and angular in shape. Commonly these clasts are oriented parallel to the bedding. Well 06-24-066-03W4, 457.79m. (B) An excellent example of a well rounded armoured clast in a matrix of medium grained oil saturated sand, common within this facies. Well 11-17-065-03W4, 448.68m. (C) Abundant large rounded clast material at the base of a channel, moving up section clast abundance as well as clast size diminishes. Note the clast material is aligned sub-parallel to the cross-stratification. Well 11-10-066-03W4, 425.9m.

organisms which are commonly found on tidal flats (Pemberton and MacEachern, 2006).

FACIES ASSOCIATION 6 (E*stuarine)*

Facies 9 - Very fine to fine grained sand with minor mud laminae

Description:

Facies 9 is rare, only appearing in two cores in the northern part of the study area. This facies consists of well sorted very fine to fine grained sand with 5-10% mud (Figure 2-8, A). Sand beds tend to be fairly thick (10cm - 50cm) and display large scale low angle cross-stratification, with planar parallel and trough cross-bedding locally which appears to be extensively wave reworked (Figure 2-8, A). Sand beds subtly coarsen-upwards and grade laterally into interbedded mud and sand toward the top of this facies. May contain fragmented shell fragments, lean zones and rare carbonaceous material. Bioturbation is rare to absent, low diversity and low intensity (BI 0-1). The assemblage contains *Planolites*, *Skolithos, Cylindrichnus,* with rare occurrences of *Rhizocorallium*, and *Asterosoma*. Most of the bioturbation is contained within muddier intervals at the top of the facies. The basal contact of Facies 9 is typically sharp and erosive (Figure 2-8, A). The top contact is typically gradational with Facies 11 above (Figure 2-8, B). Bitumen saturation is moderate to high.

Interpretation:

Facies 9 is interpreted as barrier sand bar deposits. Facies 9 appears gradationally between offshore sediments (Facies 11) to the north and muddier central basin mudstones and sandstones (Facies 10) to the south. The coarsening upward profile is characteristic of barrier bars in wave dominated estuarine settings (Reinson, 1992; Hubbard *et al.*, 1999). The well sorted nature of the sands and evidence of wave reworking indicate a strong influence from the waves and tides (Hubbard *et al.*, 1999; Hubbard *et al.*, 2002). The impoverished ichnofossil assemblage indicates true brackish water settings where organisms are subjected to environmental stresses resulting in small, diminutive opportunistic traces (Pemberton and MacEachern, 2006). In particular, the increased energy due to waves and tides at the mouth of

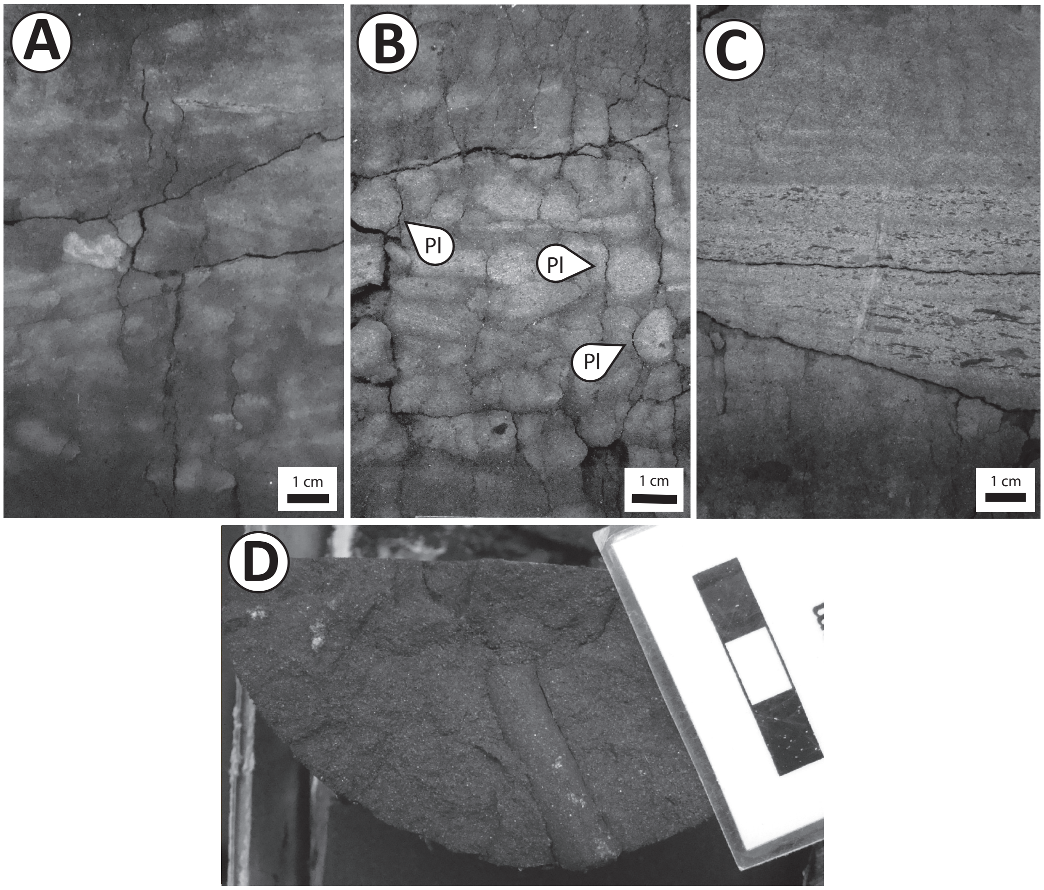


Figure 2-7: Facies Association 5 – Tidal Flats. (A) Burrowed medium grained oil saturated sand showing poorly developed ripple laminations and low angle cross bedding. Majority of the sedimentary structures have been destroyed by bioturbation, mainly Planolites burrowing. Bitumen saturation is reduced in this facies due to pervasive berthierine cement seen as the lighter coloured sand. Well 15-21-065-03W4, 432.84m. (B) Example of well defined Planolites (Pl) burrows which dominate this facies. Note the lack of sedimentary structures due to the intensity of the bioturbation. Bitumen saturation is reduced in this facies due to pervasive berthierine cement accentuated by the intense burrowing action. Well 01-29-065-03W4, 427.49m. (C) Unbioturbated section, characterized by planar laminations and carbonaceous material, caps the intensely bioturbated sand seen in A and B. This is interpreted as the top of the sand flat that is periodically subaerially exposed to the air during low tide. Well 15-21-065-03W4, 425.5m. (D) Single well defined Planolites burrow, characteristic of this facies. Well 15-21-065-03W4, 430.3m.

an estuary and increased sedimentation rates has a marked influence in the colonization of the barrier bar (Pemberton and MacEachern, 2006; Buatois *et al.*, 1999).

Facies 10 – Moderately to intensely bioturbated interbedded mud and fine sand

Description:

Facies 10 is a fine (lower to upper) -grained facies, consisting of 20-30% mud interbeds and <5% rip-up clast material (Figure 2-8, C, D). Primary structures observed where bioturbation was reduced include wavy to low angle cross-stratification, minor small scale current and climbing ripples. Mud beds are thin and are moderately bioturbated, rarely the mud beds occur as mud drapes (Figure 2-8, C, D). Muddy rip-up clasts are rare and occur mainly at the bottoms of graded beds which appear in some of the sandier intervals. The facies also contain carbonaceous material and rare soft sediment deformation structures are rarely observed. Trace fossils are rare to common, moderately low diversity and intensity, with the assemblage being dominated by *Planolites* and *Thalassinoides* (BI 2-3; Figure 2-8, C, D). Other traces observed locally include *Arenicolites*, *Rhizocorallium*, *Teichichnus*, *Asterosoma* and *Rosselia* (Figure 2-8, C, D). Facies 10 typically occurs gradationally underlying Facies 9, and is rarely found gradationally capping Facies 7. The top contact is a characteristic transgressive chert pebble lag deposit (Figure 2-8, E). Bitumen saturation is moderately high.

Interpretation:

Facies 10 resembles that of Subfacies 4B and is interpreted as the muddy deposits of a central basin in an estuarine complex. The increased amount of mud in this facies indicates a relatively low energy environment, allowing the suspended muddy sediments to be deposited indicating that either tidal and wave influence is minimal or sedimentation rates have decreased (Carmona *et al*., 2009). The prevalence of mud-rich deposits coupled with a diminished ichnodiversity level, reflecting a true brackish water assemblage seen in estuarine systems, suggests deposition within a salinity-stressed and quiescent depositional environment (Hubbard *et al.*, 1999; Pemberton and MacEachern, 2006; Dalyrmple and Choi, 2007). Rarely this facies is found capping Facies 7 and is interpreted as a small, thin retrogressive package related to autocyclic processes.

FACIES ASSOCIATION 7 (Distal *Offshore*)

Facies 11 – Dark to light grey bioturbated to parallel laminated silty mud with very minor very fine grained sand

Description:

Facies 11 is characteristic of the Grand Rapids Formation in the Cold Lake

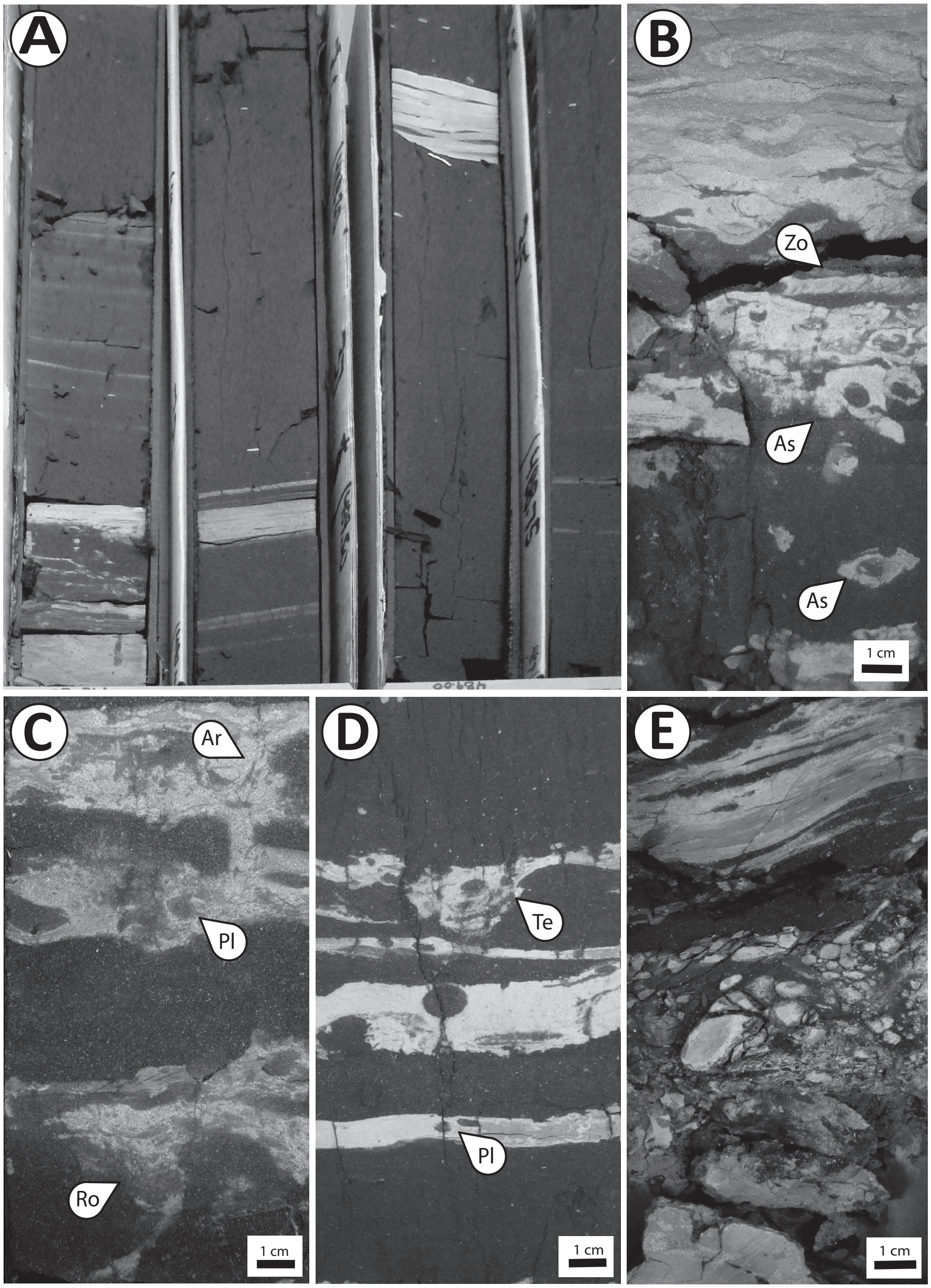


Figure 2-8: Facies Association 6 – Estuarine. (A) An example of the wave reworked low angle cross-bedded fine to very fine grained oil saturated sands of the tidal delta facies (Facies 9). Note the Glossifungites Ichnofacies indicating the lower sequence boundary. For scale, core sleeve is 3.5". Well 10-27-066-03W4, 490.25-488m. (B) Contact between the tidal delta (Facies 9) and offshore silts and muds (Facies 11), bioturbation include well-defined Zoophycos (Zo) burrows common to Facies 11. Contact is burrowed by Asterosoma (As). Well 10-27-066-02W4, 485.8m. (C) Moderately bioturbated fine grained oil saturated sand and mud. Sedimentary structures are not well preserved due to biotubation. Traces seen include Planolites (Pl), Arenicolites (Ar), and Rosselia (Ro). Well 07-36-065-03W4, 461.75m. (D) Another example of this facies where biotur

Figure 2-8 continued: bation is not as prevalent and some wavy bedding is preserved within the fine grained oil saturated sand. Traces include Planolites (Pl) and Teichichnus (Te). Well 14-10-065-03W4, 450.93m. (E) Transgressive chert pebble lags. Contact between central basin interbedded sands and muds (Facies 10) and F4/F5 (prodelta-lower delta front). Well 11-10-066-03W4, 425.5m.

area. Sediments consist of bioturbated to parallel laminated beds of grey mud intercalated with thin lenses of very fine sand and silt (Figure 2-9, A, B). Facies 11 is a coarsening upward succession, from intensely bioturbated silty mud to wave rippled and hummocky cross stratified sand. Also contains minor shell fragments and siderite nodules. Trace fossils are abundant and diverse in muddier strata and include *Zoophycos*, *Planolites*, *Asterosoma*, *Chondrites*, *Teichichnus*, *Skolithos* and *Paleophycus* (Figure 2-9, A, B). The contact between the Clearwater Formation and Grand Rapids Formation is commonly gradational, although locally erosive sharp contacts are observed.

Interpretation:

Facies 11 is interpreted as fine grained distal offshore deposits. Parallel laminated muddy strata would have accumulated from suspension and intensely bioturbated (McCrimmon and Arnott, 2002). The wave ripples and hummocky stratification indicate storm activity on a shelf environment (Walker and Plint, 1992). The shell fragments and trace fossil assemblage indicate open-marine conditions (Pemberton and MacEachern, 2006).

Paleoenvironmental Reconstruction

The studied interval, the Clearwater Formation, is clearly progradational and reflects a short-term regressive event within an overall transgressive trend within the WCSB (Hein and Cotterill, 2006). Areas reflecting tidal dominance typically have a high tidal range and low wave influence, and are commonly associated with transgressive periods (Nummedal *et al*., 2003; Willis, 2005). High tidal ranges may be amplified due to tectonically generated confinement in structurally controlled basins and are independent of fluctuations in sea-level (Martinius *et al*., 2001; McIlroy *et al*., 2005). During the mid-Cretaceous, tectonic activity significantly increased along the western margin of the WCSB rapidly infilling the foredeep with synorogenic sediment pushing the shoreline irregularly eastward (Figure 2-1; Armstrong and Ward, 1991). Coupled with a worldwide increase in sea-level and situated on a broad low gradient platform that dipped

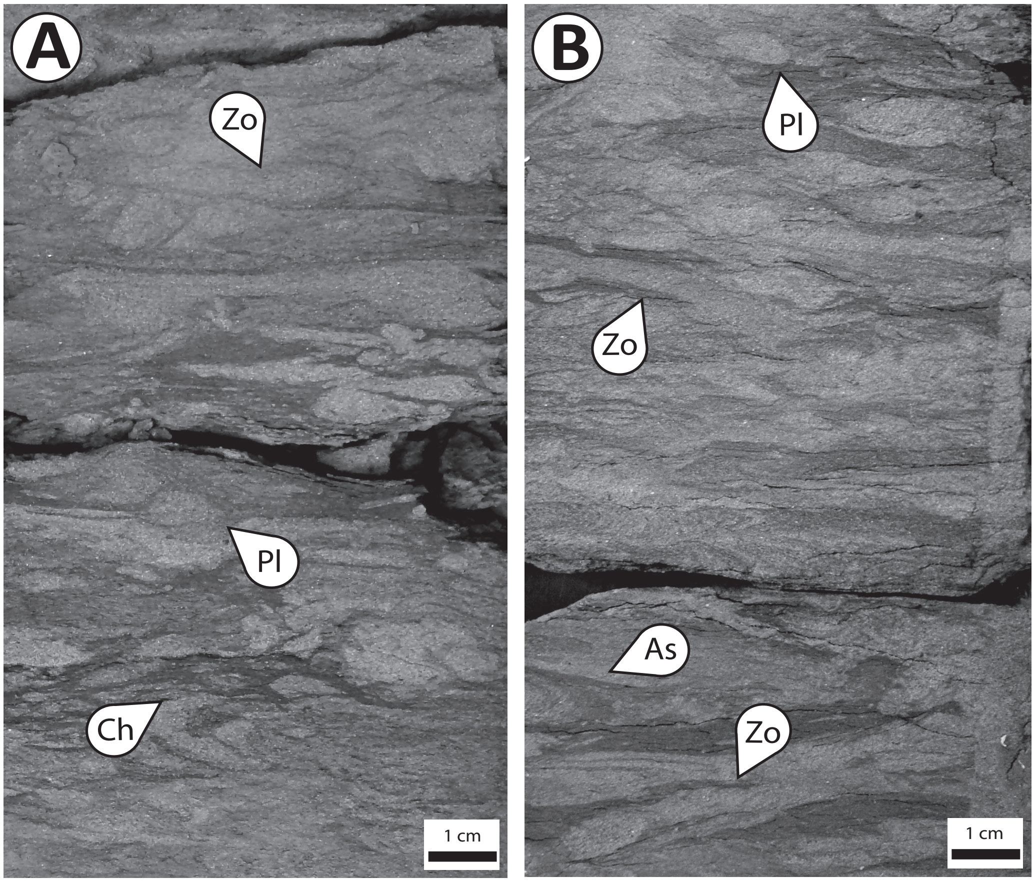


Figure 2-9: Facies Association 7 – Distal Offshore. (A) Typical Grand Rapids Formation offshore deposits. Intensely bioturbated silty mud and very fine grained sand. Pervasive bioturbation has destroyed any evidence of sedimentary structures. Most traces are difficult to discern due to level of bioturbation, traces seen include Zoophycos (Zo), Chondrites (Ch) and Planolites (Pl). Well 14-10-065-03W4, 430.00m. (B) An example of the clear offshore assemblage, Zoophycus, seen in this facies. Traces seen include Zoophycus (Zo), Asterosoma (As), Planolites (Pl). Well 14-27-065-03W4, 408.37m.

to the north, a high tidal range in the Cold Lake area during the deposition of Clearwater sediments is feasible (Armstrong and Ward, 1991). There are several lines of evidence that suggest the Clearwater sediments were deposited under a strong tidal influence. (1) Oppositely dipping ripple cross-laminations are common throughout delta front deposits, indicating tidal flood and ebb flows (Figure 2-10, A; Klein, 1977; Willis, 2005). (2) An abundance of mud drapes mantling ripple forests, reflecting changes in current velocities and mud fallout during slack water (Figure 2-10, A, B, D, E; Klein, 1977). (3) Delta front and prodelta facies are stongly heterolithic and display flaser to lenticular bedding, signifying alternating traction sedimentation and suspension fallout (Figures 2-4, 2-5; Klein, 1977). (4) Abundant mud intraclasts observed in the inter-bar channel fill facies, are regarded as common in tide-influenced settings (Figure 2-6; Dalrymple and

Choi, 2007).

While tidal influences can be established based on physical sedimentary structures and associated facies, but identifying if the tidal facies were deposited in a delta, estuary or an open-marine setting requires further investigation of strata stacking patterns. Within the Clearwater Formation in the study area, the stratal stacking pattern reflects deltaic progradation rather than the backstepping pattern typically seen in transgressive estuarine deposits (Dalrymple and Choi, 2007). However, estuarine incised valley systems also display a progradational stacking pattern due to the development of the bayhead delta during the subsequent highstand (Zaitlin *et al*., 1994). Discerning a progradational deltaic package from an estuarine prograding bayhead delta complex requires an ichnological study, as certain trace-fossil suites are indicative of particular environments.

In modern tide-dominated deltas, subaerial upper delta front to delta-top deposits such as tidal channels and adjacent tidal flats are common (Dalrymple, 1992). Upper delta front and delta-top facies generally have low preservation potential and are normally eroded during trangressive ravinement, and accordingly, there are few ancient examples that have these proximal deposits recorded (Bhattacharya and Willis, 2001; McIlroy *et al*., 2005). Willis *et al*. (1999) explained the absence of these proximal facies reflect that tide-influenced lower delta-front deposits are generated several kilometres basinward of subaerial deposits, particularly in low-gradient, low accommodation platform settings. This is consistent with Clearwater sediments; in the majority of the study area the facies associations are deposited subaqueously and reflect the basinward muddier portions of the delta (Figure 2-4). Tens of kilometres beyond the prodelta edge, locally occurring, subaerial sandy tidal flat deposits are observed indicating that Clearwater sediments were most likely deposited on a low-gradient platform setting (Figure 2-7C). In the northern half of the study area muddy deposits of the prodelta and delta front predominant. In the southern half of the study area lower delta front deposits are still prevalent but subaqueous upper delta front facies become more widespread. Within the study area the majority of the sediments were established as proximal prodelta to delta front deposits and upper delta front subaqueous channel and bar deposits.

Significant controls on the distribution of trace fossils in deltaic environments were recently analyzed by MacEachern *et al*. (2005). Tide-dominated deltas are still understudied and the main paleoenvironmental stresses such as salinity, sedimentation rates, water turbidity and oxygen acting on organisms

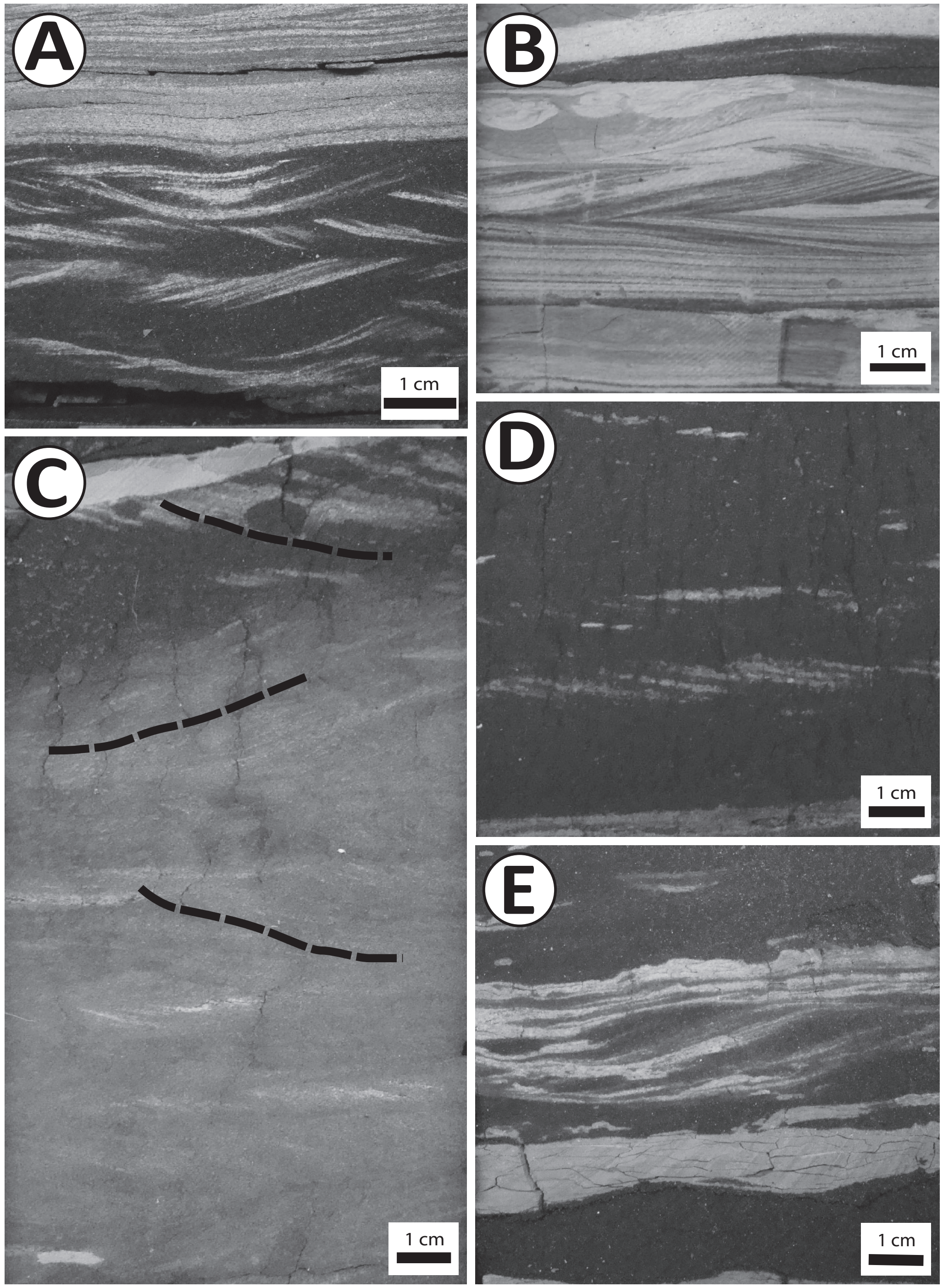


Figure 2-10: Evidence of tidal processes – mud drapes and herringbone cross-stratification. (A) Rippled oil saturated sandstone bed. Note mud drapes on foresets of ripples, dipping in opposite directions. (B) Cross-bedded sandstone with mud drapes, note tidal couplets towards the bottom half of photo. (C) Trough cross-bedded sandstone seen predominantly in FA3, marked in dashed black lines. (D) Mud drapes on a set of climbing ripples in oil saturated cross-bedded sandstone. (E) Set of mud drapes in a climbing rippled sandstone.

are poorly known (MacEachern *et al*., 2005; McIlroy *et al*., 2005; Carmona *et al*.,

2009) . Within the Clearwater Formation the ichnology observed show evidence of somewhat stressed conditions, indicated by their more restricted and diminished ichnofauna as compared with fully marine assemblages seen in the McMurray, Wabiskaw and Grand Rapids (FA1 and FA7). However, ichnodiversity levels within the Clearwater sediments are higher than those of a bay-head delta, which usually experiences strong salinity dilution. This suggests that this tidally-dominated body was not emplaced under fully marine conditions or transgressive estuarine conditions, but within a deltaic system.

Summary

The Clearwater Formation at Cold Lake was deposited in a tidally-dominated deltaic environment. Strata has been subdivided into eleven facies and subsequently grouped into seven facies associations: (1) shoreface; (2) prodelta to delta front; (3) distributary mouth bars; (4) inter-bar channel fill; (5) tidal flats; (6) estuarine valley-fill; and (7) offshore. Recognition of the tide-dominated deltaic strata was three-fold. Firstly, the identification of physical structures which indicated a strong tidal influence in the area. Tidally influenced structures seen were oppositely dipping ripple laminations, abundant mud intraclasts, mud drapes, and heterolithic bedding. Secondly, the recognition of a progradational stacking pattern, indicating either a deltaic environment or a bay-head delta sub-environment in an estuary. Lastly, an ichnological analysis then allowed for distinguishing between deltaic or bay-head delta environments. The trace-fossil suites developed in the above environments show low diversities and low to moderate abundance of ichnofauna reflecting an impoverished Cruziana ichnofacies. However, ichnodiversity levels within the Clearwater sediments are higher than those of a bay-head delta, which usually experiences strong salinity dilution. This suggests that this prograding, tidally dominated body was part of a deltaic system and not the bay-head delta of a transgressive estuarine system.

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Chapter 3
Ichnological Characteristics of the Clearwater Formation, Cold Lake oil sands, Alberta, Canada

Introduction

A paleoenvironmental reconstruction, detailed in Chapter 2, re-establishes the Clearwater Formation was deposited in a tidally dominated deltaic environment. Strata have been subdivided into eleven facies and subsequently grouped into seven facies associations: (1) shoreface; (2) prodelta to delta front; (3) distributary mouth bars; (4) inter-bar channel fill; (5) tidal flats; (6) estuarine valley-fill; and (7) offshore (Table 2-1). A progradational stratal stacking pattern, rather than a back-stepping pattern typically seen in transgressive estuarine deposits, reflects deltaic sedimentation (Dalrymple and Choi, 2007). However, estuarine incised valley systems also display a progradational stacking pattern due to the development of the bayhead delta during the subsequent highstand (Zaitlin *et al*., 1994). Discerning a progradational deltaic package from an estuarine prograding bayhead delta complex requires an ichnological study, as certain trace-fossil suites are indicative of particular environments.

Relatively abundant assemblages of ichnofauna typify the Clearwater Formation in the Cold Lake area. The ichnofauna identified in core are plentiful in the marine and marginal marine facies of Facies Association 2 (FA2 - open marine/prodelta to proximal delta front). Feeding behaviours exemplified by specific trace fossils can be used to indicate their position on the shelf in a particular depositional environment. For example, the presence of *Zoophycos*, a deposit feeding trace found in distal offshore cores, is characteristic of a low oxygen marine environment and a good indicator of deeper water conditions on the shelf (Bradley and Pemberton, 1992). The size and abundance of trace-making organisms can also be indicative of depositional environment. In general, smaller and fewer number of trace fossils tend to exist in the higher energy environments of the upper shelf, and a more diverse assemblage of ichnofossils indicate quieter waters of the lower shelf (Bradley and Pemberton, 1992). In summary, type of ichnogenera and the change in abundance from distal cores to proximal cores in the Cold Lake study area suggests an increase in the energy of the environment and a decrease in food availability (Bradley and Pemberton, 1992).

The input of freshwater into higher salinity seawater in a deltaic or estuarine environment results in the development of brackish-water conditions (Pemberton and Wightman, 1992). In brackish-water environments, the organisms are more ecologically stressed than in fully marine conditions, and as a result the diversity tends to be lower and organisms are diminutive in size (Ekdale *et al.*, 1984). The higher diversity in the ichnofossil assemblage found in the Wabiskaw Member, compared to the lower diversity assemblages in the Clearwater Formation, has been interpreted to be a result of the higher salinity marine conditions present during the Wabiskaw, in contrast to the deltaic/estuarine, brackish-water conditions present during the deposition of the remaining Clearwater sediments (Bradley and Pemberton, 1992).

This chapter discusses the ichnology observed in the Clearwater Formation and whether the observed ichnology supports this re-evaluation of the depositional setting. Moreover, the purpose of this chapter is four-fold:

1. To present past research on the ichnology of the Clearwater Formation;
2. Discuss the trace fossil assemblage expected in a tide-dominated del taic system;
3. Detail the observed ichnology seen in four representative cores;
4. Provide a preliminary framework/ichnological model in tidally domi nated settings.

Stratigraphic Setting and Study Area

The Clearwater Formation, located in east-central Alberta, is unconformably underlain by the McMurray Formation of the Lower Mannville Group (Figure 1-4). The McMurray Formation is composed of mature quartz-rich sands and silts derived from the Canadian Precambrian Shield to the east (Harrison *et al*., 1981; Feldman *et al*., 2008). The Clearwater Formation is composed of immature very fine to medium grained feldspathic litharenites (Harrison *et al*., 1981; Putnam and Pedskalny, 1983; Feldman *et al*., 2008). Due to an increase in tectonic activity along the fold- and thrust- belt of the Cordillera in the west, the sediment source switched and rivers drained northeast away from the fold- and thrust-belt, depositing material on the southern edge of the Boreal Seaway (Figure 2-1; McCrimmon and Arnott, 2002; Feldman *et al*., 2008). The Clearwater Formation was deposited during an overall transgression of the Boreal Seaway. The Clearwater Formation is unconformably overlain by the Grand Rapids Formation and Colorado Group shales (Figure 1-4). These shales represent the maximum transgression that linked the Boreal Sea and Gulfian Sea, forming the Cretaceous Interior Seaway (McCrimmon and Arnott, 2002; Feldman *et al*., 2008).

The study area is located in the eastern portion of the Cold Lake oil sands deposit. It is bounded by township 65, ranges 2-4 and township 66, ranges 2-3 west of the Fourth Meridian, a total area of approximately 500 km^2 (Figure 3-1). Forty-three cores and 157 well logs were examined to delineate facies, determine depositional processes and establish depositional environments within the Clearwater Formation.

Previous Research on the Ichnology of the Clearwater Formation

The study of ichnology has been a significant contribution to the petroleum industry, as it provides another 'tool' that, when used with detailed sedimentological analyses, can aid in establishing depositional and stratigraphic frameworks. Within the Clearwater Formation, the trace fossil assemblage has been documented by few researchers, which include: Bradley and Pemberton (1992); Wickert (1992) and more recently Feldman *et al.* (2008).

Bradley and Pemberton (1992) identify three main trace fossil assemblages that occur in the Clearwater Formation and Wabiskaw Member. They include (1) the *Glossifungites* ichnofacies; (2) *Zoophycos-Chondrites-Helminthopsis* assemblage; and (3) the *Chondrites-Zoophycos-Thalassinoides-Planolites* assemblage.

The *Glossifungites* ichnofacies is typical of firm, unlithified substrates commonly found in association with intertidally to supratidally deposited sediments because of the cyclical dewatering and successive firm-substrate burrowing activity (Pemberton and Wightman, 1992). These trace fossils range from vertical to U- or tear-shaped boring-like structures, which developing mostly through animal growth, and have a low diversity; yet individual structures may be abundant (Pemberton and Wightman, 1992). The Wabiskaw Member contains the *Glossifungites* Ichnofacies, which include forms such as *Rhizocorallium, Diplocraterion, Skolithos, Thalassinoides, Arenicolites* and *Psilonichnus* (Bradley and Pemberton, 1992). The dominant trace constituting the assemblage is large, robust, vertical *Diplocraterion* shafts, commonly found in pairs (Bradley and Pemberton, 1992). Another frequent ichnogenera found in the Wabiskaw Member is *Thalassinoides*, a relatively large networking dwelling/feeding system consisting of smooth-walled, cylindrical, branching horizontal to sub-horizontal networks

(Bradley and Pemberton, 1992; Pemberton and Wightman, 1992).

The *Zoophycos* ichnofacies represents low oxygen levels associated with abundant organic material in quiet water settings, commonly found in offshore sites below storm wave base to fairly deep water environments (Pemberton and Wightman, 1992). Climax communities (i.e. high diversity and intensity communities) develop due to the accumulation of mud, spreading over many levels or tiers, with the *Zoophycos-Chondrites* ichnofacies usually being characterized by the lowest tier (Bradley and Pemberton, 1992). *Helminthopsis,* a meandering grazing trace of a worm-like organism, is another common trace fossil associated with the distal *Cruziana* to proximal *Zoophycos* ichnofacies. The *Zoophycos-Chondrites-Helminthopsis* assemblage is found in the Clearwater Formation and is representative of lower offshore to inner shelf depositional environments (Bradley and Pemberton, 1992).

The *Chondrites-Zoophycos-Thalassinoides-Planolites* assemblage was observed locally in cores of the Clearwater Formation, and was found to be similar to trace fossil assemblages documented in Cretaceous chalks dominated by the ichnogenera *Chondrites, Zoophycos, Thalassinoides* and *Planolites* (Bradley and Pemberton, 1992). In contrast to the chalk lithofacies, the Clearwater assemblage is associated with very fine grained muddy siltstones. However, similar to the chalk, the Clearwater Formation contains distinctive bioturbation textures with obvious tiering of respective burrows (Bradley and Pemberton, 1992). The tiering of the distinctive trace fossils in the Clearwater Formation is arranged in three suites (Bradley and Pemberton, 1992). The first suite, *Planolites*, produced the background burrowed-mottled texture, and the second suite, *Thalassinoides*, produced a series of branching networks on soft to firm ground substrates (Bradley and Pemberton, 1992). The final suite, *Chondrites-Zoophycos*, is the deepest tier, where *Chondrites* are commonly found reburrowing the sediment within *Thalassinoides* and *Zoophycos*, and cross-cuts all previous burrows (Bradley and Pemberton, 1992). Other trace fossils observed in both the Wabiskaw Member and Clearwater Formation include *Asterosoma, Macaronichnus* and *Rosselia* (Bradley and Pemberton, 1992).

Feldman *et al.* (2008) more recently studied the ichnology of the Clearwater Formation. Feldman *et al.* (2008) considered trace fossil assemblages very important in interpreting brackish to marine depositional environments which are subdivided based on the presence of traces restricted to marine salinities or traces that are known to survive in a range of salinities. Through the works

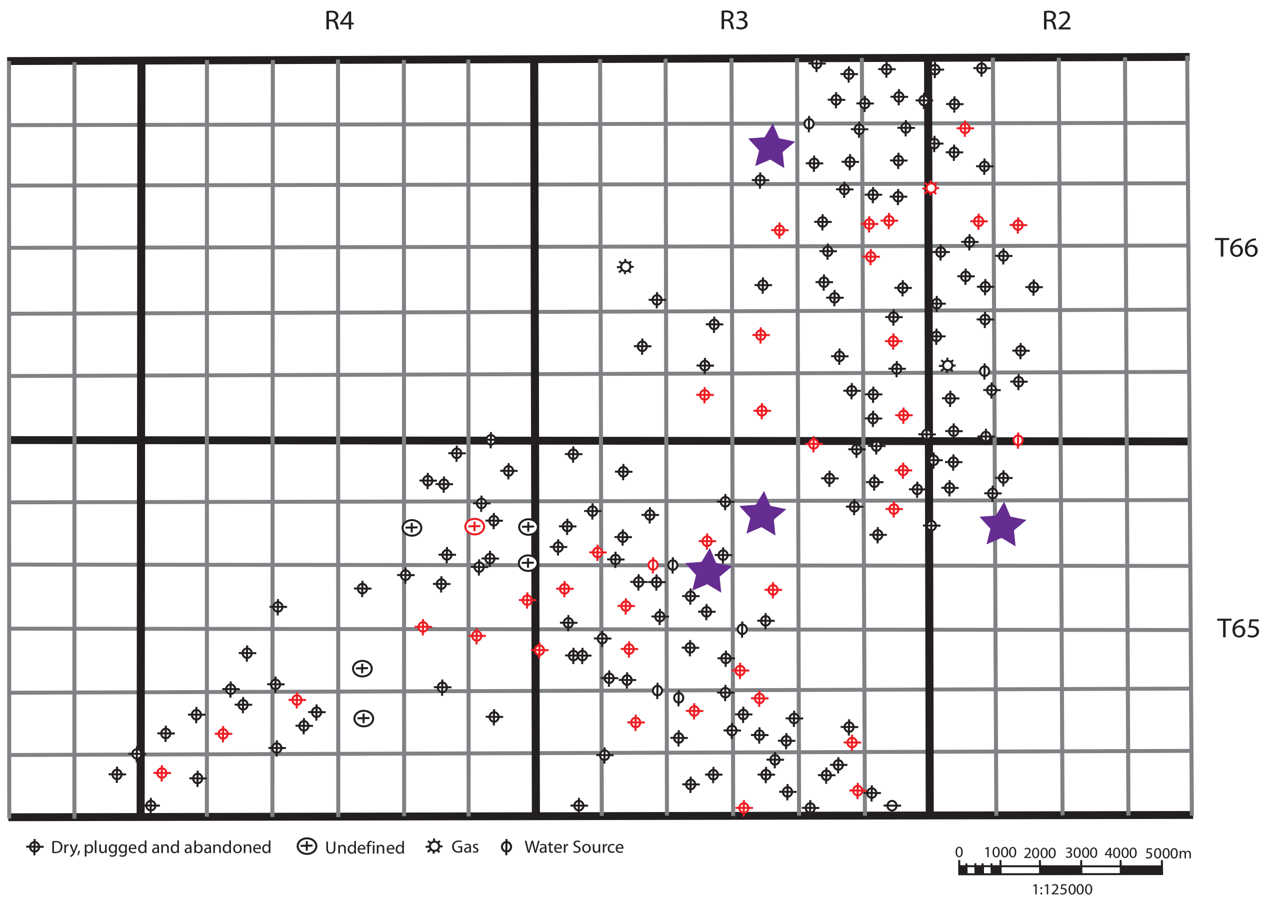

Figure 3-1: Map of the study area in the Cold Lake area of northeastern Alberta. Wells utilized in the study are indicat ed, wells with core are in red. Purple stars represent the locations of the wells used in this chapter (Figures 6-9).

of Benyon and Pemberton (1992), Pemberton and Wightman (1992), MacEachern and Pemberton (1994), MacEachern *et al.* (2005), and Buatois *et al.* (2005), various zonations based on the traces found in the Clearwater were identified (Feldman *et al.*, 2008). From the least diverse assemblages in the most proximal valley-fill areas to open-marine trace assemblages, there is complete gradation between all the trace assemblages (Feldman *et al.*, 2008).

The first assemblage (1) is the most restricted and consists of sparse *Planolites* and small *Skolithos*, both of which occur in open-marine through non-marine settings (Pemberton and MacEachern, 2006). The restricted nature of this assemblage suggests stressed conditions, probably representing freshwater or nearly freshwater environments (Feldman *et al.*, 2008). The second trace assemblage (2) is more diverse but it is dominated by a single trace, *Teichichnus* (Feldman *et al.*, 2008). This low-diversity *Cruziana* assemblage typically includes traces common to brackish environments such as *Palaeophycus*, *Diplocraterion* and *Thalassinoides* and lacks traces more common to open-marine conditions (Pemberton and MacEachern, 2006). Increasing diversity in assemblages 3 and 4, with traces such as *Rosselia* and *Asterosoma*, may represent outer estuarine settings. Individual beds, however, are dominated by one or the other (Feldman *et al.*, 2008; Pemberton and MacEachern, 2006). The last two assemblages (5 and 6) represent marine distal *Skolithos* assemblages and a more typical marine *Cruiziana* assemblage, respectively (Feldman *et al.*, 2008). Traces include *Schaubcyclindrichnus freyi*, *Zoophycos* and *Helminthopsis*; diversity is high and forms are subequal in abundance (Feldman *et al.*, 2008). The *Glossifungites* assemblage also appears in a few cores and is interpreted to occur on sequence boundaries (Feldman *et al.*, 2008).

Ichnology of Tide-Dominated Deltas

Deltas, commonly defined as "discrete shoreline protuberances formed where rivers enter oceans, semi-enclosed seas, lakes or lagoons (standing bodies of water), and supply sediment more rapidly than can be redistributed by basinal processes" (Elliott, 1986). Deltas are characterized as a prograding coastal system, typically forming during falling or reasonably stable positions of relative sea-level. Deltas have been fairly common throughout the entire stratigraphic succession, particularly in the post-Pleistocene, due to high sediment supply and high sea levels (Pemberton and MacEachern, 2006). The Western Canada Sedimentary Basin is no exception, with several intervals interpreted as deltaic environments. Examples include the Dunvegan Formation (Bhattacharya and Walker, 1991a, b, 1992; Bhattacharya, 1993), the Belly River Formation (Lerand and Oliver, 1975; Power and Walker, 1996), the Bow Island Formation (Raychaudhuri and Pemberton, 1992) and parts of the Cadotte Member (Moslow and Pemberton, 1988; Saunders *et al*, 1993).

Delta morphology is controlled by a complex interrelationship of environmental factors. Factors such as the relative density of the river inflow, geometry of the basin, tectonics, shelf gradient, climate and relative sea-level change are just a few that control delta morphology. However, more commonly, deltas are typically classified using three end-members: a dominance of river sediment influx, wave-energy influx, and tidal influence (Figure 3-2; Galloway, 1975). Tidally dominated deltaic systems evolve in areas where tidal currents are stronger than fluvial outflow and where wave action is minimal. Tidal processes redistribute the sediment into a large funnel-shaped channel, commonly indicative of most estuarine complexes (Figure 3-3; Dalyrmple, 1999; Dalyrmple and Choi, 2007). Therefore, to be regarded as a delta there must be net progradation (Dalyrmple, 1999). Other indications of a strong tidal influence are major sand bars and tidal ridges oriented parallel to tidal flow (perpendicular to shoreline) and tidal flats along margins of tidal channels (Figure 3-3; Bhattacharya and Walker, 1992). Sedimentary structures commonly identified in tidal settings include herringbone cross-stratification, tidal bundles and reactivation surfaces (Bhattacharya and Walker, 1992). A number of modern tide-dominated examples exist, such as the Fly River Delta in Papua New Guinea; Ganges-Brahmaputra Delta in India; the Ord River Delta in Australia and the Colorado River Delta in the United States/Mexcio. However, the preservation potential of tide-dominated deltas is low and, as a consequence, only a few are actually identified in the rock record. Examples include the Lower Miocene Chenque Formation, Patagonia, Argentina (Carmona *et al.*, 2009); Upper Jurassic Sognefjord Formation on the Troll West Field, Norwegian North Sea (Dreyer *et al.*, 2005) and mid-Miocene Belait Formation in Brunei (Lambiase *et al.*, 2003). McCrimmon and Arnott (2002) document the Clearwater Formation as tide-dominated deltaic sediments. However, Feldman *et al.* (2008) more recently characterized it as proximal tidal to fluvial estuarine sediments infilling incised valleys.

In each of the modern and ancient examples, sedimentological characteristics are documented in great detail. Conversely, ichnology and trace fossil identification is poorly understood in deltaic environments. Dalyrmple and Choi

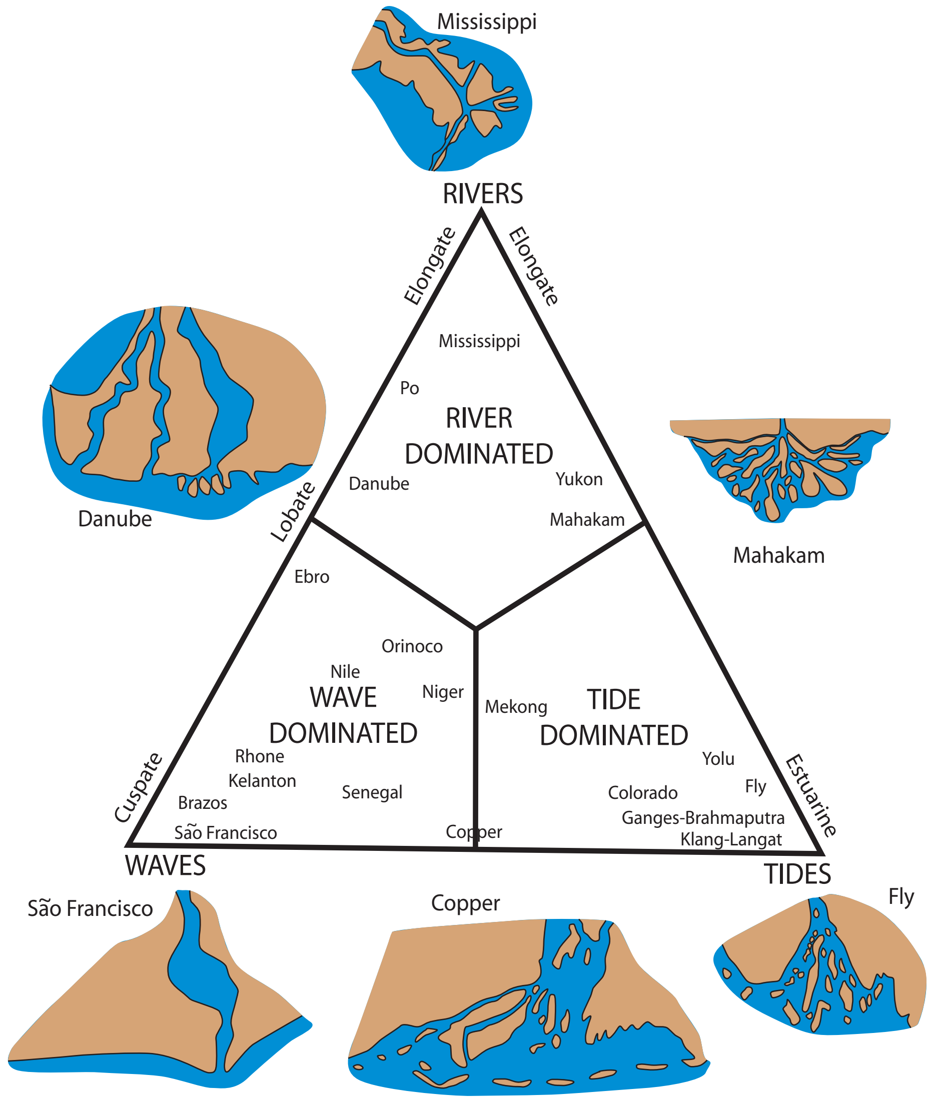

Figure 3-2: Galloway's (1975) triangular diagram classifying river deltas according to the relative influence of the three major factors affecting their development: the river, waves, and tides.

(2007) briefly summarize data from other authors' work: the longitudinal trends for diversity of benthic intervebrate organisms, burrow size and relative number of individuals per square meter, which one would expect to see in a tide-dominated delta (Figure 3-3). However, due to the lack of ancient examples of tidally dominated deltaic environments, a consistent ichnological framework is non-existent. Many of the authors identify various trace fossils seen in core and outcrop, but fail to interpret the implications that these assemblages have for the identification of the depositional environment.

Observed Ichnology

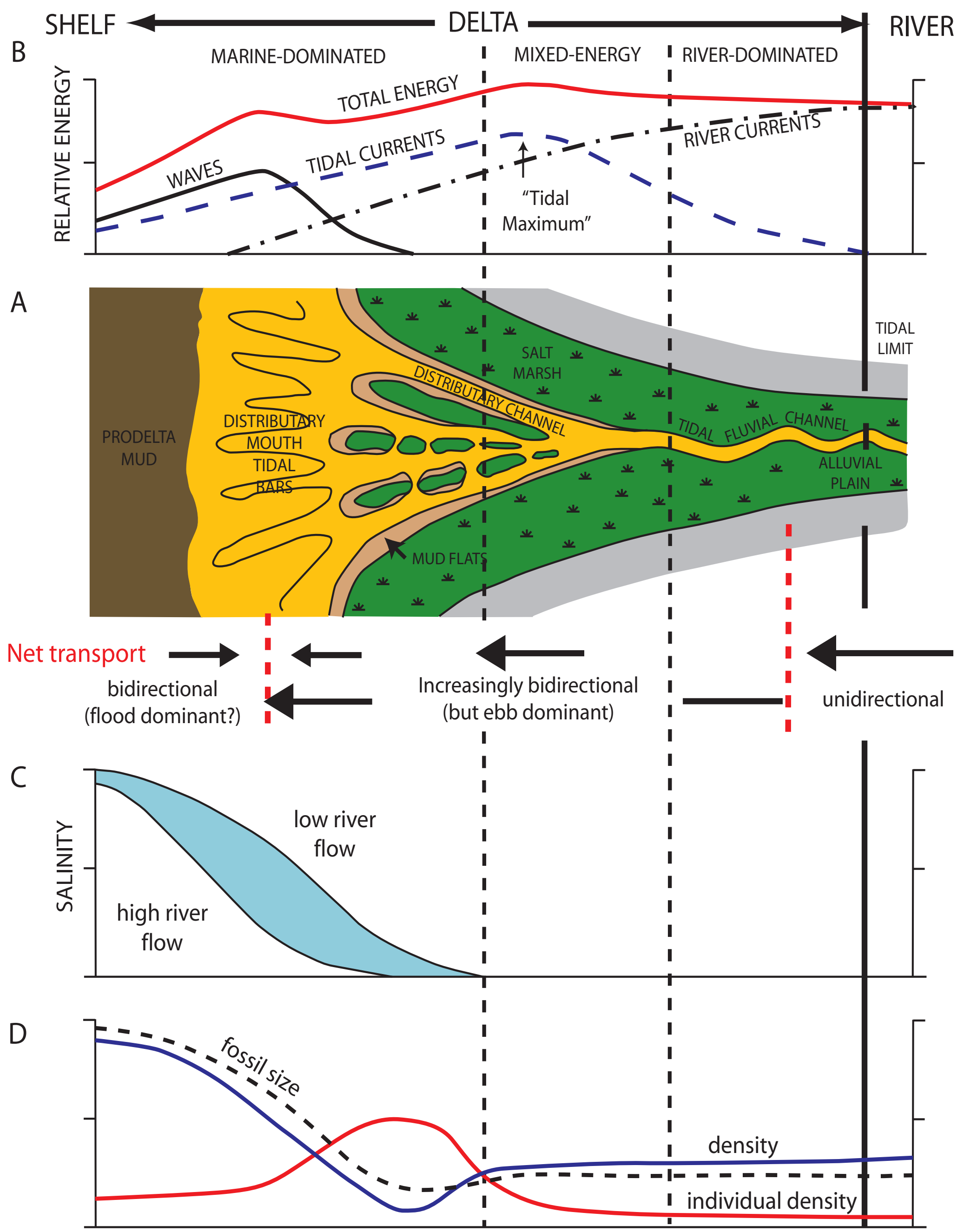

Figure 3-3: (A) Dalyrmple and Choi's (2007) schematic map of a tide-dominated delta, based loosely on the Fly River delta, Papua New Guinea. Note the funnel shape, the separation of distributaries by islands, absence of the "straight"-meandering-"straight" channel geometry that characterizes tide-dominated estuaries, elongate tidal bars in the seaward part, and the fringing muddy tidal flats and salt marshes. (B) This chart represents the longitudinal variation of the intensity of the three main physical processes, river currents, tidal currents and waves, through a tide dominated delta. (C) Longitudinal variation in salinity levels. As expected the salinity gradient is displaced seawards when discharge from river is high and landwards when discharge is low. Also, there may be significant variation between distributary channels, i.e. active channels will contain water with lower salinities than inactive channels with negligible river input. (D) Longitudinal variation of: the diversity of benthic invertebrate organisms, their burrow diameter, and the relative number of individuals per square meter. Modified from Dalyrmple and Choi (2007).

For the purpose of this chapter, four core where chosen to represent the study area and the ichnology observed. Each core was examined in detail, identifying grain size, bedding, shale content, and trace fossil assemblages. The ichnofauna identified in core are abundant in the marine and marginal marine facies Facies Association 2 - prodelta to delta front (BI 2-6; Figure 2-2). The locations of the cored wells analyzed are: 07-28-065-03W4; 15-21-065-03W4; 12-29-065-02W4 and 10-27-066-03W4 (Figure 3-1). Symbols used in Figures 6-9 are found in Table 3.1.

07-28-065-03W4

In well 07-28-065-03W4, FA2 constitutes approximately 17.5m thick succession of interbedded mud and lower fine to upper fine sand (Figure 3-4). Most of the succession is moderately to intensely bioturbated (BI 2-6), with increasing bioturbation intensity generally associated with higher mud content. Sand beds are oil saturated and are dominated by current ripples, wavy bedding, low angle cross-stratification, planar laminations and rip-up clasts and carbonaceous material (Figure 3-4, A). Calcite concretions are also common in this interval. Rarely, where bioturbation is lower (BI 2-3), sand beds have sharp lower contacts and feature a basal planar stratified interval and an upper current rippled interval. Some beds may display a coarsening upward trend, but due to the high level of oil saturation, structures and trends were often hard to identify within the sand beds.

In general, the ratio of sand to mud plays an important role in the diversity and abundance of trace fossils. In the proximal prodelta deposits, mud content is the main constituent with only thin beds of sand interbedded with thick, highly bioturbated muds, displaying a high diversity and high abundance assemblage. These highly bioturbated muds contain traces ranging from small (<5mm) to large (>20mm), complex and simple structures. Moving up-section, proximal prodelta deposits quickly move into delta front deposits, where thick successions of sand dominate over the bioturbated muds with a lower diversity and low abundance assemblage (Figure 3-4, A). Diversity and abundance of ichnofossils continue to diminish up-section, with traces progressively becoming smaller (<5mm).

The trace fossil assemblage found in this interval was dominated by *Planolites* and *Thalassinoides*. Other traces found in abundance were *Teichichnus*,

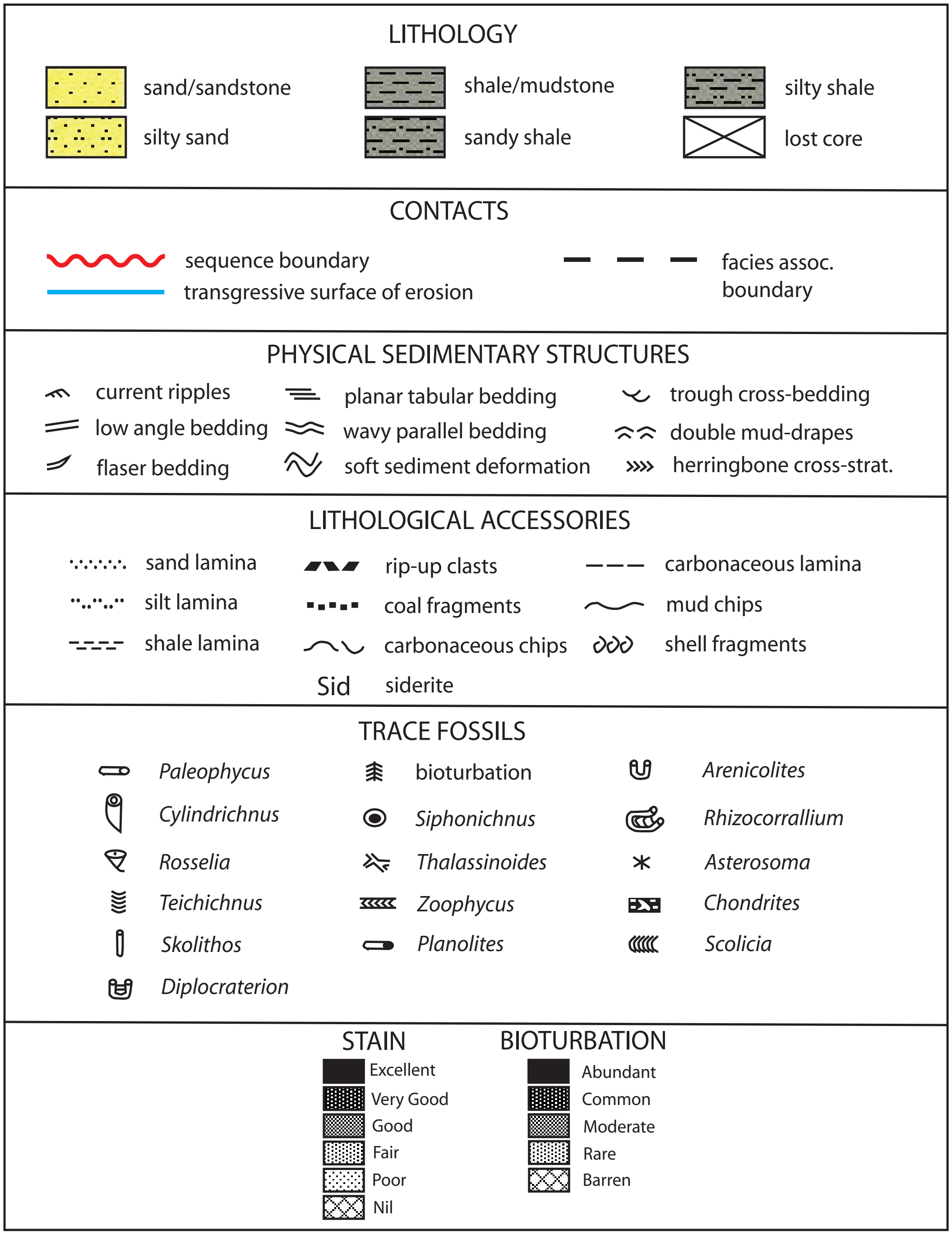

Table 3-1: Legend to symbols used in Figures 4-7.

Asterosoma, *Arenicolites*, *Rhizocorallium, Scolicia*, and in lesser amounts *Diplocraterion*, *Cylindrichnus*, and *Skolithos* (Figures 3-4, B-C).

15-21-065-03W4

In well 15-21-065-03W4, FA2 comprises an approximately 13m thick succession of interbedded mud and upper fine to lower fine sand (Figure 3-5). Similar to the previous well, the succession is moderately to highly bioturbated (BI 2-6) with an increase in bioturbation intensity with increasing mud content (Figure 3-5, A). The sand beds are oil saturated and dominated by current ripples, wavy bedding, soft sediment deformation, planar laminations, low-angle cross-stratification, rip-up clasts, and possibly some evidence of wave generated ripples (Figure 3-5, B). Calcite concretions were also observed in this interval, and carbonaceous material was found at the bases of beds lower in the section. Due to the high oil saturation in the sand beds, structures and trends were difficult to identify.

The sand to mud ratio again plays an important role in the diversity and abundance of trace fossils. At the base of FA2, there is an equal amount of sand and mud beds, which display a low diversity and high abundance assemblage. Generally there is a slight increase in the mud content moving up-section, where the assemblage becomes more diverse and a higher abundance of trace fossils are observed. Towards the top of the section, sand beds increase both in abundance and thickness, however the diversity and abundance of trace fossils only increases slightly. Traces are predominately medium-sized (5-20mm), and typically generate simple to complex structures. In general the bioturbation steadily increases up-section and rapidly decreases within a metre, moving into proximal delta front deposits (mouth bar and inter-bar channel fill) where brackish and fluvial processes take over.

For the greater part of this interval, bioturbation intensity is high enough that a mottled bioturbate texture is observed (Figure 3-5, A). The trace fossil assemblage is dominated by *Planolites* in this interval, which occurs throughout the entire section. Other traces found in abundance include *Thalassinoides*, *Skolithos*, *Rhizocorallium*, *Asterosoma*, *Siphonichnus* and *Teichichnus*, and in lesser amounts *Scolicia* (Figures 3-5, C-E).

12-29-065-02W4

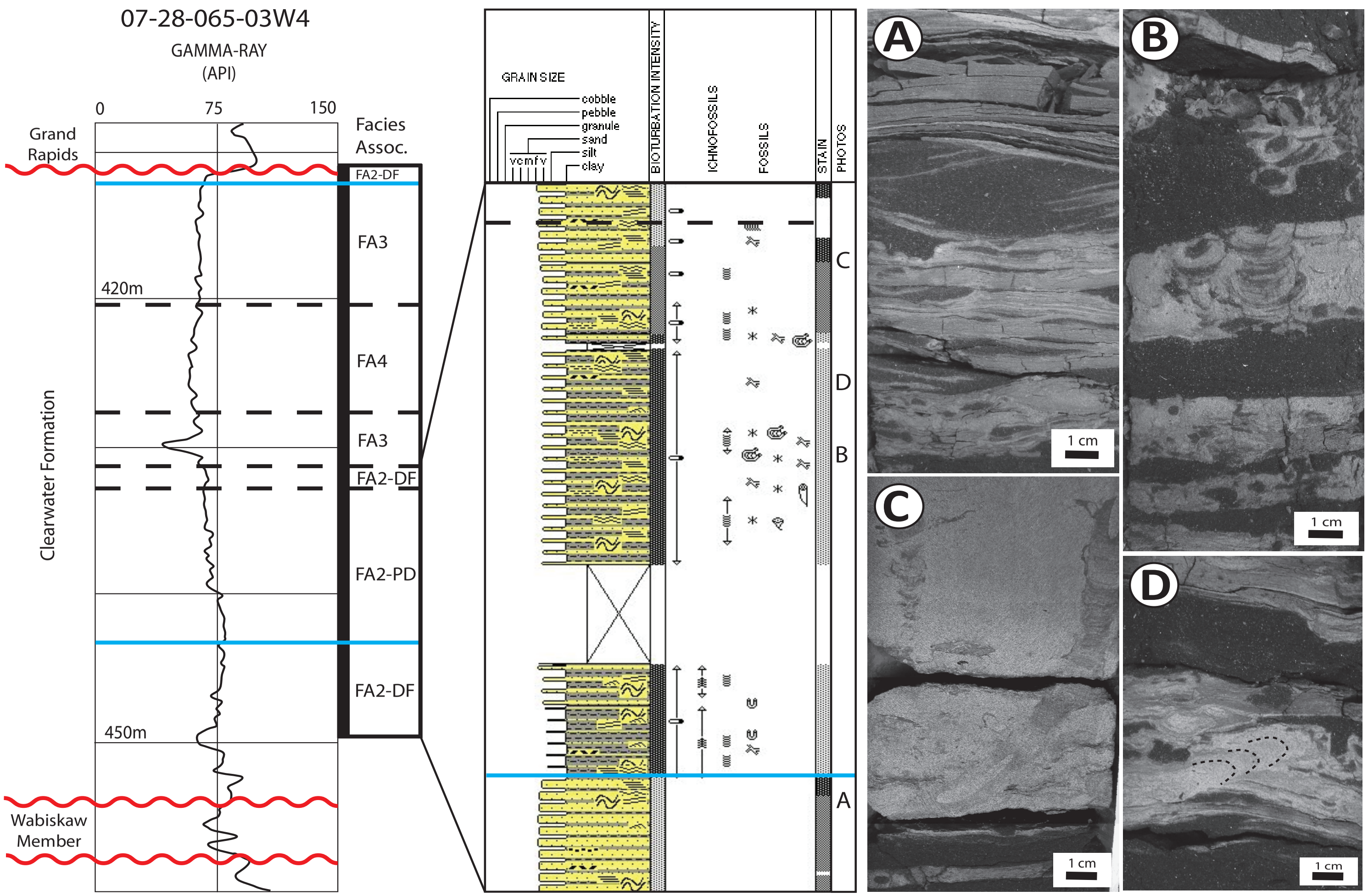

Figure 3-4: A typical well (07-28-065-03W4) from the south central portion of the study area. On the far left is the gamma ray showing the entire Clearwater Formation including the Wabiskaw Member. Core is shown by the solid black line in which facies associations were identified. In the middle is the core log for

Figure 3-4 continued: FA2 sediments showing lithology, grain size, physical sedimentary structures, lithological accessories, bioturbation intensity, trace fossils, bitumen staining and corresponding photographs. (A) Typical distal lower delta front sediments showing predominately wavy bedding with minor current ripples showing minor mud drapes on the foresets and minor carbonaceous lamina. Bioturbation is minimal, but some disruption (Planolites) to the structures can be seen in the bottom half. (B) An example of the types of trace fossils found in proximal prodelta sediments. Seen here are Asterosoma, Teichichnus, Planolites, Thalassinoides and ?Cylindrichnus. (C) Siphonichnus trace fossil seen preserved in a calcite concretion. (D) Examples of more robust complex trace structures: Rhizocorallium, Asterosoma and Teichichnus.

In well 12-29-065-02W4, FA2 comprises approximately 21m, split over two intervals related to transgressive surfaces of erosion (Figure 3-6). Each interval is moderately to highly bioturbated (BI 2-6), which is typically controlled by the mud content. Sand beds are mostly oil saturated, with the exception of the lower half of the first interval due to an oil-water contact seen at approximately 463.5m (Figure 3-6A). Physical sedimentary structures observed include low-angle to trough cross-stratification, wavy bedding with minor current ripples and rip-up clasts toward the top of each interval. Calcite concretions and minor carbonaceous material are also observed.

Within distal expressions of FA2, muds dominate the sand to mud ratio, and typically is highly bioturbated displaying a high diversity, high abundance assemblage. Where individual traces are discernable (i.e. where bioturbation intensity is slightly decreased) they normally form medium (5-20mm) to large (>20mm) robust, more complex structures. Moving up-section to proximal FA2 deposits, oil saturated sand beds increase in thickness and abundance, with bioturbated muds decreasing, becoming thin and often discontinuous. With this decrease in mud content, bioturbation decreases, often reflected in a lower diversity and abundant assemblage. With a decrease in bioturbation, traces also decrease in size, ranging from small (<5mm) to medium (5-20mm), however, smaller more simple traces tend to dominate.

The trace fossil assemblage found in these intervals was again dominated by *Planolites*, *Palaeophycus* and *Thalassinoides*. Other traces found in abundance were *Teichichnus*, *Rhizocorallium*, *Asterosoma, Siphonichnus* and *Scolicia*, and in lesser amounts *Cylindrichnus*, *Skolithos* and *Arenicolites* (Figures 3-6, B-D).

10-27-066-03W4

In this last well, 10-27-066-03W4, FA2 comprises approximately 12m, split into two intervals, with the bottom interval containing the majority of this facies

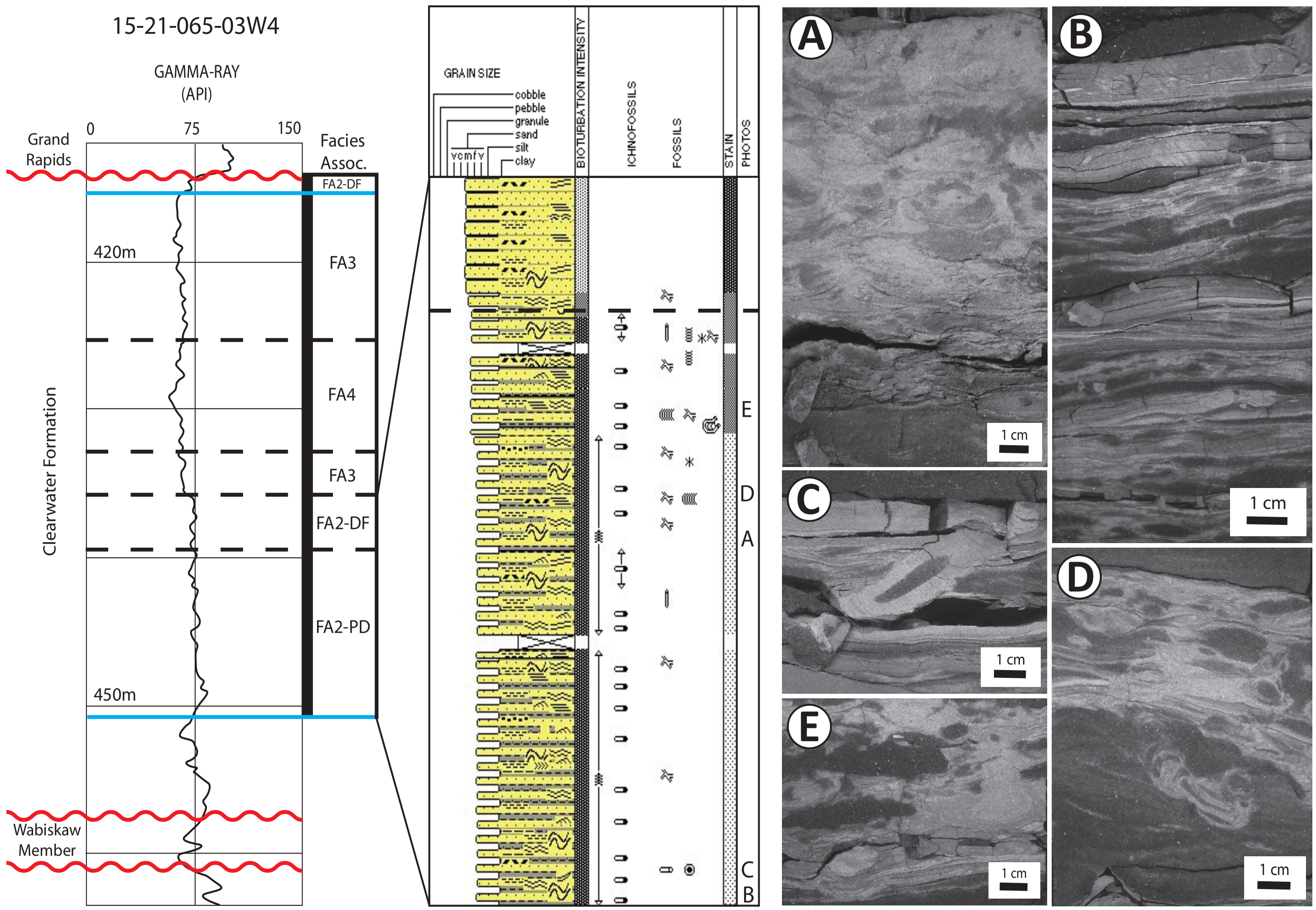

Figure 3-5: Well (15-21-065-03W4) from the central portion of the study area. On the far left is the gamma ray showing the entire Clearwater Formation in-

Figure 3-5 continued: cluding the Wabiskaw Member. Core is shown by the solid black line in which facies associations were identified. In the middle is the core log for FA2 sediments showing lithology, grain size, physical sedimentary structures, lithological accessories, bioturbation intensity, trace fossils, bitumen staining and corresponding photographs. (A) Typical proximal prodelta sediments which are highly biotubated and often show a mottled texture, sedimentary structures are indistinguishable as well as individual trace types. (B) Lower delta front sediments from higher up in the section. These sediments are wavy bedded to low angle cross-stratified with minor ripple laminations. Note the marked decrease in bioturbation levels. (C) Well defined Siphonichnus trace fossil. (D) Example of complex, robust structures of Scolicia, Rhizocorallium combined with simpler traces, Planolites and Thalassinoides. (E) Another example of Scolicia.

association (Figure 3-7). Similar to all the previous wells, bioturbation intensities are indicative of the ratio of mud in the interval. Each interval is moderately to highly bioturbated (BI 2-6), with varying amounts of mud (Figures 3-7, A-B). Sandier beds are oil saturated and are typically wavy bedded. Other physical sedimentary structures observed include low-angle cross-stratification, planar laminations and minor soft-sediment deformation and current ripple laminations. Carbonaceous material is also observed.

Again, similar to all the previous wells, the diversity and abundance of trace fossils is dependent on the sand to mud ratio. Below the transgressive surface of erosion (TSE), proximal prodelta sediments dominate which contain significantly less mud that above the TSE where distal prodelta muds are present (Figure 3-7A-B). Proximal prodelta muds contain a moderate to high diversity and abundant assemblage, whereas distal prodelta muds are rarely to moderately bioturbated due to the rate of sedimentation and rapid settling out of fines. Overall, traces tend to be medium-sized (5-20mm) robust structures, with a few larger (>20mm) robust, more complex structures. Moving stratigraphically upward in each interval, sand beds increase in thickness and abundance. Conversely, mud beds decrease and become less bioturbated with a lower diversity and abundance of ichnofossils. Again, with this decrease in bioturbation, smaller (<5mm), simple traces dominate.

The trace fossil assemblage seen in these intervals is dominated by *Planolites*. Other traces found in abundance include *Thalassinoides*, *Teichichnus*, *Asterosoma*, and in lesser amounts *Cylindrichnus*, *Scolicia*, *Rhizocorallium* and *Arenicolites* (Figure 3-7A-D).

Discussion

Ichnology, the study of trace fossils, allows for the further refinement of depositional environments when used in conjunction with sedimentology.

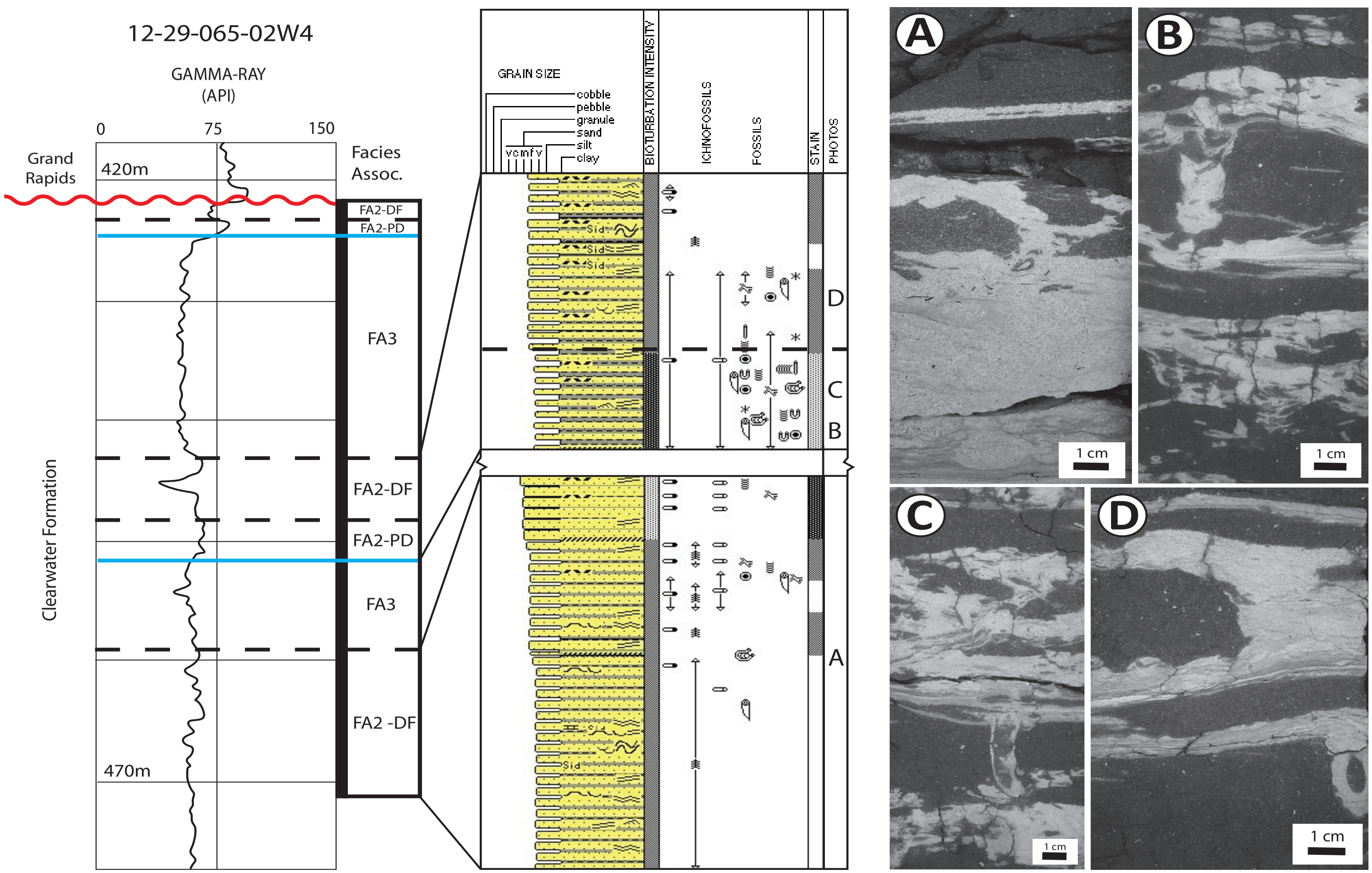

Figure 3-6: Well (12-29-065-02W4) from the east central portion of the study area. On the far left is the gamma ray showing most of the Clearwater Formation. Core is shown by the solid black line in which facies associations were identified. In the middle is the core log for FA2 sediments showing lithology, grain

Figure 3-6 continued: size, physical sedimentary structures, lithological accessories, bioturbation intensity, trace fossils, bitumen staining and corresponding photographs. (A) Rhizocorrallium trace fossil occurring at the oil-water interface. (B) Examples of traces found in proximal prodelta sediments. Seen here are Teichichnus, Rhizocorallium, ?Diplocraterion and ?Asterosoma, Planolites and Thalassinoides. (C) Large ?Cylindrichnus trace, Teichichnus and ?Arenocolites. (D) Well defined Siphonichnus trace in transitional prodelta to distal lower delta front sediments.

Preliminary work has been done to identify trace fossil assemblages within the Clearwater Formation, with the most recent work being conducted by Feldman *et al*. (2008).

At first glance, the ichnology follows that of the proposed depositional model by Feldman *et al.* (2008), which is an estuarine incised valley fill from a fluvial setting to the tidal bars in the outermost part of the estuary. The trace fossil assemblage included *Planolites*, *Teichichnus*, *Thalassinoides*, *Skolithos*, *Cylindrichnus*, *Asterosoma* and *Arenicolites*, which according to Pemberton and Wightman (1992), are indeed diagnostic of brackish-water environments. However, each of these traces can be found in a number of other marginal marine and shoreface environments. For example, *Planolites* and *Skolithos* can be found in a wide range of environments from freshwater to deep marine; *Teichichnus* and *Thalassinoides* are commonly found in the lower shoreface to offshore; and *Cylindrichnus* and *Arenicolites* are generally found on sandy tidal flats or low energy shoreface environments (Pemberton and MacEachern, 2006). Trace fossil assemblages seen in FA1 (shoreface/proximal offshore) and FA7 (distal offshore) provide this study with a baseline for identification of a fully marine environment. Therefore, the presence of traces such as *Rhizocorallium*, *Siphonichnus*, *Scolicia* and *Asterosoma*, which occur frequently throughout the core, may raise some doubts about a true brackish water depositional environment as these traces are generally only found in fully marine, shoreface to deep marine, conditions with normal or near normal salinities (Figures 3-4 - 3-7). Particularly, the occurrence of *Scolicia* (Figure 3-5), a trace produced by echinoids and gastropods, creates a problem for an interpretation based in a predominantly brackish-water environment, as its tracemaker cannot survive in salinity stressed settings.

Due to these questionable traces, re-evaluation of the depositional setting of the Clearwater Formation was imperative, and a tide-dominated deltaic system was re-established. Along with the sedimentology outlined in Chapter 2, a detailed ichnological analysis of highly bioturbated prodelta to delta front sediments (FA2) was conducted. Looking at the observed ichnology from the four representative cores in the study area, a number of trends were identified:

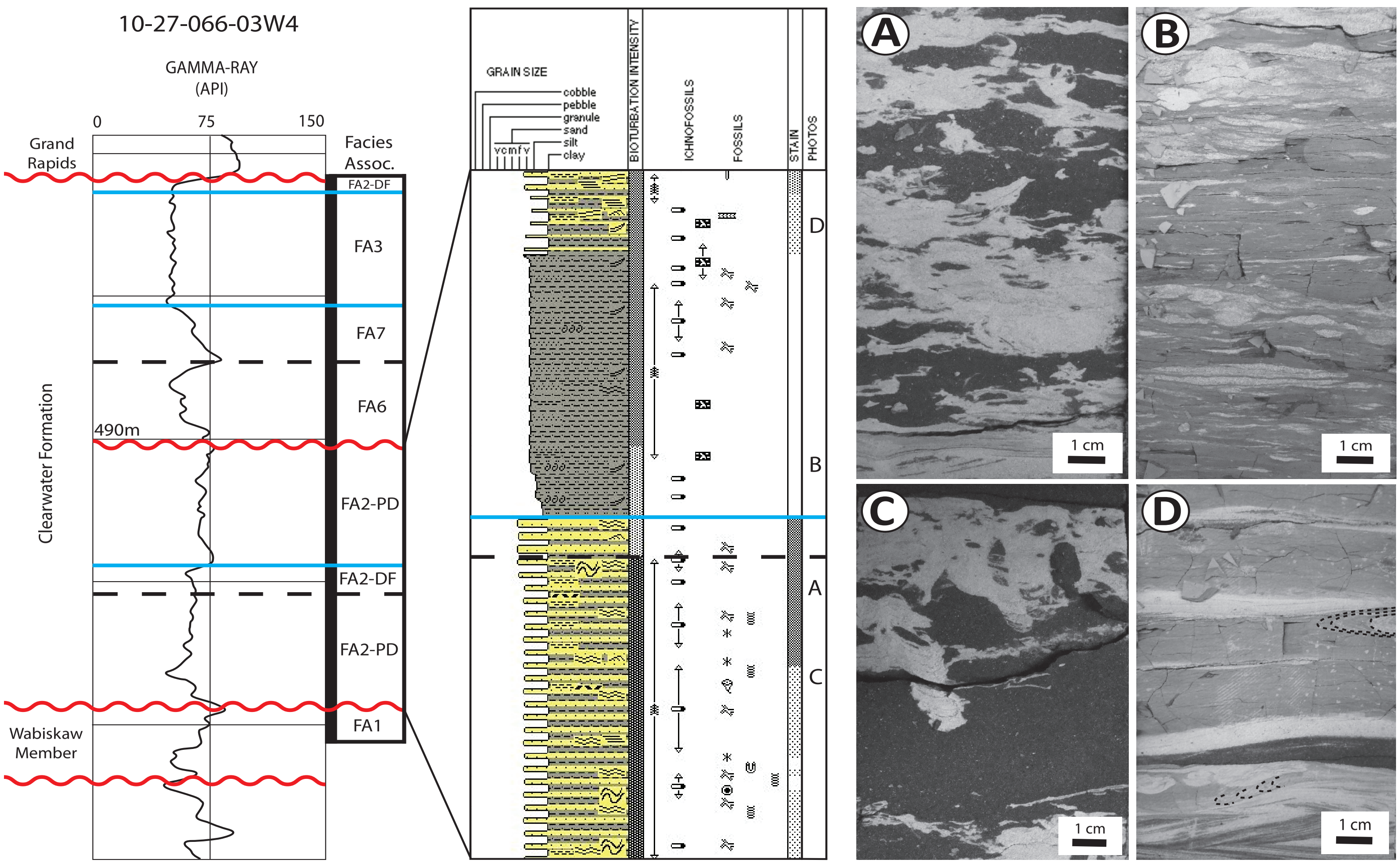

Figure 3-7: Well (10-27-066-03W4) from the northern portion of the study area. On the far left is the gamma ray showing the entire Clearwater Formation including the Wabiskaw Member. Core is shown by the solid black line in which facies associations were identified. In the middle is the core log for FA2

Figure 3-7 continued: sediments showing lithology, grain size, physical sedimentary structures, lithological accessories, bioturbation intensity, trace fossils, bitumen staining and corresponding photographs. (A) An example of proximal prodelta sediments; muddier sediments are moderately bioturbated. Traces are hard to distinguish due to the intensity of bioturbation. May include Planolites, Thalassinoides, ?Asterosoma and ?Siphonichnus. (B) An example of very muddy distal prodelta sediments showing minor sand lenses and bioturbation. Traces seen include Teichichnus and Planolites. (C) Multiple Teichichnus trace fossils in proximal prodelta deposits. (D) ?Zoophycos or ?Rhizocorallium and half a Astersoma trace fossil in distal prodelta deposits.

(1) a moderate to high diversity of trace fossils is typical of FA2 sediments; (2) bioturbation levels are variable, but tend to be high; (3) traces tend to be larger and more robust; (4) more complex structures are found in abundance; and (5) a selection of predominately fully marine traces are observed consistently. The ichnology and trends observed show evidence of somewhat stressed conditions, indicated by the more restricted and diminished ichnofauna. However, higher ichnodiversity, larger trace sizes and the predominance of more fully marine forms support sediment deposition in a deltaic system rather than a bay-head delta of a transgressive estuarine system (Thompson *et al.*, 2008).

Ichnological Framework for Tidally Dominated Settings

Taking into account the observed ichnology, a preliminary ichnological framework for tide-dominated deltaic environments, based on the Clearwater Formation, is established. Firstly, diversity and abundance of trace fossils is typically moderate to high below low tide. Above low tide the diversity and abundance dramatically decreases due to high water turbidity and constantly migrating large-scale bedforms (tidal sand bars/ridges), which pose problems for infaunal colonization. Second, bioturbation levels are typically high, but can be quite variable laterally. This is because tides constantly change the dynamics of the system both seasonally and diurnally, especially with small scale salinity fluctuations. Third, trace fossils are typically larger in size than their counterparts in typical brackish-water environments, but smaller than seen in fully marine conditions. Fourth, traces develop robust, more complex structures (i.e. large *Teichichnus* or *Rhizocorallium*) as well as simple structures (i.e. *Planolites* and *Thalassinoides*). Lastly, the trace fossil assemblage is dominated by an impoverished *Cruziana* ichnofacies, displaying a range of fully marine traces (i.e. *Scolicia*, *Siphonichnus*, and *Rhizocorallium*). It is important to note these ichnological characteristics are only seen in distal portions of the delta, below the low tide mark. Above the low tide, sediments are subjected to high but periodic tidal current energy, which often cannibalizes and redistributes the sediment constantly, making it difficult for colonization.

This framework should however be used with caution as tide-dominated settings are prone to experience extremely variable conditions. Conditions such as climate (hot and humid vs. cold and dry), sedimentation rates, shelf gradients and changes in salinity over tidal cycles and/or seasonally in response to river discharge are unique to each locale, and may diverge from results seen in the Clearwater Formation.

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Chapter 4
Allostratigraphic (Sequence Stratigraphic) Analysis of the Clearwater Formation, Cold Lake, Alberta Canada

Introduction

Due to frequent association with hydrocarbon deposits, shallow marine clastic sequences have been the focus of abundant research. The Clearwater Formation is no exception as it is a significant bitumen-saturated interval within the Cold Lake oil sand deposit on the eastern margin of the Western Canada Sedimentary Basin. Bitumen is found in the coarser-grained sands of mouth bars and inter-bar channels, deposited as part of a tide-dominated delta. An understanding of this depositional setting, as well as factors which may have influenced sedimentation during the Lower Cretaceous, allows prediction of the richest and most economic areas of the deposit.

The main objective of this paper is to redefine the stratigraphy of the Clearwater Formation in the Cold Lake oil sands deposit, and to utilize this framework in the interpretation of an overall allostratigraphic/sequence stratigraphic model and associated depositional characteristics in the study area. Concepts of allostratigraphy and sequence stratigraphy have been applied in this study. Allostratigraphy was used principally to define a generic way of mapping discontinuity-bounded rock successions. Each allomember was interpreted considering controls on deposition due to transgressive-regressive cycles affected by eustatic sea-level fluctuations. This type of local to limited-regional paleogeographic analysis provides the basic framework for interpreting the primary economic zones and additional resource plays within and outside of the study area.

Previous work and Historical Overview of Stratigraphy

In 1882, Robert Bell of the Geological Survey of Canada was the first to describe the Lower Cretaceous `tar sands`. These first geological descriptions of Mannville Group sediments were conducted from observations seen in outcrop along the Athabasca and Clearwater Rivers in north-central Alberta. McConnell (1893) formally named the Clearwater Formation; he defined it as the thick grey shales above the `tar sands` and below the sands of the Grand Rapids Formation. The `tar sands` unit was formally assigned the name McMurray Formation by

McLearn in 1917.

Initial descriptions of the subsurface geology in east-central Alberta placed the McMurray, Clearwater and Grand Rapids Formations as part of the Fort St. John Group of the lower Athabasca River section (McLearn, 1932, 1944). The Mannville Group was first known as the `Mannville Formation` from the Vermillion region in east-central Alberta (Nauss, 1945). Nauss (1945) defined the `Mannville Formation` as all the sediments from the overlying Colorado Group down to the lower erosional surface of the Devonian Winterburn and Woodbend Groups. Badgley (1952) raised the `Mannville Formation`to group status and correlated sediments with the McMurray, Clearwater and Grand Rapids Formations in the lower Athabasca River valley. He also correlated the Mannville Group with the upper Bullhead Group, Bluesky, Spirit River and part of the Peace River Formation. The Mannville Group was then subdivided into Upper and Lower units by Glaister (1959), who correlated sediments of the Blairmore Group in the southern and central Foothills area. The Upper and Lower Mannville were further redefined by Mellon and Wall (1961). Further subdivision of the McMurray Formation into members was achieved by Williams (1963).

Current definitions of the Mannville Group of east-central Alberta divide the group into Lower and Upper units. The Lower Mannville Group consists of the McMurray Formation. In the Lloydminster area, the McMurray Formation is laterally equivalent to the Dina Formation, the Ellerslie Formation in southern Alberta and the Gething Formation in the Peace River Area (Figure 4-1). The Upper Mannville is comprised of the Clearwater Formation and Grand Rapids Formation. The Wabiskaw Member, with occurs at the base of the Clearwater Formation, is a glauconite-rich unit that marks the transition between the Lower and Upper Mannville. The Wabiskaw Member is equivalent to the Cummings Formation in the Lloydminster area, the Glauconite Member of southern Alberta and the Bluesky Formation in the Peace River area (Figure 4-1). In the Lloydminster area, the Clearwater Formation is further sub-divided into four sub-units: Lloydminster, Rex, General Petroleum Sand and Sparky (Figure 4-1). In southern Alberta, it constitutes the Lower Upper Mannville and the Wilrich Shale in Peace River area (Figure 4-1). The Clearwater Formation is overlain by the Grand Rapids Formation in east-central Alberta. The Grand Rapids Formation, like the Clearwater Formation, is sub-divided into three sub-units based on different facies: Waseca, McLaren, and Colony (Figure 4-1; McLean and Putnam, 1983).

Posamentier *et al*. (1988) defines sequence stratigraphy as “the study of

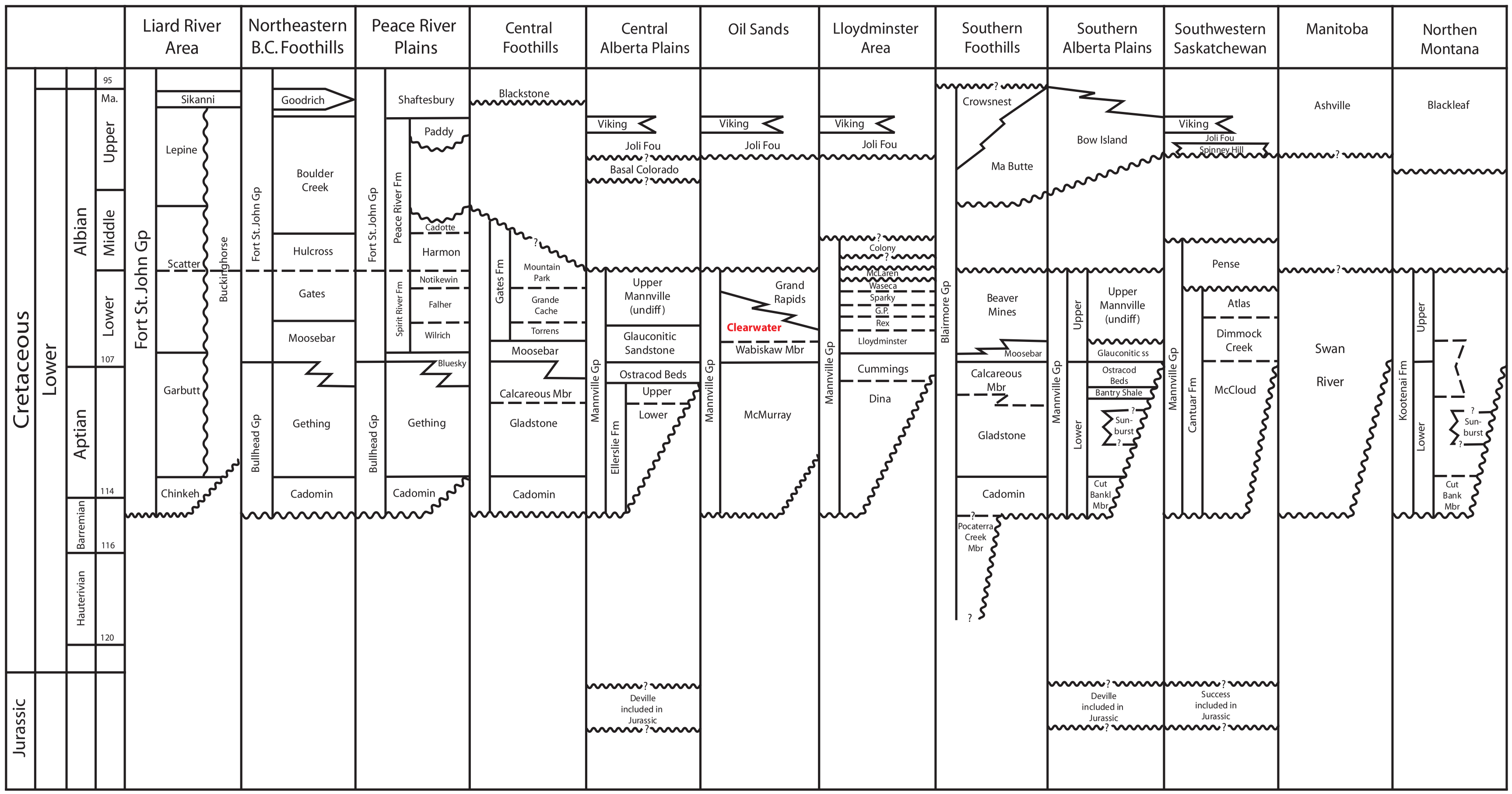

Figure 4-1: Lower Cretaceous stratigraphic relationships in the Western Canadian Sedimentary Basin. The Clearwater Formation (shown in red) is roughly correlated with the Lloydminster, Rex, G.P., and Sparky members in the Lloyminster region, Moosebar and Beaver Mines in southern, central and northern Foothills and the Wilrich member of the Spirit River Formation in Northwest Alberta. The Clearwater Formation was deposited during an overall transgression (Aptian/Albian Clearwater Transgression), and is Albian in age. Modified from Hayes et al. (1994).

relationships within a chronostratigraphic framework wherein the succession of rocks is cyclic and is composed of genetically related stratal units (sequences and systems tracts)". The sequence stratigraphy and the depositonal history of the Clearwater Formation has been the focus of many papers, including: Minken, 1974; Harrison *et al.*, 1981; Jackson, 1984; Dekker *et al.*, 1987; Hutcheon *et al*., 1989; Beckie and McIntosh, 1992; Leckie and Smith, 1992; Wickert, 1992; McCrimmon, 1996; McCrimmon and Cheadle, 1997; Pearson, 1998; McCrimmon and Arnott, 2002 and Feldman *et al*., 2008. The depositional models presented by these authors vary; they seem to have evolved through time from a basic prograding deltaic shallow marine system (Wickert, 1992) to a northeast-trending river-dominated delta (Minken, 1974; Harrison *et al.*, 1981; Jackson, 1984; Dekker *et al.*, 1987; Hutcheon *et al*., 1989; Beckie and McIntosh, 1992; Leckie and Smith, 1992) to a prograding tidal-deltaic shallow marine system cut by a number of large incised valleys (McCrimmon , 1996; McCrimmon and Cheadle, 1997; Pearson, 1998; McCrimmon and Arnott, 2002). The most recent attempt at deciphering the complex history of the Clearwater sediments expands on the McCrimmon and Arnott (2002) model. Feldman *et al.*, 2008 describes the Clearwater Formation as consisting of thirteen fluvial to estuarine incised valley-fills.

Paleogeography and Tectonic Setting

The Western Canadian Sedimentary Basin (WCSB) was formed due to regional compressional tectonism associated with the progressive development of the Cordillera, causing subsidence and flexure of the craton in the east (McCrimmon and Arnott, 2002; Feldman *et al*., 2008). During the mid-Cretaceous, tectonic activity significantly increased along the western margin of the WCSB, rapidly infilling the foredeep with synorogenic sediment pushing the shoreline irregularly eastward, creating the embayed Boreal Seaway (Figure 2-1; Armstrong and Ward, 1991).

Lower Mannville (McMurray Formation) sediments are typically derived from eastern sources and are primarily mature quartz rich fluvial sands but gave way to more marine sediments as the Boreal Sea continued to transgress southward (Harrison *et al*., 1981; Feldman *et al*., 2008). Upper Mannville sediments (Clearwater Formation and Grand Rapids Formation) are derived from western sources and are composed of immature volcanic and feldspathic sands deposited in a nearshore or deltaic/estuarine setting (Figure 2-1; Harrison *et al*., 1981; Putnam and Pedskalny, 1983; Feldman *et al*., 2008). Overlying Mannville sands, the

Colorado Group marine shales mark a major transgression linking the Boreal Sea and Gulfian Sea to form the Cretaceous Interior Seaway (McCrimmon and Arnott, 2002; Feldman *et al*., 2008).

Methods and Stratigraphic Approach

Well-log data from 157 wells and 43 measured core sections were used to construct a network of fourteen cross-sections (Figure 4-2). Most wells analyzed in the study had suitable wire-line log suites, i.e. gamma-ray, resistivity and induction logs, which were necessary for accurate correlations. The study area encompasses townships 65 and 66 and ranges 2 to 5, approximately 600 km^2 (Figure 4-2).

Facies associations from cored intervals were compared to corresponding well log signatures in order to distinguish the facies associations in wells where no core data was available. This process was then applied to construct a number of cross-sections in the Clearwater Formation.

Two trends are identified in the Clearwater Formation, a NW-SE and N-S (Figure 4-2). In the N-S trend, five strike-oriented cross-sections (A-A', B-B', C-C', D-D', and E-E'; Figures 4-3 - 4-7), and three dip-oriented cross-sections (F-F', G-G' and H-H'; Figures 4-8 - 4-10) comprise the network. In the NW-SE trend an additional five strike-oriented cross-sections (I-I', J-J', K-K', L-L', and M-M', Figures 4-11 - 4-15), and one dip-oriented cross-section (N-N'; Figure 4-16) were constructed to complete the network. Most of the wells were tied to core, and a number of wells were used in both strike- and dip- sections.

Subdivision of the Clearwater Formation was defined using a time-stratigraphic or allostratigraphic approach rather than stratigraphic schemes exclusively based on a lithostratigraphic correlation. An allostratigraphic unit is defined by the North American Commission on Stratigraphic Nomenclature (1983, p.865) as "a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities". Allostratigraphic units contain laterally heterogeneous facies. A bounding discontinuity signifies a hiatus or break in deposition which may or may not be accompanied by erosion (Catuneanu, 2006). Sedimentary cycles (i.e. coarsening upward or fining upward cycles) are frequently bounded by physical surfaces which can be used in correlation and stratigraphic subdivision. Eustatic sea-level fluctuations are also important in interpreting the deposition of sediments, since transgressive-regressive cycles were prominent in the Cretaceous.

The Clearwater Formation is subdivided into five allomembers - each allomember represents a genetically related package of interstratified sandstones, silts and shales separated by widespread bounding discontinuities (Trangressive Surfaces of Erosion/Sequence Boundaries; NACSN, 1983). Each allomember also takes into consideration eustatic sea-level change. Allomembers are variable in thickness, ranging from 0-60 m. Within each member, facies associations are separated using "shazam lines". Shazam lines imply that diachronous facies association boundaries are not physical surfaces but gradational boundaries (Gani and Bhattacharya, 2005).

Facies Associations

The Cold Lake area has been the subject of extensive drilling, resulting in an extensive data set for the study. A total of 43 cores were described in detail and used to calibrate and correlate across a grid of cross-sections (Figure 4-2). Each core was examined with particular reference to the lithology, grain size and sorting characteristics, bedding styles and bed thicknesses, nature of bedding contacts and bounding surfaces, biogenic and physical sedimentary structures, trace fossil assemblages, bioturbation intensity, and the degree of bitumen saturation. Eleven lithofacies were identified and grouped into seven facies associations (Table 2-1). Bioturbation intensity (BI) was assessed visually on a scale from one to six, one being unbioturbated sediments and six representing complete obliteration of sedimentary structures (Figure 2-2). In the photographs accompanying each of the facies associations (contained in Chapter 2), as a result of the high bitumen saturation, porous sand layers are stained black with bitumen, whereas finer grained facies with lower permeability appear lighter in colour.

Facies Association 1 – Shoreface - Proximal Offshore

Facies Associaton 1 (FA1) consists of very fine to medium grained sediments, mainly interbedded muds and very fine silts and sands, and is interpreted as being deposited on a shoreface to proximal offshore evironment. FA 1 consists of two units. The first, characteristic of the McMurray Formation, is dominantly light grey, interbedded upper silt to very fine lower sand, with 20-30% mud (Figure 2-3, A-C). The McMurray Formation is interpreted as tempestite deposits on a shelf/shoreface environment. Sand/silt interbeds are oscillation wavy to parallel laminated with possible short wavelength hummocky-swaley cross-stratifica-

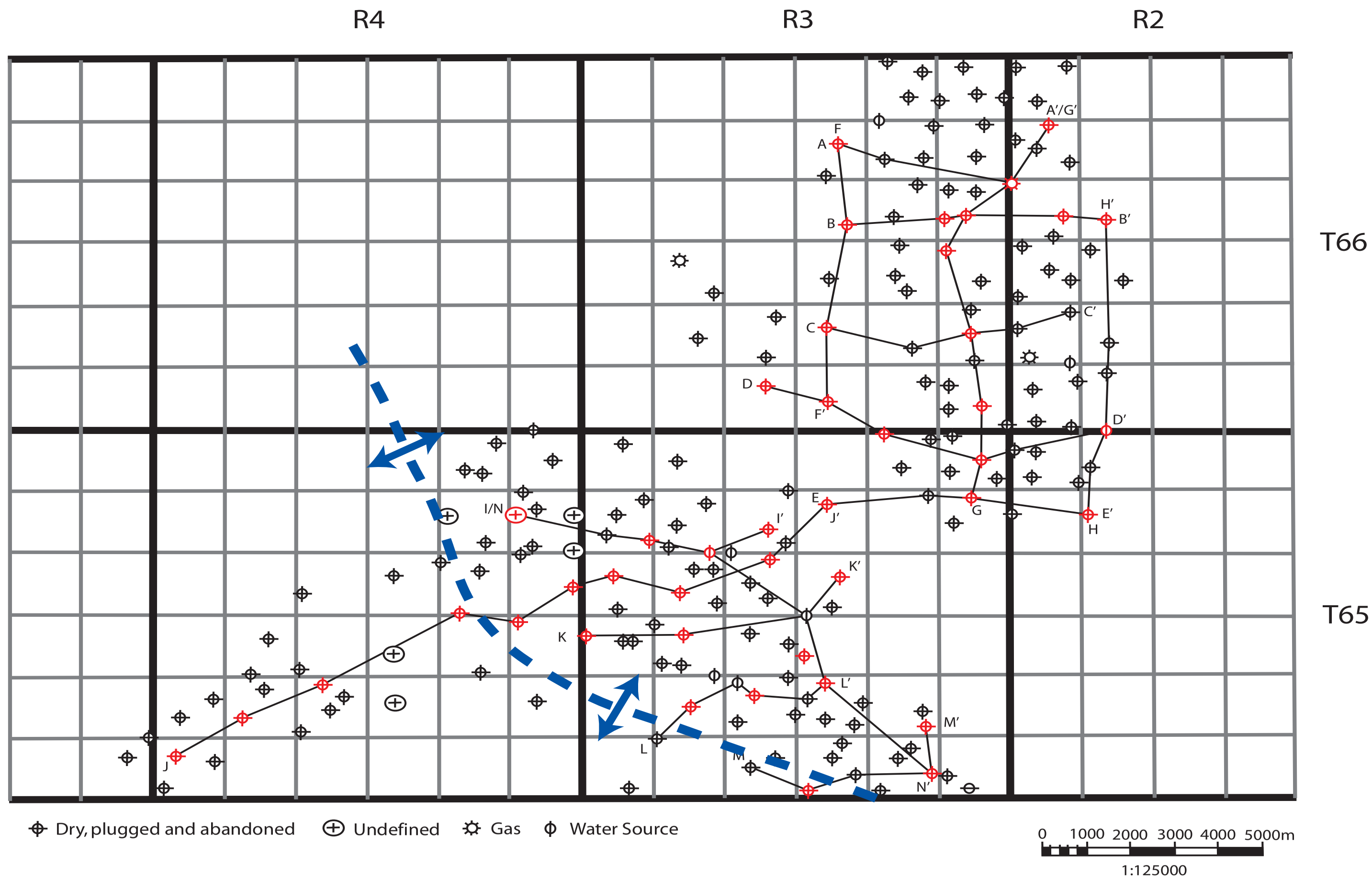

Figure 4-2: The network of fourteen stratigraphic cross-sections used for stratigraphic analysis of the Clearwater Formation. The cross-sections used petrophysical wireline logs from 157 wells and 43 measured core intervals (shown in red). Location of the Athabasca Anticline shown as a blue dashed line (McCrimmon, 1996). A-A' through to H-H' are oriented along a N-S trend, with A-A', B-B', C-C', D-D' and E-E' are oriented along strike and F-F', G-G', H-H' are oriented along dip. I-I' through to N-N' are oriented along a NW-SE trend, with I-I', J-J', K-K', L-L' and M-M' oriented along strike and N-N' oriented along dip.

tion, which typically indicate high energy events, such as storms (Figure 2-3, A-C; Pemberton and MacEachern, 2006). The sediment within these sand interbeds was likely deposited fairly rapidly due to the lack of bioturbation and occasional escape traces (Dott and Bourgeois, 1982). Muddier interbeds cap the sand/silt interbeds and are moderately bioturbated by a low diversity suite of ichnofossils including *Planolites*, *Paleophycus, Phycosiphon*, minor *Chondrites* and fugichnia (Figure 2-3, A-C). The mud interbeds gradationally overlie the sand interbeds, indicating a decrease in energy, i.e. the storm is waning (Figure 2-3, C; Dott, 1988; Pemberton and MacEachern, 2006). The mud interbeds reflect the final fall-out of suspended sediment in fair-weather conditions (Dott and Bourgeois, 1982). The second unit characterizes the Wabiskaw Member and commonly appears as greenish-grey interbedded fine lower to medium lower sand with approximately 10-40% mud (Figure 2-3, E-G). Variable amounts of glauconite give the deposit its characteristic green colour. The Wabiskaw Member is interpreted as a transgressive shoreline deposit. The abundance of glauconite suggests the sediment was deposited on a continental marine proximal offshore shelf with slow rates of accumulation (MacKenzie, 2005). Towards the bottom of the Wabiskaw Member primary structures observed include hummocky/swaley cross-stratification and parallel laminations indicating that storm activity is still prevalent (Figure 2-3, E, F). Moving up-section, primary structures are mostly obliterated due to biogenic reworking (Figure 2-3, G). Typically this glauconitic unit is extensively bioturbated, sometimes making traces indistinguishable; therefore a mottled/churned texture is reported. In intervals were bioturbation is somewhat diminished, some traces observed include *Planolites*, *Teichichnus*, *Diplocraterion*, *Siphonichnus*, *Asterosoma*, *Rhizocorallium*, *Palaeophycus*, *Thalassinoides*, *Skolithos*, fugichnia and *Chondrites*. Fully marine deposition is also supported by this diverse trace fossil assemblage (Pemberton and MacEachern, 2006).

Facies Association 2 – Prodelta to delta front

Facies Association 2 (FA2) consists of very fine grained to fine grained sand interbedded with silty mud (30-90%) (Chapter 2, Figure 2-4). FA2 sediments are interpreted as distal prodelta silts and muds to wavy bedded sands and muds of the delta front. Distal prodelta muds are deposited on the shelf where they are unaffected by both tidal and wave processes. These muds are characterized as grey, thinly laminated with minor symmetrical small scale crossbedding

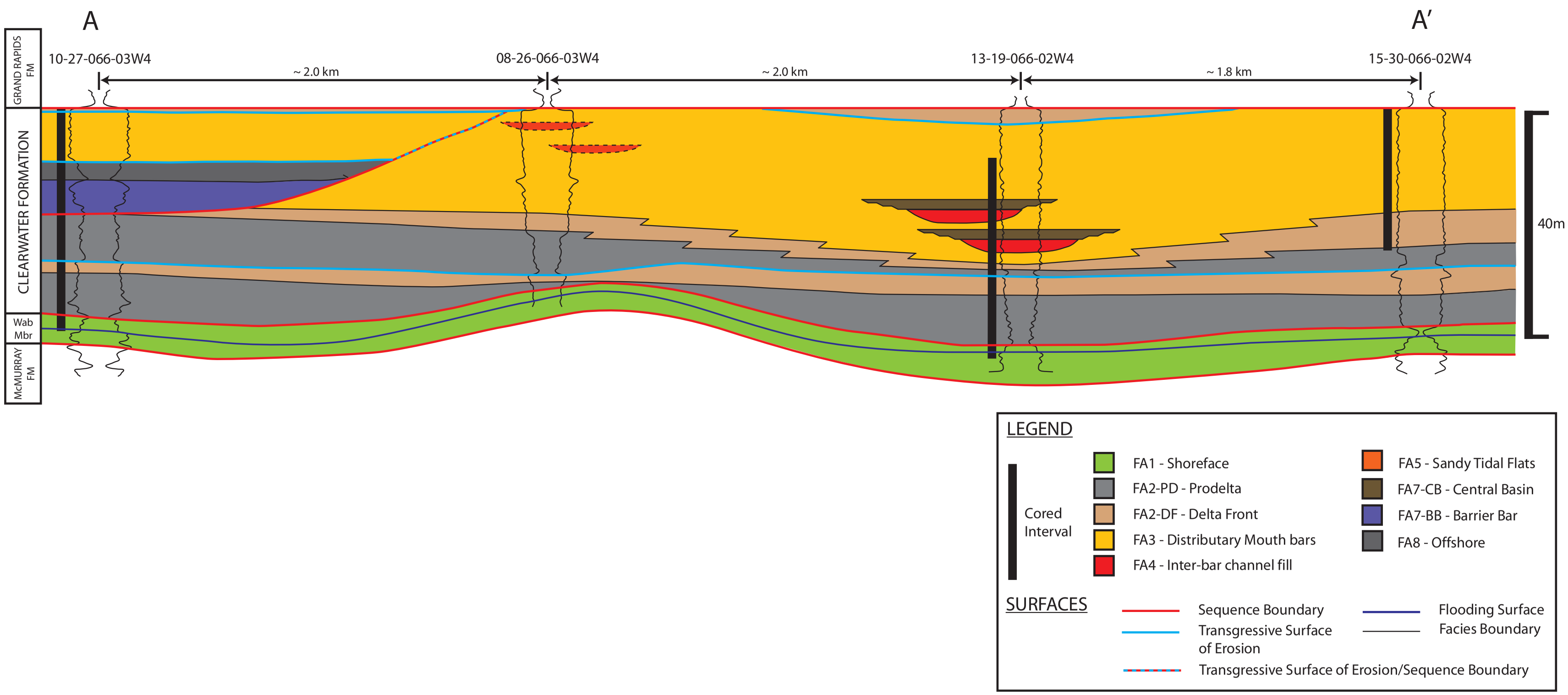

Figure 4-3: Stratigraphic cross-section A-A′. The section is the first of five strike-oriented sections in the network of cross-sections, tracing the northern portion of the N-S trend in the study area. The section contains four wells, from 10-27-066-03W4 in the west, to 15-30-066-02W4 in the east, a distance of approximately 5.8km. Allomembers 1 to 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

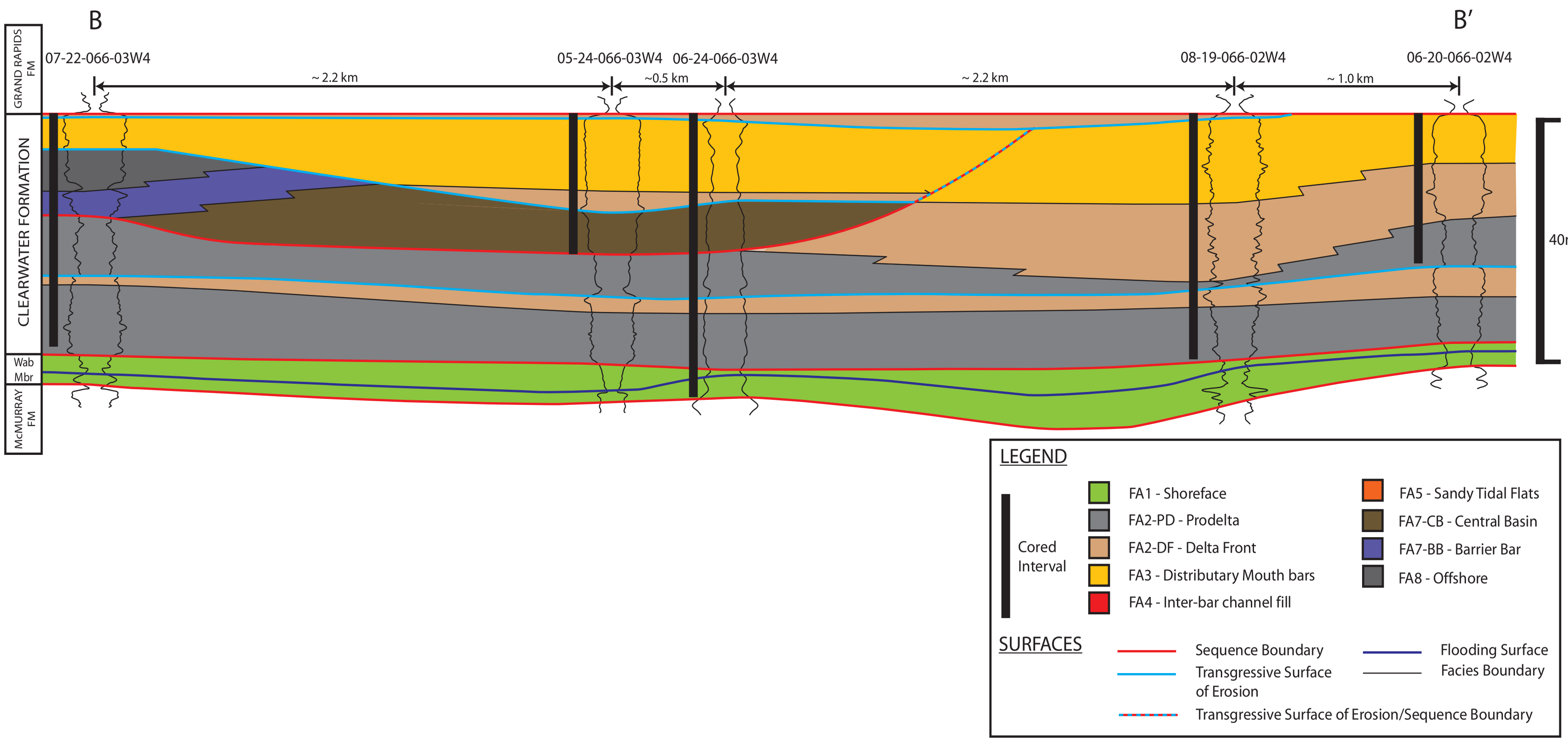

Figure 4-4: Stratigraphic cross-section B-B′. The section is the second of five strike-oriented sections in the network of cross-sections, tracing the northern portion of the N-S trend in the study area. The section contains five wells, from 07-22-066-03W4 in the west, to 06-20-066-02W4 in the east, a distance of approximately 5.9km. Allomembers 1 to 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

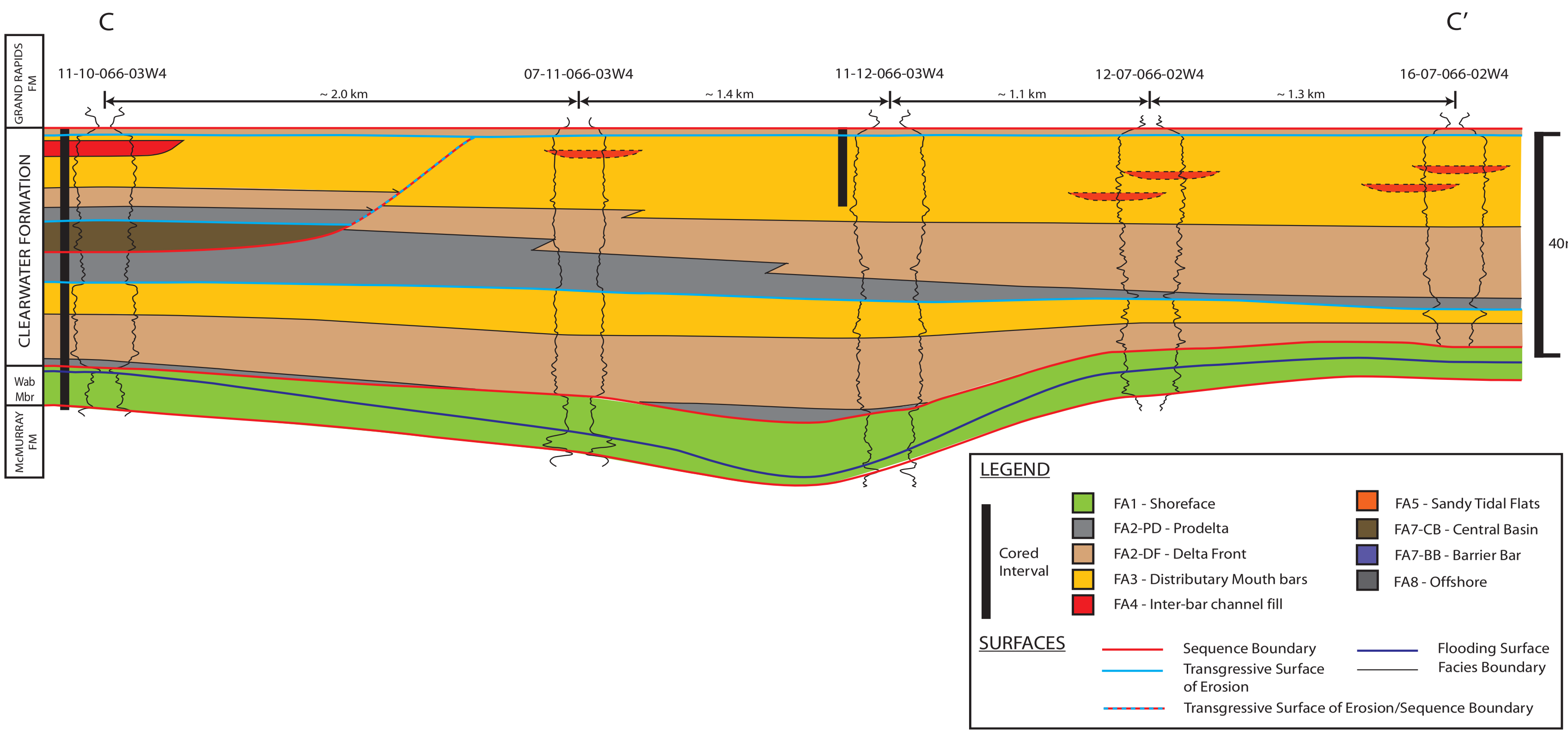

Figure 4-5: Stratigraphic cross-section C-C'. The section is the third of five strike-oriented sections in the network of cross-sections, tracing the middle portion of the N-S trend in the study area. The section contains five wells, from 11-10-066-03W4 in the west, to 16-07-066-02W4 in the east, a distance of approximately 5.8km. Allomembers 1 to 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

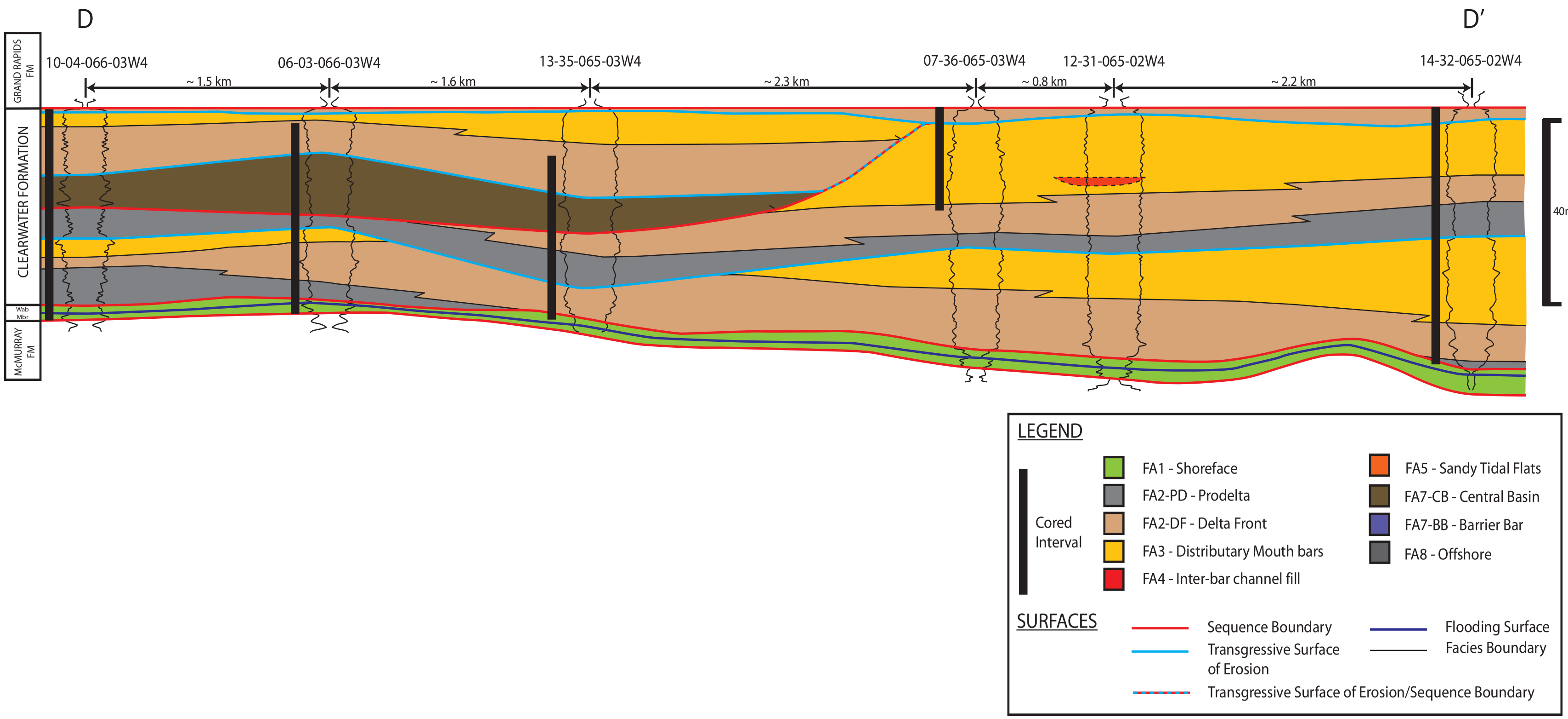

Figure 4-6: Stratigraphic cross-section D-D′. The section is the fourth of five strike-oriented sections in the network of cross-sections, tracing the southern portion of the N-S trend in the study area. The section contains six wells, from 10-04-066-03W4 in the west, to 14-32-065-02W4 in the east, a distance of approximately 8.4km. Allomembers 1 to 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

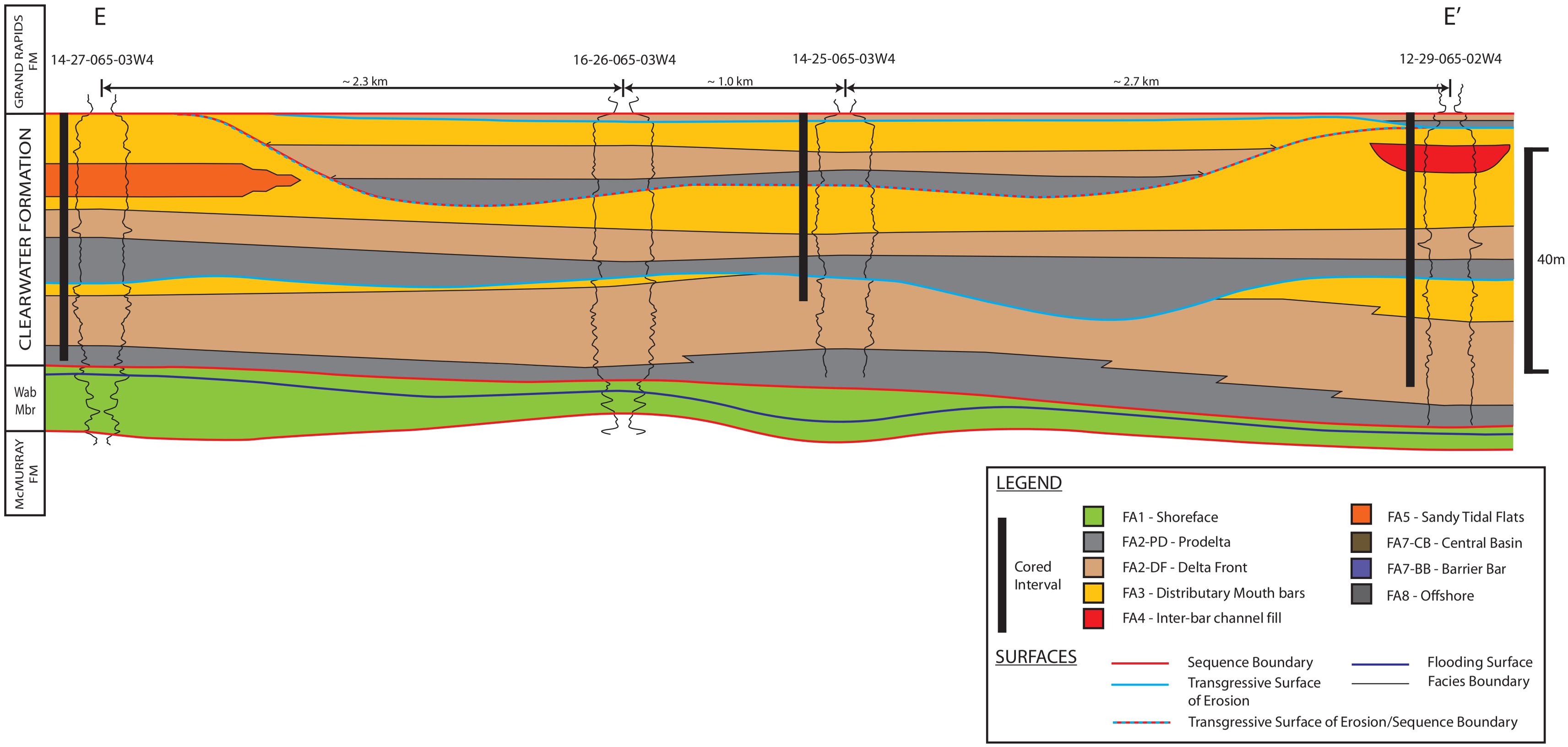

Figure 4-7: Stratigraphic cross-section E-E′. The section is the last of five strike-oriented sections in the network of cross-sections, tracing the southern portion of the N-S trend in the study area. The section contains four wells, from 14-27-065-03W4 in the west, to 12-29-065-02W4 in the east, a distance of approximately 6.0km. Allomembers 1, 2, 4 and 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

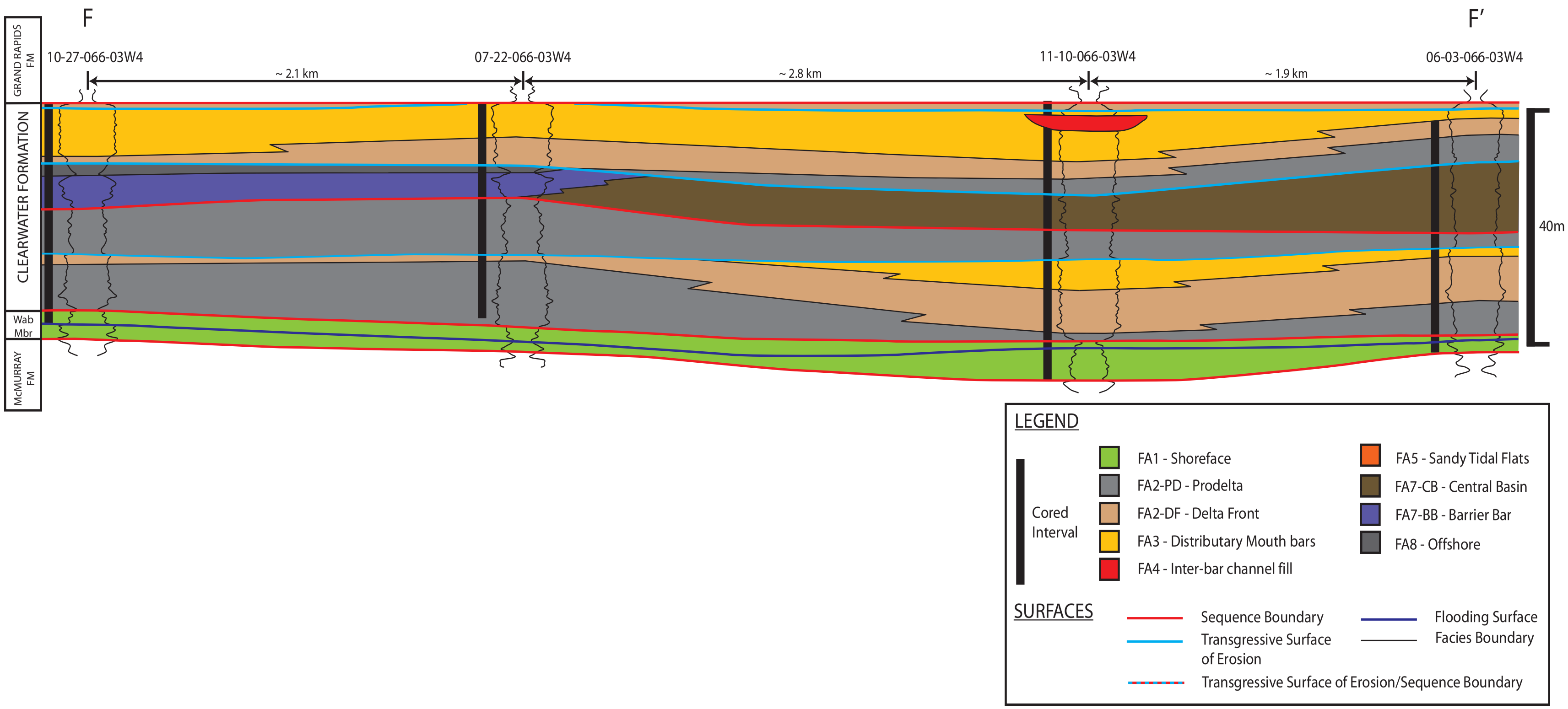

Figure 4-8: Stratigraphic cross-section F-F′. The section is the first of three dip-oriented sections in the network of cross-sections, tracing the western portion of the N-S trend in the study area. The section contains four wells, from 10-27-066-03W4 in the north, to 06-03-066-03W4 in the east, a distance of approximately 6.8km. Allomembers 1 to 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

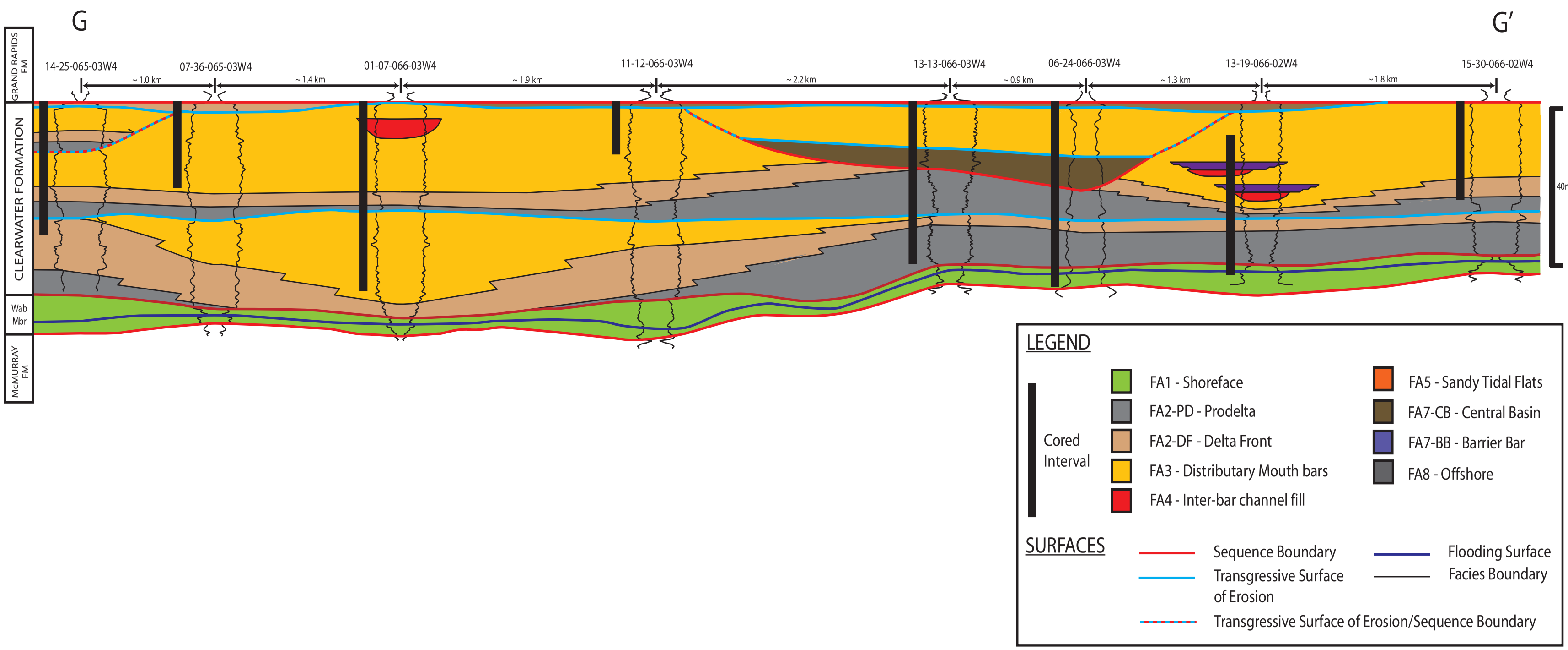

Figure 4-9: Stratigraphic cross-section G-G'. The section is the second of three dip-oriented sections in the network of cross-sections, tracing the middle portion of the N-S trend in the study area. The section contains eight wells, from 14-25-065-03W4 in the south, to 15-30-066-02W4 in the north, a distance of approximately 10.5km. Allomembers 1 to 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

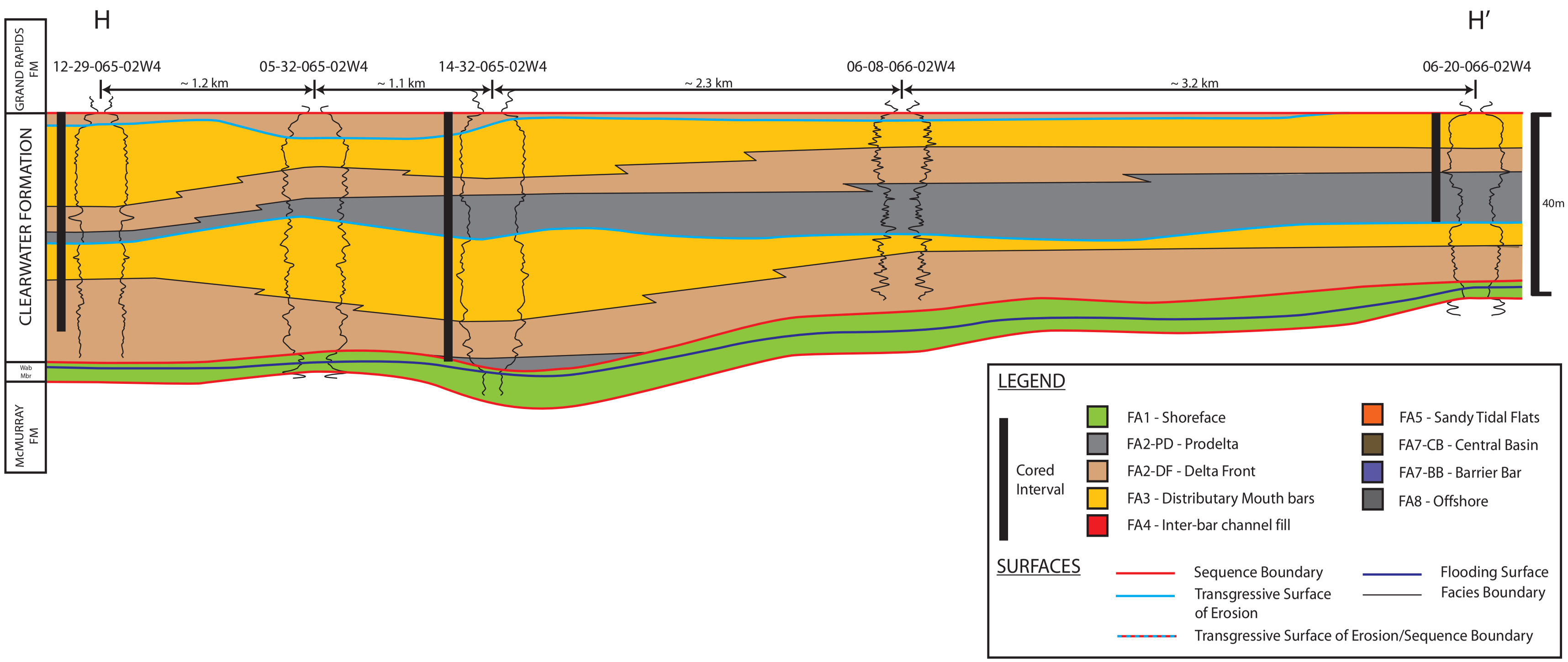

Figure 4-10: Stratigraphic cross-section H-H’. The section is the last of three dip-oriented sections in the network of cross-sections, tracing the eastern portion of the N-S trend in the study area. The section contains five wells, from 12-29-065-02W4 in the south, to 06-20-066-02W4 in the north, a distance of approximately 7.8km. Allomembers 1, 2, and 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

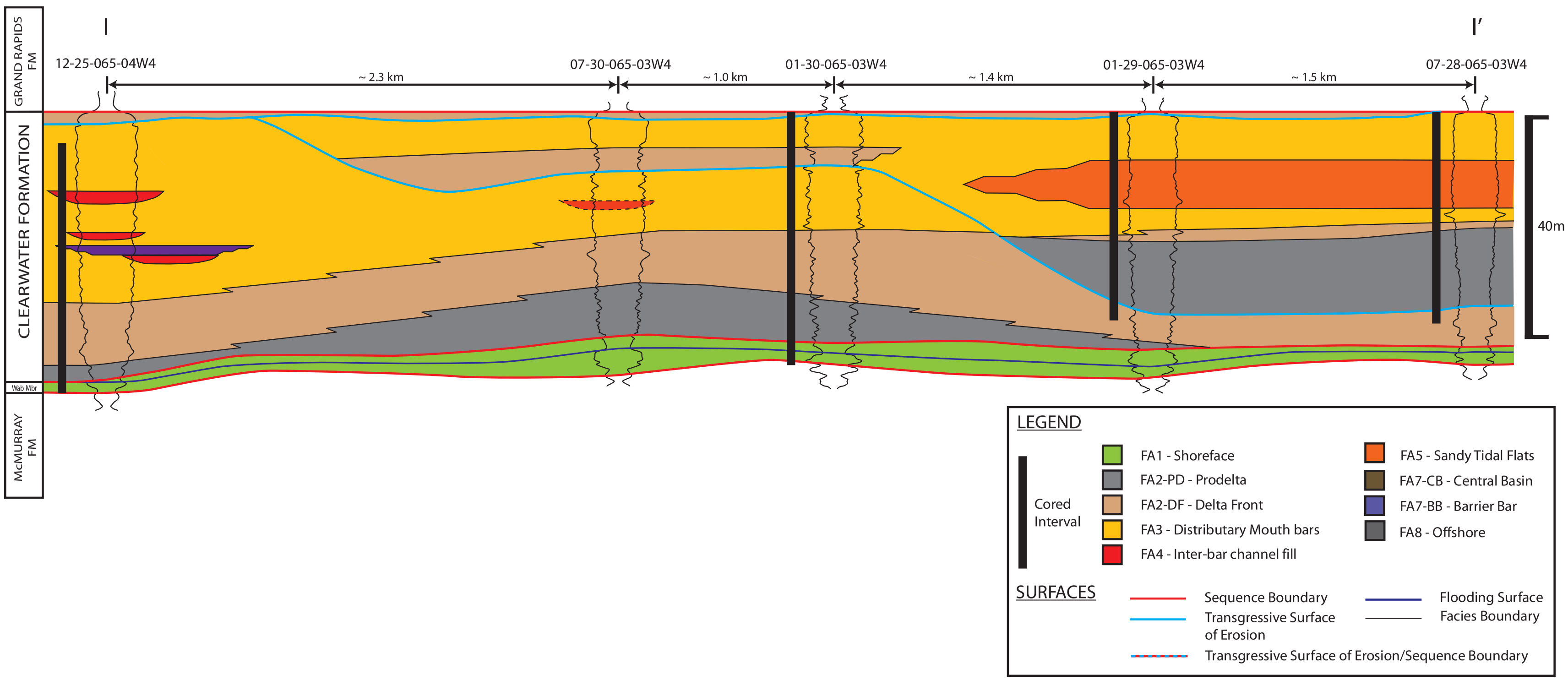

Figure 4-11: Stratigraphic cross-section I-I'. The section is the first of five strike-oriented sections in the network of cross-sections, tracing the northern portion of the NW-SE trend in the study area. The section contains five wells, from 12-25-065-04W4 in the west, to 07-28-065-03W4 in the east, a distance of approximately 6.2km. Allomembers 1, 2, and 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

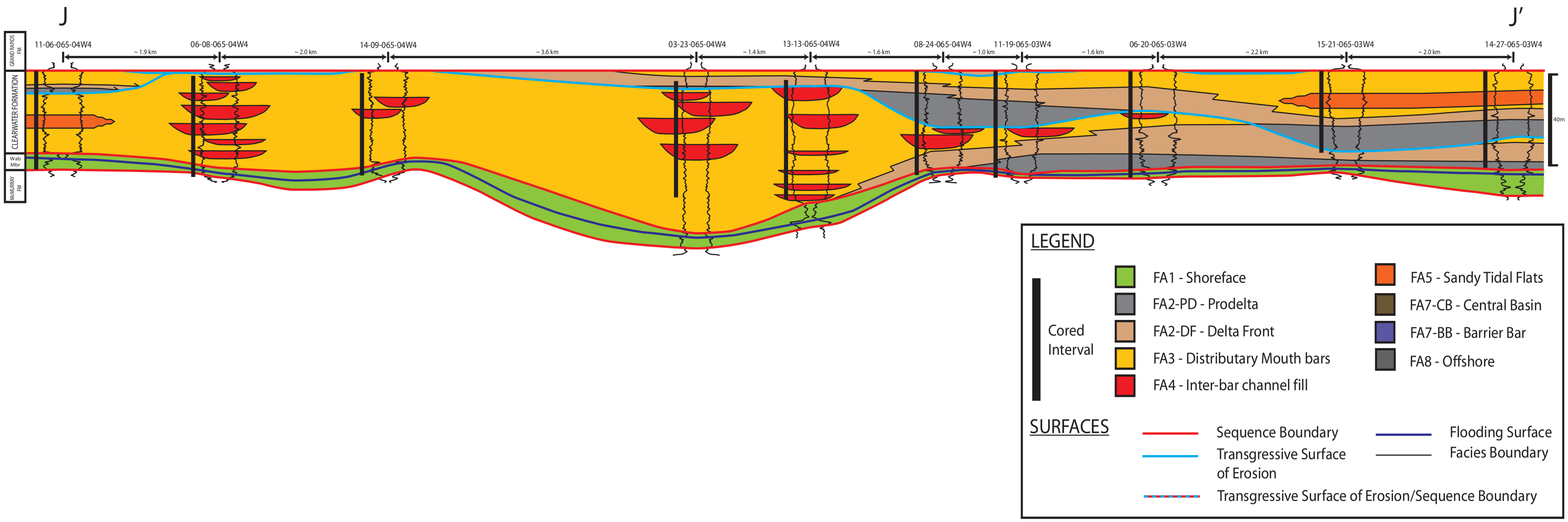

Figure 4-12: Stratigraphic cross-section J-J'. The section is the second of five strike-oriented sections in the network of cross-sections, tracing the northern portion of the NW-SE trend in the study area. The section contains ten wells, from 11-06-065-04W4 in the southwest, to 14-27-065-03W4 in the northeast, a distance of approximately 17.3km. Allomembers 1, 2, and 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

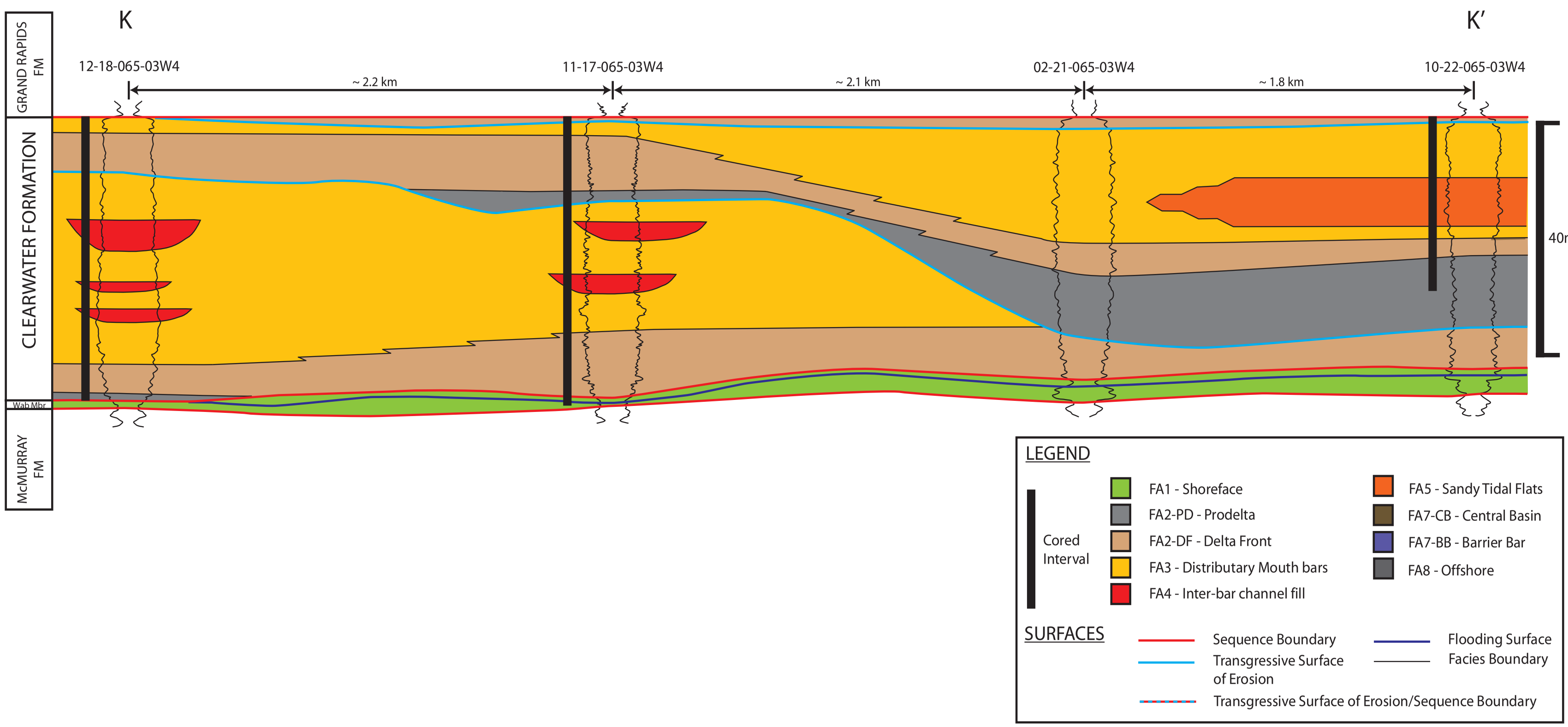

Figure 4-13: Stratigraphic cross-section K-K′. The section is the third of five strike-oriented sections in the network of cross-sections, tracing the middle portion of the NW-SE trend in the study area. The section contains four wells, from 12-18-065-03W4 in the west, to 10-22-065-03W4 in the east, a distance of approximately 6.1km. Allomembers 1, 2, and 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

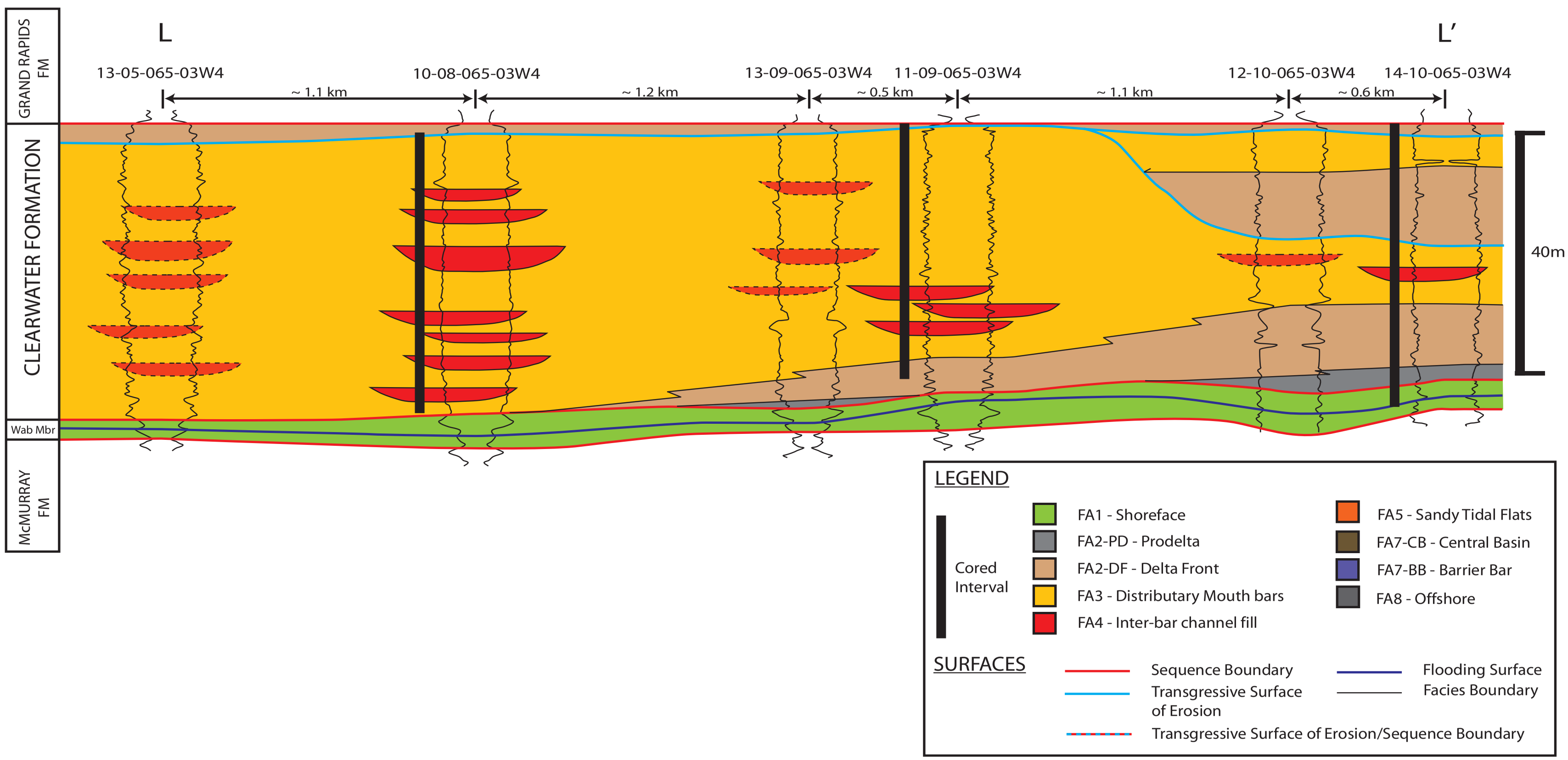

Figure 4-14: Stratigraphic cross-section L-L′. The section is the fourth of five strike-oriented sections in the network of cross-sections, tracing the southern portion of the NW-SE trend in the study area. The section contains six wells, from 13-05-065-03W4 in the west, to 14-10-065-03W4 in the east, a distance of approximately 4.5km. Allomembers 1, 2, and 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

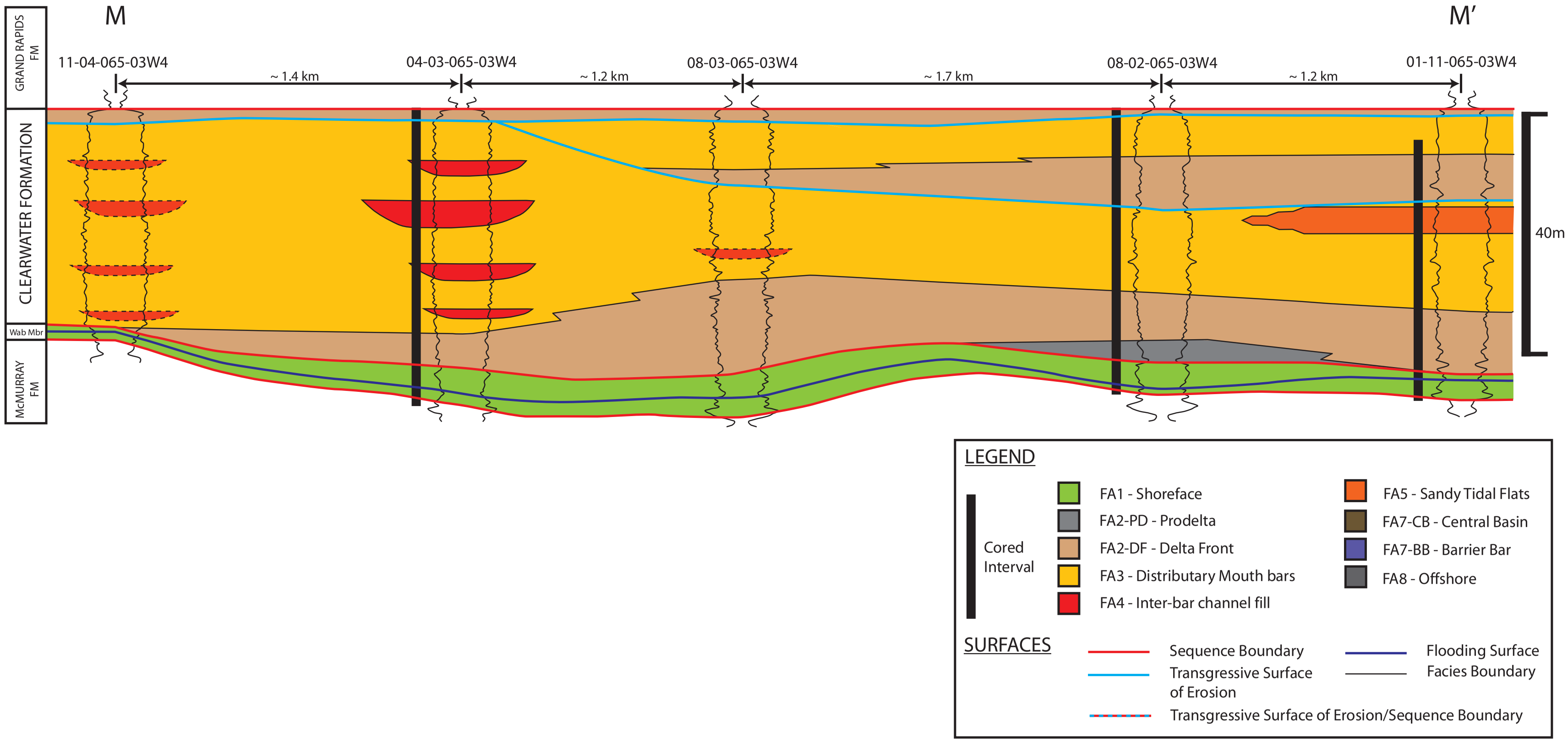

Figure 4-15: Stratigraphic cross-section M-M′. The section is the last of five strike-oriented sections in the network of cross-sections, tracing the northern portion of the NW-SE trend in the study area. The section contains five wells, from 11-04-065-03W4 in the west, to 01-11-065-03W4 in the east, a distance of approximately 5.5km. Allomembers 1, 2, and 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

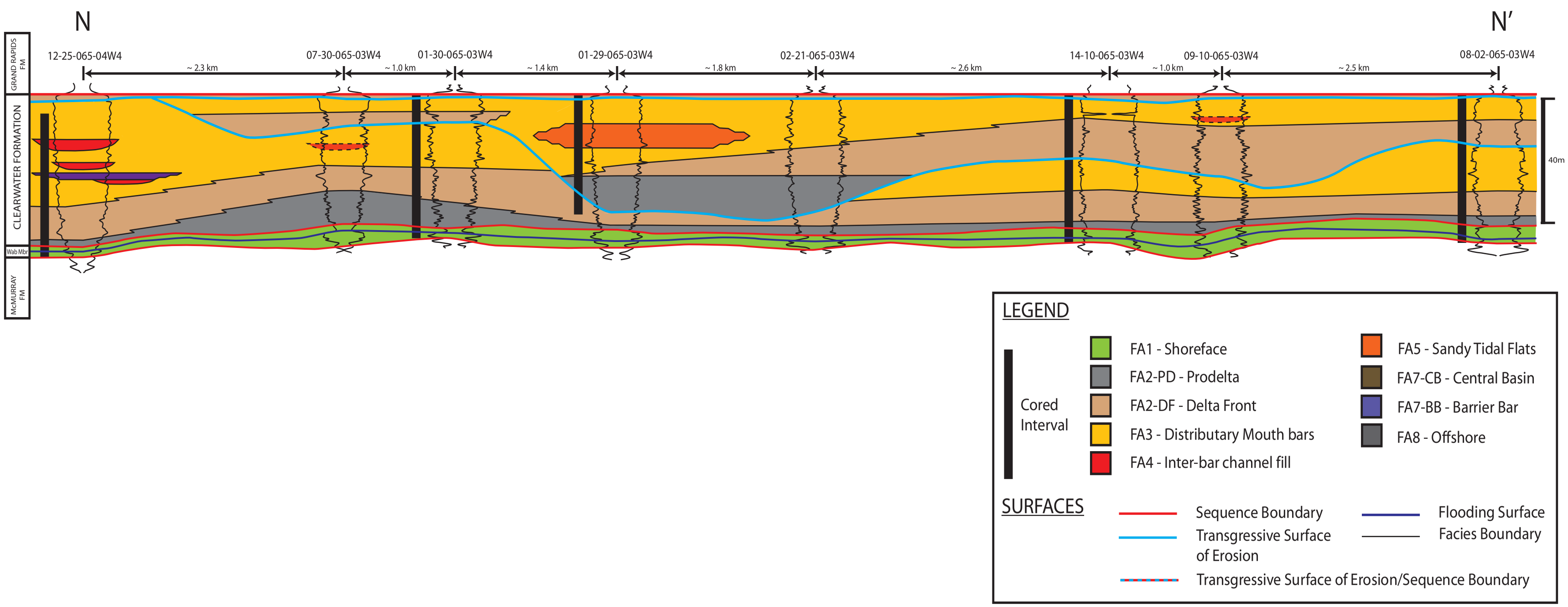

Figure 4-16: Stratigraphic cross-section N-N′. The section is a dip-oriented section in the network of cross-sections, tracing the through the middle portion of the NW-SE trend in the study area. The section contains eight wells, from 12-25-065-04W4 in the northwest, to 08-02-065-03W4 in the southeast, a distance of approximately 12.6km. Allomembers 1, 2, and 5 are seen in this section. See Legend for colour distinctions in facies associations and surfaces. Cored intervals are marked by a solid black line next to the respective curves. Gamma-gamma curves (butterfly curves) were used for accurate correlations. The datum for all the sections is the top of the Clearwater Formation. See body and text for discussion and interpretations.

and soft sediment deformation structures (Figure 2-4, A, B). Observed primary structures indicate a low energy environment where fine muds and silts have settled out of suspension (Pemberton and MacEachern, 2006). Soft sediment deformation structures are also common in prodeltaic sediments due to mass movements higher up in the delta front region (Carmona *et al*., 2009). In proximal prodelta sediments and transitional deposits between the proximal prodelta and delta front, sedimentation rates still remain low due to high amounts of mud and silt allowed to settle out of the water column. However sedimentation rates increase slightly moving into the transitional sediments as increased sand content is observed (Carmona *et al*., 2009). Primary structures are obliterated as a result of the high degree of bioturbation in the proximal prodelta (Figure 2-4, C-G). The proximal prodelta is heavily influenced by normal marine salinities as bioturbation intensity and diversity remain high (McIllroy, 2007). However, moving upwards into the transition, planar to wavy bedding with low angle cross-bedding and current/wave ripples are observed locally, which indicate that tidal/wave processes are minor (Carmona *et al*., 2009). In the transitional facies, salinity mixing becomes more prevalent as the intensity and diversity of ichnofossils decrease significantly upward (Buatois *et al*., 2003). Supported by the degree of bioturbation, proximal to transitional delta front sediments are deposited in fully aerobic waters were organisms can flourish (McIllroy, 2007). Delta front sediments contain the greatest amount of sand in FA2, with sand beds increasing in thickness stratigraphically upward. Thin mud drapes occur stratigraphically higher in the delta front, implying an increase in the tidal influence (Klein, 1977; Carmona *et al*., 2009). Sand beds are generally well sorted and consist of low angle cross bedding and small scale structures such as current ripples and climbing ripples (Figure 2-4H). Mud interbeds are moderately bioturbated with moderate intensity and diversity of ichnofossils. Ichnogenera within these mud interbeds are medium to large in size and fairly robust, but become more sporadic up section. This suggests that, due to an increase in tidal influence combined with possible effects of storm activity, influxes of normal marine salinity is episodically making conditions more hospitable (though sporadic) for colonization of marine traces (Buatois *et al*., 2003). As these conditions lessen stratigraphically higher in the lower delta front, burrows decrease in size and intensity.

Facies Association 3 – Distributary Mouth Bars

Facies Association 3 (FA3) consists of fine upper to medium lower sand interbedded with thin and often discontinuous fluid mud drapes/laminae (0-20%) and mud rip-up clasts (0-10%) (Figure 2-5). FA3 sediments are interpreted as distributary mouth bar sands deposited above the delta front region. Primary structures observed include large-scale low-angle to trough cross-stratification and small-scale features such as current ripples, climbing ripples and fluid mud (Figure 2-5). Fluid muds, common in mouth-bar environments, are deposited from suspension during periods of slack water, and appear to 'drape' over the large scale cross-stratification features in the sand beds (Nio and Yang, 1989; Dalyrmple *et al.*, 2003). The upward decrease in abundance and thickness of mud drapes implies that they were formed by the deposition from fluid muds in the bottom of a channel between bars (Dalyrmple *et al.*, 2003). Fluid muds tend to dominate lower lying or more distal portions due to higher amounts of suspended sediment. However, moving up-section tidal/wave action frequently inhibits the deposition of these muds or resuspends it during periods of slack water (Dalyrmple *et al.*, 2003). Within the mud laminae, a low abundance and low diversity assemblage dominated by small *Planolites* and rare *Rosselia* are observed (Figure 2-5, C). This restricted trace fossil assemblage is also commonly observed in mouth bar deposits and is documented by such authors as Dalrymple *et al*., 2003 and Buatois *et al*., 2005.

Facies Association 4 – Inter-bar Channel Fill

Facies Association 4 (FA4) sediments consist of lower fine to lower medium sand with minor thin, often discontinuous mud drapes (<5%) interbedded with layers containing abundant poorly sorted angular to rounded mud clasts (Figure 2-6). FA4 is interpreted as tidally-influenced inter-bar channel fill. Clast beds range from 15 cm to over 1 m thick and generally thin upwards, with clast material also decreasing upwards (Figure 2-6, B). The abundance of mud clasts are interpreted to have been eroded from muddy upper delta plain deposits and delta front (FA2) heterolithic strata, inferring that the channels are tidal in origin (Feldman *et al*., 2008). Minor mud drapes, commonly occurring in couplets, and large, rounded armoured mud clasts further supports a strong tidal component (Figure 2-6, C). Primary structures include large-scale low-angle to trough cross-stratification and local current ripples. No bioturbation was observed in the sand, although a low abundance (BI 0-1) and low diversity ichnofossil assemblage dominated by small *Planolites* occurs within some of the mud clasts and mud drapes. Again, this low abundance, low diversity ichnofossil assemblage is due in part to the constant shifting of the substrate, caused by channel avulsion, which softground burrowers would have found inhospitable (Pemberton *et al*., 2001; Pemberton and MacEachern, 2006).

Facies Association 5 – Tidal Flats

Facies Association 5 (FA5) consists of medium lower sand with very minor mud and rip-up clast material (Figure 2-7, A-C). FA 5 sediments are interpreted as sandy tidal flat deposits. The abundance of sand indicates there is a strong tidal influence, not conducive to the deposition of mud (Arnott and Hand, 1989). Primary structures have been completely obliterated by intense bioturbation, although locally and very rarely, small scale current ripples, planar laminations and carbonaceous material are observed (Figure 2-7, A, C). These structures typically occur in a 5-10 cm thick bed that seem to cap the intensely bioturbated sand. These beds are interpreted as the top of the sand flat that is periodically subaerially exposed during low tide (Figure 2-7, C). The relative degree of bioturbation is very intense (BI 5-6) but diversity is very low. The ichnofossil assemblage is dominated by large *Planolites* burrows, approximately <1 cm in diameter, which reflect deposit-feeding infaunal polychaetes or worm-like organisms which are commonly found on tidal flats (Pemberton and MacEachern, 2006). Bitumen saturation is reduced in this facies association due to pervasive berthierine cement accentuated by the intense burrowing action. Berthierine cement (common in most deltaic environments) indicates a shallow marine environment where the pore water composition is brackish (Hornibrook and Longstaffe, 1996). This is also reflected in the impoverished trace fossil suite.

Facies Association 6 – Estuarine

Facies Association 6 (FA6) consists of very fine to fine grained sand with varying amounts of mud (approximately 20-30%) (Figure 2-8). FA6 sediments are interpreted to represent an estuarine valley fill consisting of barrier bar sands and central basin muddy deposits. FA6 is rare and only appears in the northern section of the study area, confined in a valley system. Barrier sand bar deposits appear gradationally between offshore sediments to the north and muddier central basin mudstones and sandstones to the south. The coarsening upward profile and large scale cross-stratification structures are characteristic of barrier bars in wave dominated estuarine settings (Figure 2-8, A; Reinson, 1992; Hubbard *et al.*, 1999). The well sorted nature of the sands and evidence of wave reworking indicate a strong influence from the waves and tides (Hubbard *et al.*, 1999; Hubbard *et al.*, 2002). Bioturbation is rare to absent (BI 2-3), containing minor *Planolites*, *Skolithos, Cylindrichnus,* with rare occurrences of *Rhizocorallium* and *Asterosoma.* These traces indicate an impoverished ichnofossil assemblage seen in true brackish-water settings where organisms are subjected to environmental stresses resulting in diminutive, opportunistic traces (Pemberton and MacEachern, 2006). In particular, the increased energy at the mouth of an estuary and increased sedimentation rates has a marked influence in the colonization of the barrier bar (Pemberton and MacEachern, 2006; Buatois *et al.*, 1999). Central basin deposits resemble that of proximal prodelta to lower delta front sediments (Figure 2-8, B-D). However, their occurrence stratigraphically below the barrier bar sands indicate a retrogradational package related to an estuarine complex. The increased amount of mud in this facies suggests a relatively low energy environment. The mud implies minimal wave and/or tidal action or a decrease in sedimentation rates (Carmona *et al*., 2009). The prevalence of mud-rich deposits coupled with a diminished ichnodiversity, reflects a true brackish-water assemblage seen in estuarine systems. This suggests deposition within a salinity-stressed and quiescent depositional environment (Hubbard *et al.*, 1999; Pemberton and MacEachern, 2006; Dalyrmple and Choi, 2007).

Facies Association 7 – Distal Offshore

Facies Association 7 (FA7) is characteristic of the Grand Rapids Formation in the Cold Lake area. FA7 sediments are interpreted as fine grained distal offshore deposits. Sediments consist of bioturbated to parallel laminated beds of grey mud intercalated with thin lenses of very fine sand and silt (Figure 2-9, A-B). FA7 is a coarsening upward succession, from intensely bioturbated silty mud to wave rippled and hummocky cross-stratified sand. The wave ripples and hummocky stratification indicate storm activity on a shelf environment (Walker and Plint, 1992). Additionally, FA7 contains minor shell fragments and siderite nodules. Trace fossils are abundant (BI 5-6) and diverse in muddier strata, and include *Zoophycos*, *Planolites*, *Asterosoma*, *Chondrites*, *Teichichnus*, *Skolithos* and *Palaeophycus*. This very diverse trace fossil assemblage indicates open-marine conditions (Pemberton and MacEachern, 2006).

Allostratigraphy and Depositional History

Correlations and Depositional History

Fourteen stratigraphic cross-sections were constructed through the Clearwater Formation at Cold Lake, and are presented in Figures 4-3 to 4-16. The majority of wells contain core that were analyzed as part of this study. All sections were hung on the sequence boundary at the top of the Clearwater Formation. This sequence boundary marks the transition from mainly regressive sediments of the Clearwater Formation to transgressive sediments of the Grand Rapids Formation (Beynon, 1991). Correlation of facies associations reveals the Clearwater Formation can be subdivided into the Wabiskaw Member and five allomembers, each of which are described below.

Wabiskaw Member

The Wabiskaw Member is bounded below and above by sequence boundaries (SB). The Wabiskaw Member, at the base of the Clearwater Formation, represents a thin veneer of sediment ranging from 0 to 15 m thick (Figure 4-17). The lower SB is typically sharp-based and erosive, and reflects an abrupt change in lithology and grain size (Figure 4-23, A). Below, the McMurray Formation, is typically very fine grained and quartz-rich (Minken, 1974; Jackson, 1984). The Wabiskaw Member is a glauconitic litharenite which is coarser grained (fine to medium sand) than the underlying McMurrary Formation (Harrison *et al.*, 1981; McCrimmon and Arnott, 2002). This lower SB also represents the contact between the Upper and Lower Mannville.

In most cores where the Wabiskaw Member is present, the upper SB is typified by large, robust burrows of the *Glossifungites* Ichnofacies that extend downward from the surface (Figure 4-23, B; Pemberton and MacEachern, 2006). The *Glossifungites* Ichnofacies is often coincident with sequence boundaries, and indicates burrowing in a semi-consolidated substrate (Pemberton and MacEachern, 2006). Locally within the Wabiskaw Member a flooding surface (FS) is observed. This surface represents two retrogressively stacked, shoaling-upward successions. Overall, the Wabiskaw Member represents a transgressional shoreface deposit which was terminated by a relative sea-level fall forming the upper

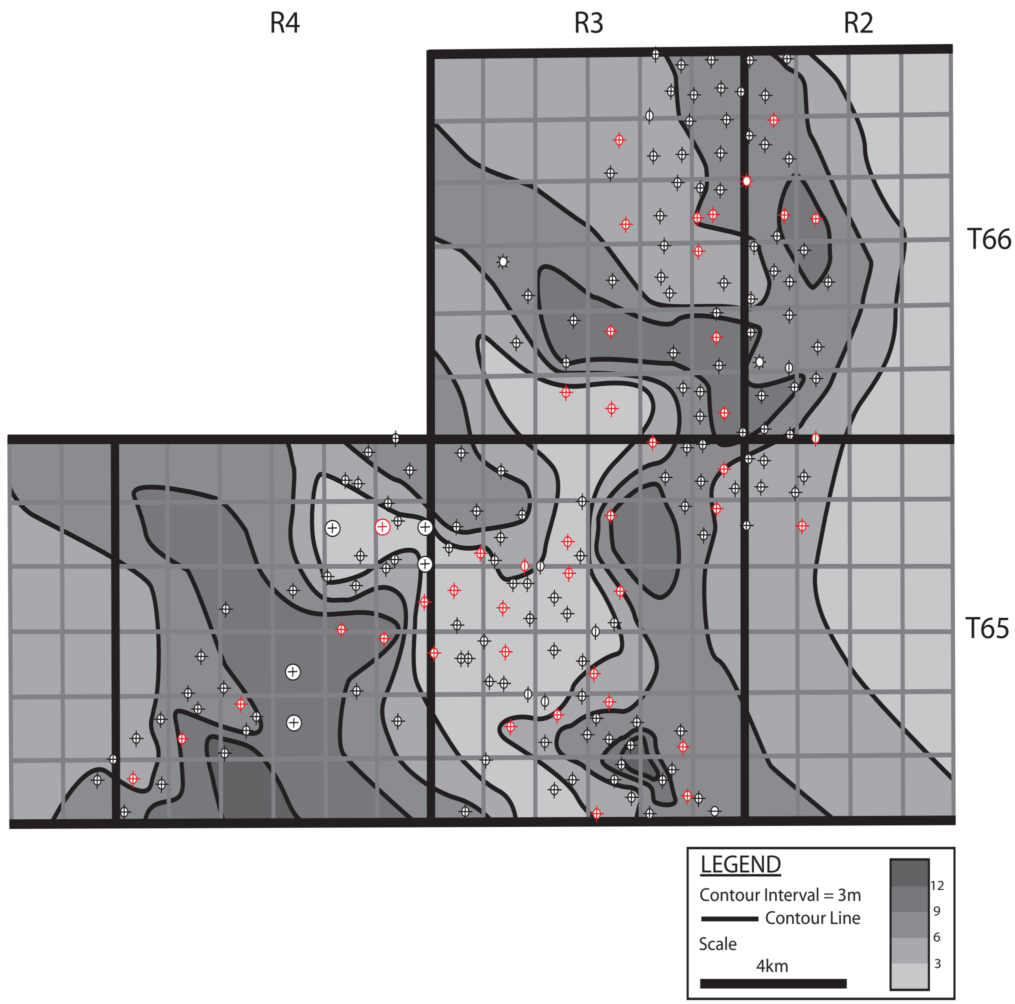

Figure 4-17: Isopach map of the Wabiskaw Member.

SB.

Allomember 1

Allomember 1 (A1) is bounded below by the upper SB of the Wabiskaw Member and above by a transgressive surface of erosion (TSE). A1 ranges from 0 to 66 m thick, the thickest deposits observed in the southern half of the study area (Figure 4-18). The lower SB is sharp-based and often exhibits the *Glossifungites* Ichnofacies (Figure 4-23, B; Pemberton and MacEachern, 2006). This contact reflects a change in lithology, from a fine to medium grained glauconitc litharenite to a fine- to medium-grained feldspathic litharenite (Harrison *et al.*, 1981; Hutcheon *et al.*, 1989). A1 consists of predominantly prodelta to delta front sediments (FA2), and lesser, mouth bar (FA 3) and inter-bar channel fill (FA

4) deposits. Prodelta to delta front sediments occur mostly to the northern part of the study area, whereas more proximal sediments (FA3 and FA4) occur in the southern part. Moreover, the thickest deposits, occurring in the southern portion of the study area, are primarily composed of these proximal facies associations (Figures 4-12 - 4-16, 4-18). These observations indicate that the marine basin lay in a general northward direction.

Tectonism in the Western Cordillera was thought to be significant during the deposition of the Clearwater, which resulted in episodic high sediment influxes (Wickert, 1992; Armstrong and Ward, 1993). Combined with core evidence, A1 was deposited under a progradational system. The upper contact, a TSE, reflects erosion of these marginal-marine deposits due to an abrupt sea-level rise (Posamentier and Allen, 1999). In core, the TSE is sharp-based and erosive. Overall, A1 represents progradation of a tide-dominated delta in an approximate north-south direction (Figure 4-24, A). Progradation was terminated because of a significant transgression of the Boreal Seaway forming the upper TSE.

Allomember 2

Allomember 2 (A2) is bounded below by a transgressive surface of erosion (TSE) and above by either a sequence boundary or transgressive surface of erosion (SB/TSE). A2 ranges from 0 to 43 m thick, with the thickest deposits trending north-south on the eastern side of the study area (Figure 4-19). The lower boundary, a TSE, is sharp-based with proximal delta front (proximal FA2), mouth bar (FA3) and inter-bar channel fill (FA4) sediments erosionally overlain by more distal prodelta sediments (distal FA2). Similar to A1, A2 consists of prodelta to delta front (FA2), mouth bar (FA3) and inter-bar channel fill (FA4) sediments. However, this allomember is dominated by more proximal FA2 (delta front) and mouth bar/inter-bar channel fill (FA3/FA4) sediments, with prodelta sediments occurring in the northern part of the study area (Figure 4-3 - 4-10, 4-19). This suggests the shoreline, thought to be south of the study area (Wickert, 1992), has moved basinward as a result of the rate of progradation being higher than transgression of the Boreal Seaway. In the northern part of the study area, the upper boundary of A2 is documented as a SB. This boundary is sharp-based and the *Glossifungites* Ichnofacies is observed below the surface (Figure 4-23, C). This suggests rapid sea-level fall causing valley incision in the northern part of the study area (Zaitlin *et al.*, 1994). Elsewhere in the study area, the upper boundary

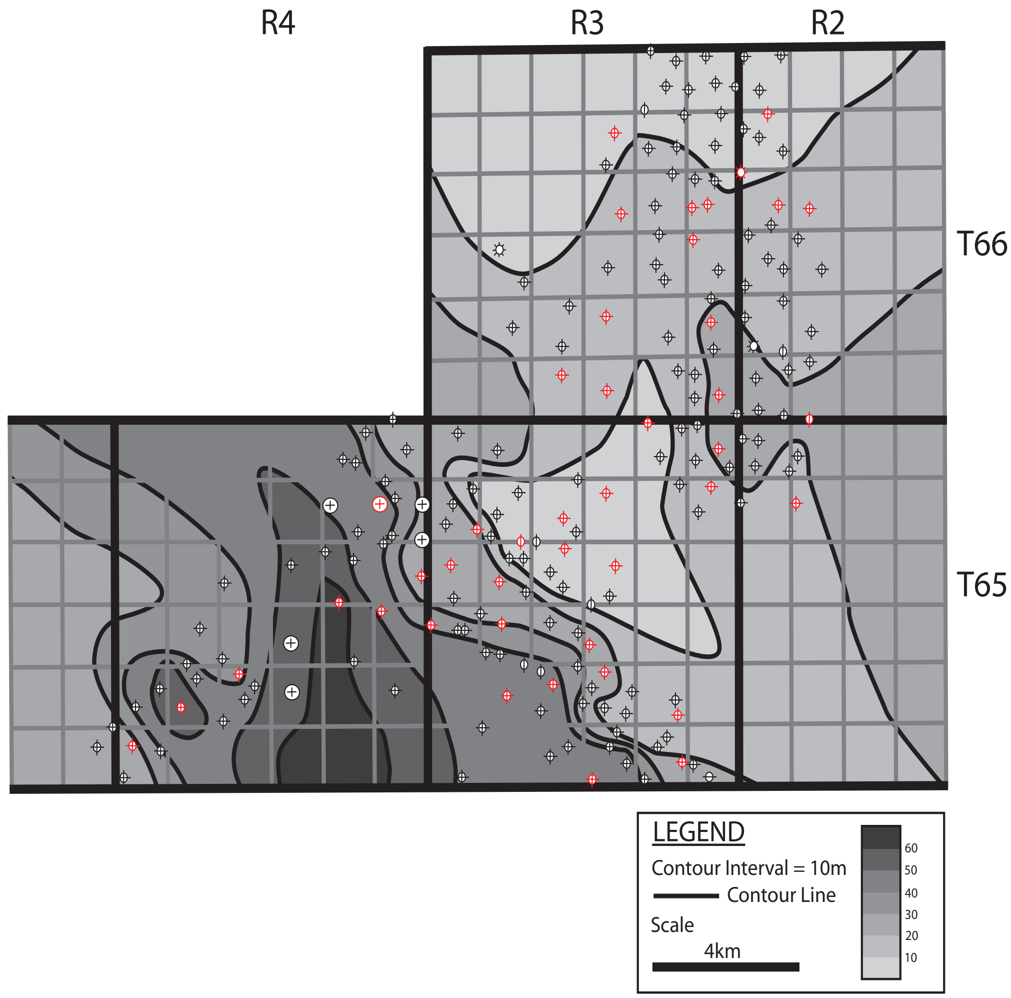

Figure 4-18: Isopach map of Allomember 1 showing deposition of tide-dominated deltaic sediments primarily in the NW-SE trend.

of A2 is a TSE, recording erosion due to a rapid rise in relative sea-level.

Similar to A1, deposition of A2 commenced with a rise in relative sea level. High sediment influx caused a tide-dominated delta, oriented north-south to prograde over the study area (Figure 4-24, B). An area of non-deposition in the southwest corner of the study area is observed, and trends approximately northwest-southeast. This can be attributed to uplift on the Athabasca Anticline, which trends northwest-southeast through the study area (Figure 4-2; McCrimmon, 1996).

Allomember 3

Allomember 3 (A3) is bounded below by a SB and above by a TSE, and is only observed in the northern part of the study area. A3 ranges from 0 to 17.5 m

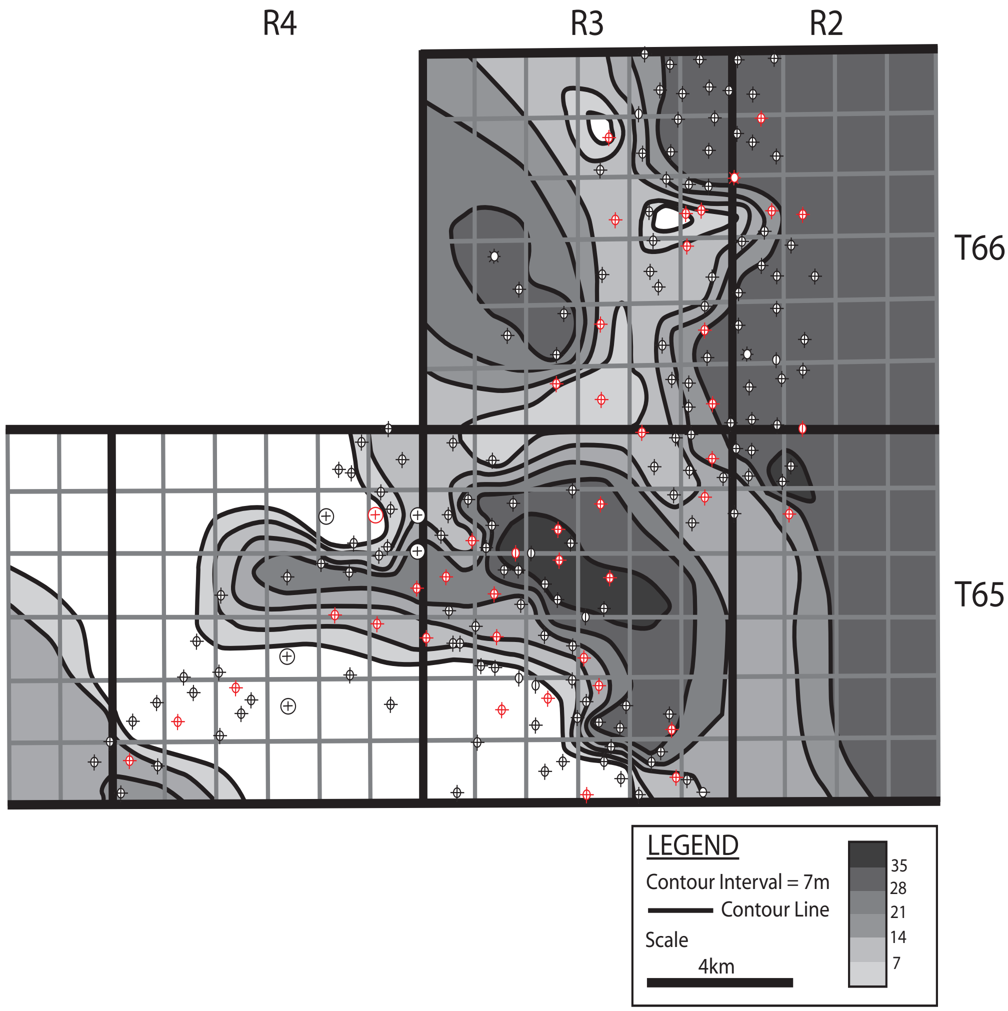

Figure 4-19: Isopach map of Allomember 2 showing that deposition of tide-dominated sediments has switched to the N-S trend.

thick (Figure 4-20). The lower boundary of A3 is a SB, observed as sharp-based, erosive and exhibiting the expected *Glossifungites* Ichnofacies indicative of most sequence boundaries (Figure 4-23, C; Pemberton and MacEachern, 2006).

Unlike previous allomembers, A3 commenced with a fall in relative sea-level. This began the incision of a paleovalley, which was subsequently filled by a retrogradational package of estuarine sediments (FA6) during the ensuing relative sea-level rise (Figures 4-3 - 4-9, 4-24, C; Zaitlin *et al.*, 1994). A TSE caps this allomember. This surface is overlain by a 2-5 cm thick transgressive lag deposit of rounded chert pebbles, indicating significant erosion due to rapid transgression of the Boreal Seaway (Figure 23, D; Posamentier and Allen, 1999).

Allomember 4

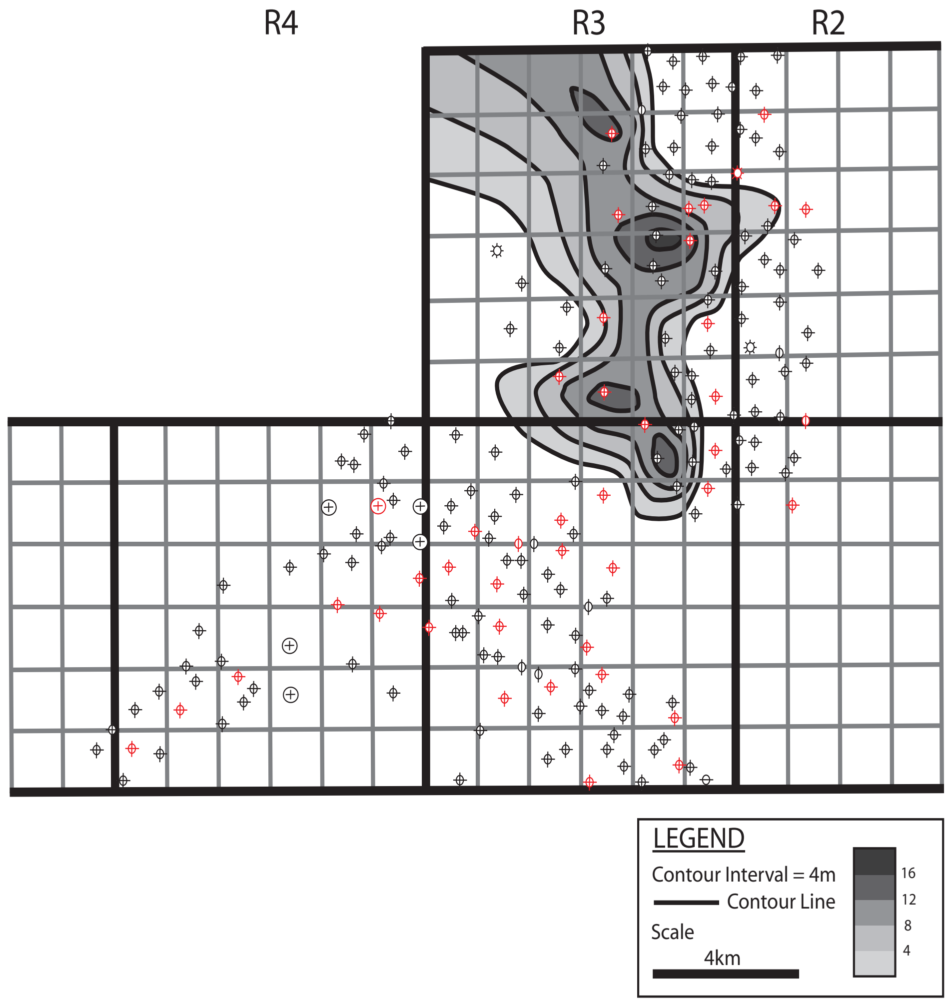

Figure 4-20: Isopach map of Allomember 3 showing deposition of retrogradational estuarine sediments in an incised paleovalley in the northern portion of the study area.

Allomember 4 (A4) is bounded below and above by TSEs. A4, similar to A3, is only observed in the northern part of the study area within the valley system, and ranges from 0 to 21.3 m thick (Figure 4-21). The lower TSE is sharp-based and erosive, often overlain by a 2-5 cm thick chert pebble transgressive lag deposit (Figure 4-23, D). A4 consists of prodelta to delta front (FA2), mouth bar (FA3) and inter-bar channel fill (FA3) sediments. Thicker, distal to proximal prodelta deposits occur farther north in the study area, and thicker, more proximal deposits (FA3 and FA4) occur in the southern half of the study area (Figures 4-3 - 4-9). The upper TSE boundary merges with the upper TSE of A2 where A3 is not observed. This surface is characterized as again sharp-based and erosional, overlain by a 1-10 cm thick layer of angular muddy rip-up clasts and chert pebbles (Figure 4-23, E).

A4 began because of a rise in relative sea-level. Another pulse in high sedimentation rates initiated progradation of a third tide-dominated delta (Figure 4-24, D). At the time of progradation, this tide-dominated delta likely covered the entire study area. However, due to the significant erosion along the upper TSE, A4 is only preserved and contained in the paleovalley system incised at the beginning of A3 (Figure 4-21).

Allomember 5

Allomember 5 (A5) is bounded below by a TSE and above by a SB, and is the youngest allomember in the Clearwater Formation. A5 is relatively thin compared to previous allomembers, ranging from 0 to 13 m thick (Figure 4-22). A5 only contains prodelta to delta front sediments (FA2) (Figures 4-3 - 4-16). Prodelta sediments are observed in the north, and delta front sediments occur towards the southern part of the study area, maintaining that the basin remains to the north. The upper boundary, a SB, marks the end of Clearwater sedimentation. This boundary is sharp-based and erosive, overlain either by a thick massive transgressive mud or fully marine/offshore silts and muds (FA7) (Figure 4-23, F).

A5 commenced with a rise in relative sea-level. Similar to A1, A2 and A4, high sedimentation rates initiated progradation (although short-lived) of a tide-dominated delta (Figure 4-24, E). A subsequent fall in relative sea-level created the upper SB, followed by sea-level rise, commencing the deposition of the Grand Rapids Formation hereafter.

Discussion

Clearwater sediments were deposited in the shallow Boreal Seaway during a period of overall third order eustatic sea-level rise called `The Aptian/Albian Clearwater Transgression' (Figure 4-25; Haq *et al.*, 1987; Hien and Cotterhill, 2006). Tectonism-induced increased sedimentation rates during this period were sufficient to overcome the effect of this major transgression. This resulted in transgressive-regressive cycles of relative sea-level fall, regression of the shoreline and progradation of deltaic sediments in the study area. Progradation is believed to have occurred towards the north as sediment was supplied by rivers draining from the south-southwest. During the main deltaic phases of the Clearwater Formation, the shoreline is approximately south-southwest of the study area and oriented east to west/northwest to southeast (Maher, 1989). It

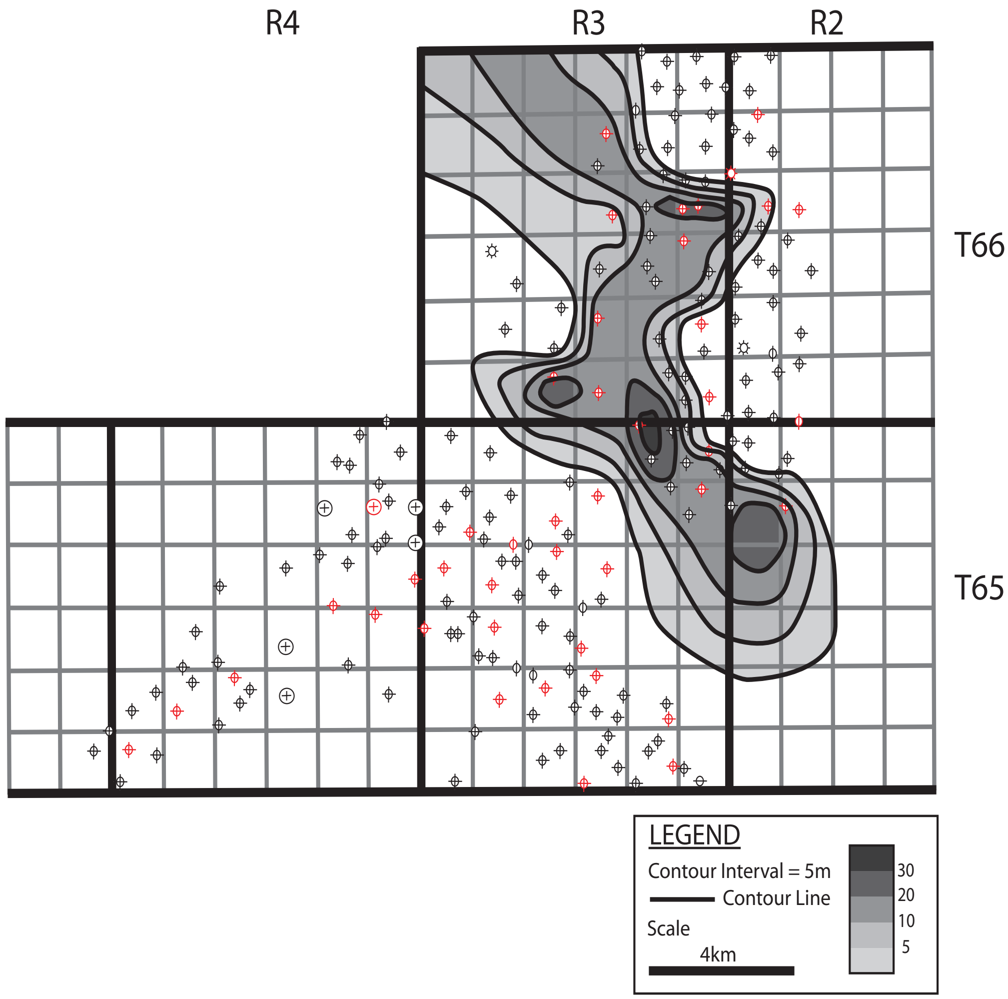

Figure 4-21: Isopach map of Allomember 4 showing the preserved deposition of tide-dominated deltaic sediments inside the extended incised paleovalley.

is unknown how far away the shoreline was during deposition as there is no core evidence of subaerial exposure within the study area.

In the study area, the majority of sediments consist of prodelta to delta front very fine grained muds, silts and sands (FA2), distributary mouth bar, cross-bedded sands (FA3) and inter-bar channel fills (FA4). Correlation of the facies associations and their bounding surfaces (TSEs and SBs) suggests that the Clearwater Formation consists of the Wabiskaw Member and five disconformity-bounded allomembers (Figure 4-24). Each allomember represents a regressional cycle of deposition of tide-dominated deltaic sediment that accumulated when sediment influx exceeded that of relative sea-level rise. A3 reflects the preserved trangressional cycle following the A2 regression, whereas between other regressional cycles, transgression is marked by a transgressive surface of erosion. Each

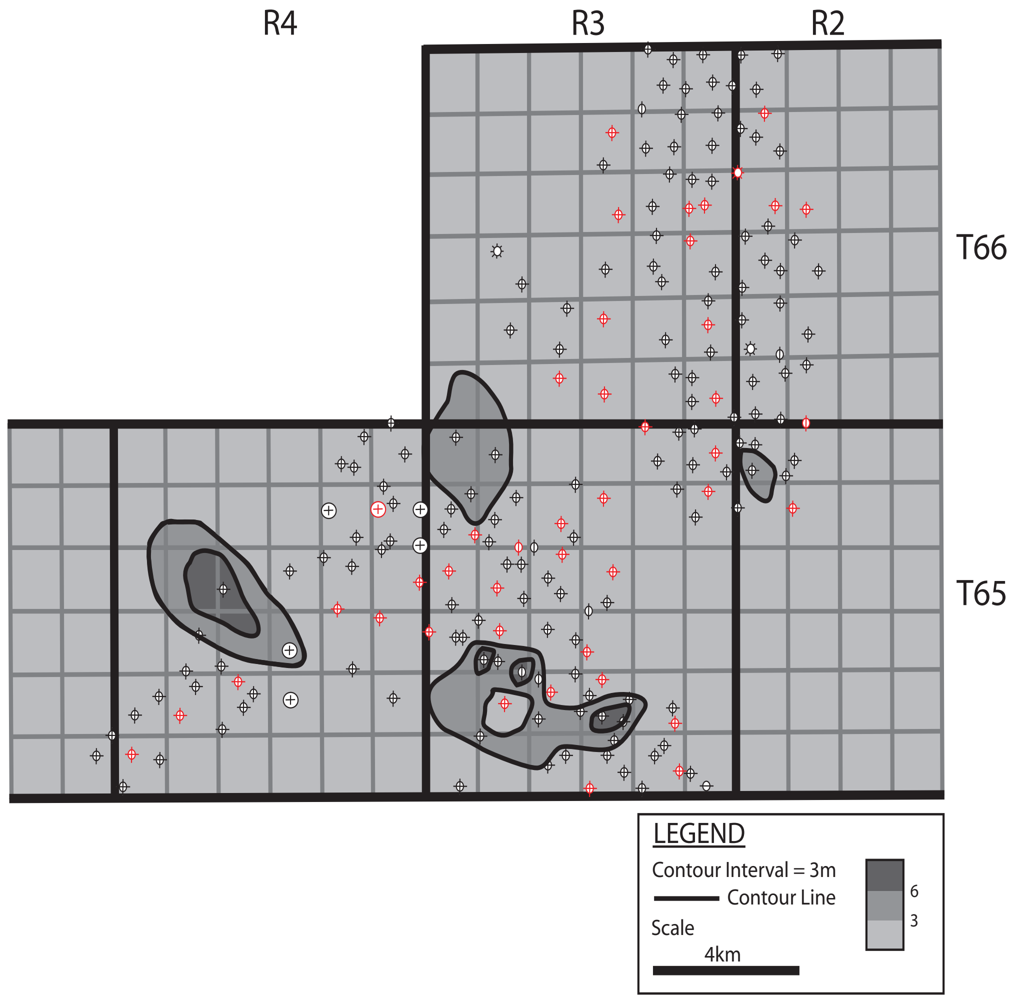

Figure 4-22: Isopach map of Allomember 5 showing the last pulse of progradational tide-dominated deltaic sediments covering the entire study area.

transgressive-regressive cycle most probably represents a smaller scale 4th order relative sea-level fluctuation superimposed on the larger scale 3rd order rise in sea-level (Figure 4-25). Moreover, each succeeding cycle indicates successive progradation of deltaic deposits into the Boreal Sea; despite that deposition of the Clearwater Formation occurred during a long-term relative sea-level rise.

Recognition of tide-dominated deltaic sediments and outlined allostratigraphic units within the Clearwater Formation considerably improves the predictability of quality reservoir material in the Cold Lake area. The highest-quality reservoir material is found in strata comprising FA3 and FA4. In the study area, these strata occur in each allomember (except A3), but make up more of the stratal volume in younger allomembers. Therefore, in A1 the spatial distribution of reservoir material is inferred to exist approximately south of the study area.

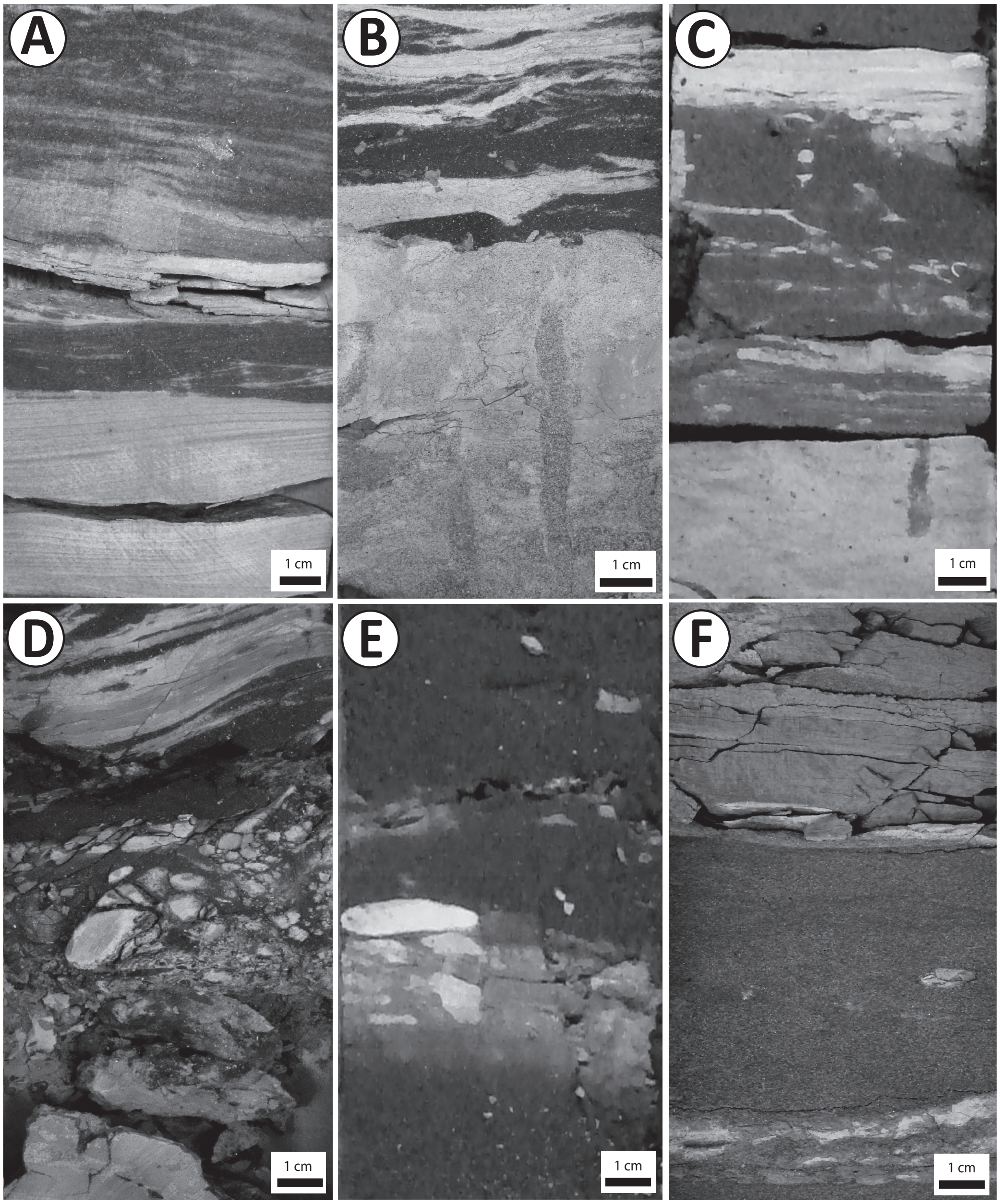

Figure 4-23: Examples of the types of surfaces seen in the Clearwater Formation in Cold Lake. A) Sharp erosive contact between the McMurray Formation and the Wabiskaw member above. Well 06-03-066-03W4. B) Glossifungites trace assemblage at the upper sequence boundary of the Wabiskaw member. Well 04-03-065-03W4. C) Sharp erosive sequence boundary with Glossifungites trace fossil assemblage associated with the incised paleovalley in Allomember 3. Well 10-27-066-03W4. D) Chert-pebble transgressive lag deposit associated with a transgressive surface of erosion between Allomember 3 and Allomember 4. Well 11-10-066-03W4. E) Transgressive surface of erosion showing a thin pebble lag deposit. Facies below are typically proximal tidal bar and tidal channel deposits, whereas, the facies above are muddier with biotubation levels and types of trace fossils increasing an becoming more marine in character showing an abrupt deepening of the water column. Well 07-01-065-03W4. F) Sharp erosive boundary between the Clearwater Formation and Grand Rapids Formation, shows an deepening of facies as the Grand Rapids in the study area is typically very muddy with a diverse marine assemblage associated with it. Well 11-06-065-04W4.

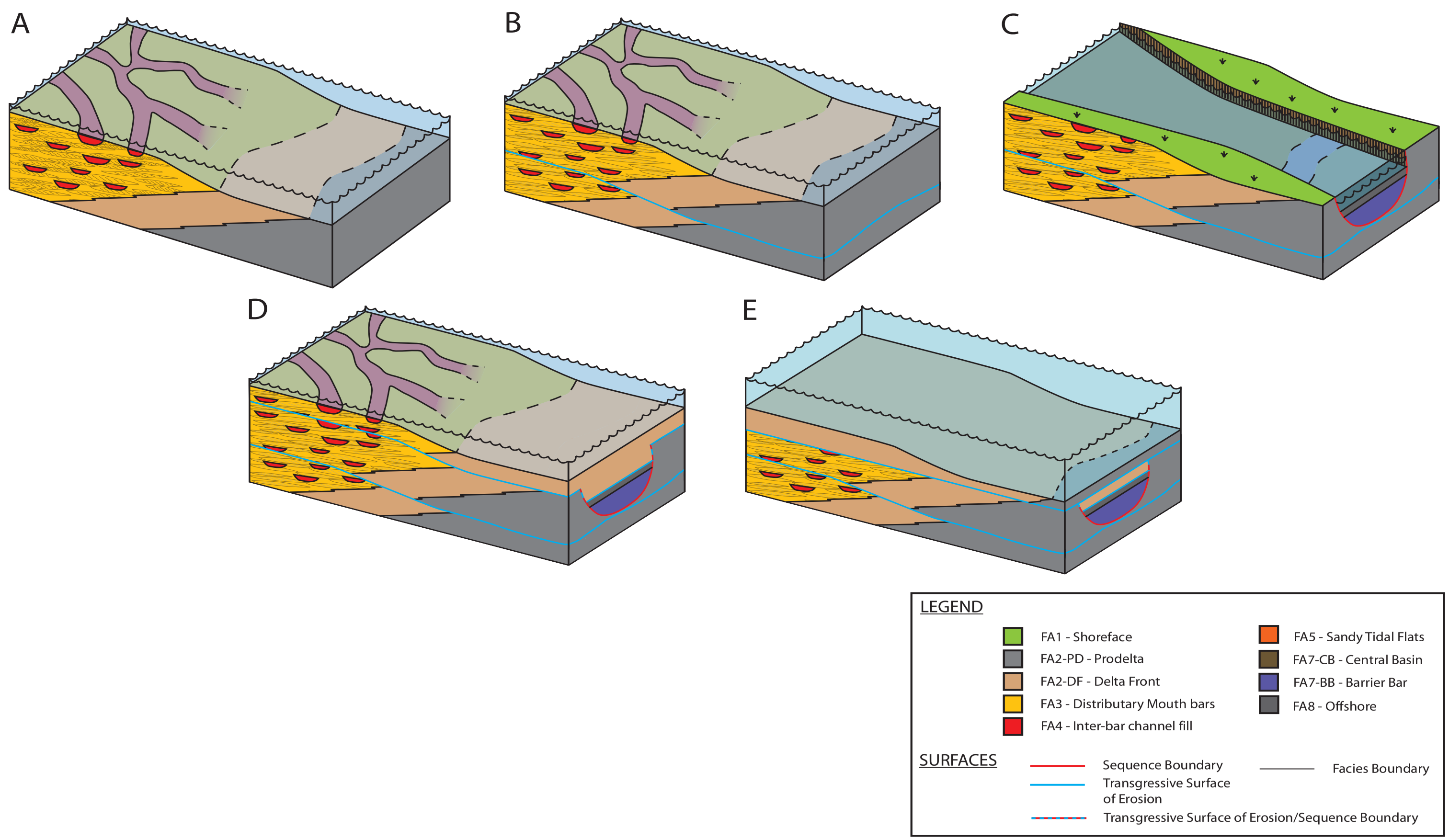

Figure 4-24: Schematic representations of the evolution of the Clearwater Formation in Cold Lake. A) Allomember 1 – Rate of sedimentation > rate of transgression, initiates progradation of tide-dominated sediments across the study area. First major transgression at the end of Allomember 1 creates a transgressive surface of erosion. B) Allomember 2 – Rate of sedimentation > rate of transgression, initiates progradation of tide-dominated sediments across the study area. Major regression at the end of Allomember 2 creates an incised paleovalley bounded below by a sequence boundary. C) Allomember 3 – Rate of transgression > rate of sedimentation, initiates retrogradation of estuarine facies infilling paleovalley in the northern half of the study area. Major transgression

Figure 4-24 continued: at the end of Allomember 3 creates a transgressive surface of erosion. D) Allomember 4 – Rate of sedimentation > rate of transgression, initiates progradation of tide-dominated sediments across the study area. Major transgression at the end of Allomember 4 creates a transgressive surface of erosion. E) Allomember 5 – Rate of sedimentation > rate of transgression, initiates a final phase of progradation of tide-dominated sediments across the study area. A subsequent fall in sea-level creates a SB followed by a major transgression that ends deposition of the Clearwater Formation and deposition of the Grand Rapids Formation begins.

Additionally, in A2, the thickest deposits of reservoir material occurred towards the eastern side of the study area (Figure 4-19), it is suggested that further reservoir material is to be found east of the study area. Furthermore, additional reservoir material in younger allomembers would also exist south of the study area when considering Dalrymple and Choi's (2007) tide-dominated deltaic model.

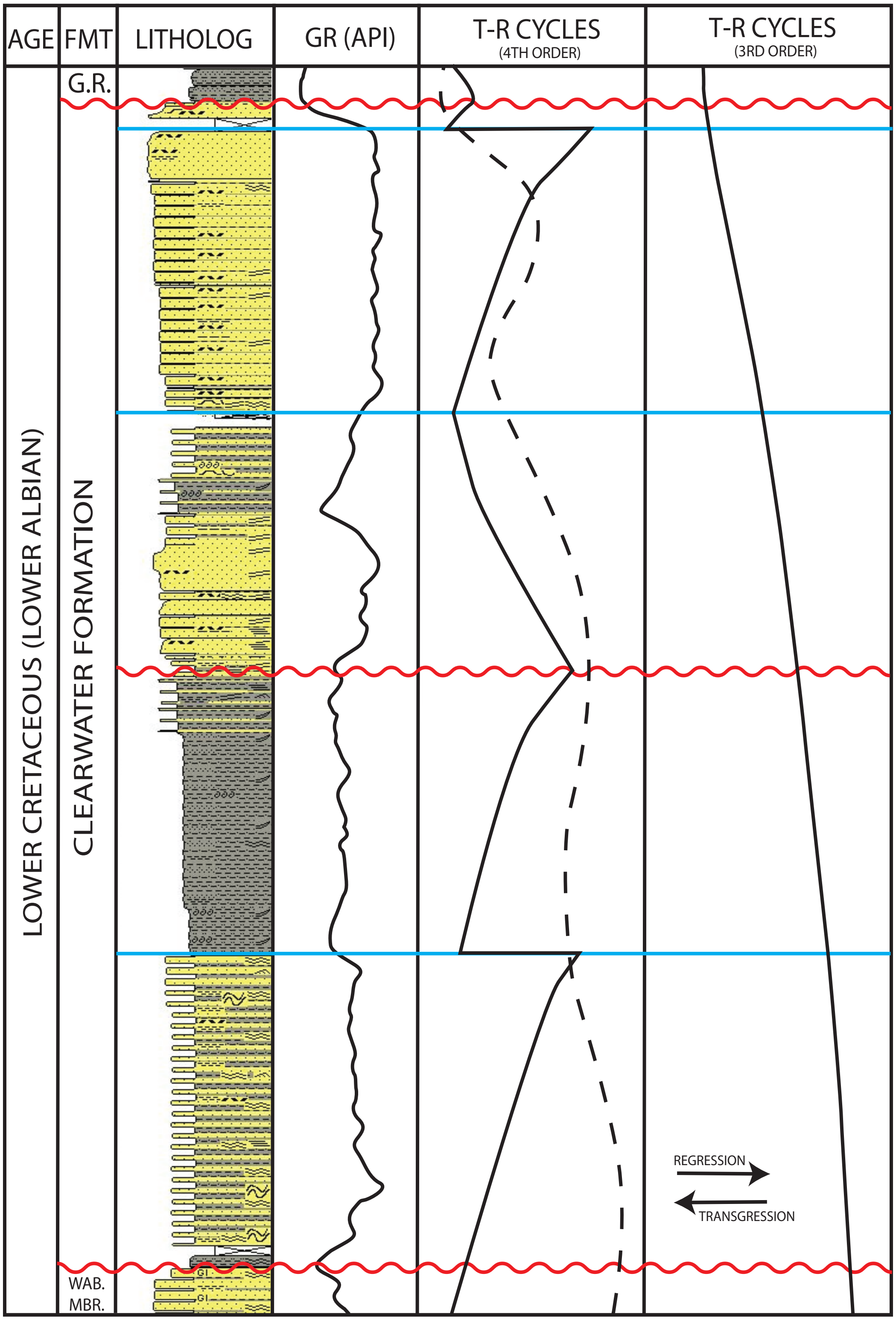

Figure 4-25: Third order and fourth order transgressive-regressive cycles observed in the Clearwater Formation. Third order curve and dashed fourth order curve from Haq et al., 1987. Fourth order solid curve interpreted through this study. Wavy red lines – SBs; Blue solid lines – TSEs; G.R. – Grand Rapids Formation; Lithology and Gamma Ray (GR) – well 10-27-066-03W4.

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Chapter 5
Summary and Conclusions

This thesis examines the sedimentological, ichnological and stratigraphic characteristics of the Clearwater Formation in the Cold Lake oil sands deposit in east central Alberta. The primary objectives of this study were to redefine and describe/interpret facies and facies relationships along with a detailed analysis on the ichnology within the Clearwater Formation. These observations led to the determination of the lateral and vertical extent of these facies and ultimately the development of a depositional model and stratigraphic framework to characterise the Clearwater Formation. Overall, this research contributes to the geologic understanding of the complex nature under which Aptian-aged strata was deposited in the Western Canada Sedimentary Basin. The first contribution is an alternative paleoenvironmental interpretation of the Clearwater Formation than is currently used to characterise the deposit. The second concerns the application of ichnology which supports the reevaluation of the paleoenvironmental anaylsis and provides a preliminary ichnological framework in which to recognize tidally dominated strata. Lastly, an alternative stratigraphic model/framework was developed using an allostratigraphic approach for reservoir characterization. The data and interpretations from these aspects provide valuable insights for exploration and production of oil sands within this interval.

Regional Geology and Controls on Sedimentation

On the eastern margin of the Western Canada Sedimentary Basin (WCSB), deposition of the Clearwater Formation within the Mannville Group was a result of a number of events prior to and during the early Cretaceous. As a result of major tectonism in the West during the Columbian orogeny, development of the foreland basin began in the mid-Jurassic (Armstrong and Ward, 1993). This, combined with major episodes of subsidence of eroded sediments which accumulated in a large wedge on the frontal ranges of the Rockies, led to the asymmetrical configuration of the basin (Hayes *et al.*, 1994). Erosion continued throughout the Cretaceous, with a significant increase in tectonism during the late Aptian/early Albian, providing the immature, volcanic-rich detritus deposited on the eastern margin as Clearwater sediments (Armstrong and Ward, 1993, Hayes *et al.*, 1994).

Deposition on the eastern margin was largely controlled by the inundation of the Boreal sea from the north, resulting in the development of marine and marginal-marine conditions in east-central Alberta. Some structural features that controlled the paleogeography of Mannville Group sediments include: (1) the asymmetrical configuration of the WCSB with the development of a foredeep trough and hingeline on the eastern flank; (2) the Athabasca Anticline, located on the eastern margin of the basin; and (3) the development of an eastern low (Harrison *et al.*, 1981, Jackson, 1984, Hayes *et al.*, 1994).

Paleoenvironmental Reconstruction and Ichnological Framework

Clearwater sediments were deposited near the edge of the Boreal sea during its inundation into western Canada during the Cretaceous. Chapter 2 develops a facies classification scheme based on sedimentological and ichnological criteria. Identification of eleven facies, organized into seven facies associations gave rise to the interpretation that the strata was predominately deposited in a tide-dominated deltaic environment. Recognition of a tide-dominated deltaic setting in the Clearwater Formation included recognition of tidally influenced sedimentary structures such as oppositely dipping ripple laminations, abundant mud intraclasts, mud drapes, and heterolithic bedding. A progradational stacking pattern observed in the Clearwater Formation indicates deltaic sedimentation, rather than a retrogradational pattern seen in estuarine systems (Dalyrmple and Choi, 2007; Carmona *et al.*, 2009).

Sedimentological characteristics of tide-dominated settings are well documented; however, ichnology and trace fossil identification is poorly understood (Dalyrmple and Choi, 2007; Carmona *et al.,* 2009). Many authors identify various trace fossils seen in core and outcrop, but fail to interpret the implications that these assemblages have to the identification of the depositional environment. Within the Clearwater Formation, the trace fossil assemblages have been documented by Bradley and Pemberton (1992) and briefly by Wickert (1992) and more recently Feldman *et al.* (2008) as part of a larger sedimentological analysis.

Chapter 3 addresses the ichnology observed in the Clearwater Formation and the implications trace fossils have on the tide-dominated deltaic interpretation. Four core were chosen to represent the study area and the ichnology seen in the tidally dominated strata of the Clearwater Formation (07-28-065-03W4; 15-21-065-03W4; 12-29-065-02W4 and 10-27-066-03W4). Following this analysis, a number of characteristics were observed, including: (1) diversity and abundance of trace fossils is typically moderate to high below low tide (BI 2-6).

Above low tide the diversity and abundance dramatically decreases due to high water turbidity and constantly migrating large-scale bedforms (tidal sand bars/ ridges), which pose problems for infaunal colonization (Pemberton and MacEachern, 2006; Dalyrmple and Choi, 2007); (2) bioturbation levels are typically high, but can be quite variable laterally. This is because tides constantly change the dynamics of the system both seasonally and diurnally, especially with small scale salinity fluctuations (Dalyrmple and Choi, 2007); (3) trace fossils are typically larger in size than in their counterparts in typical brackish-water environments, but smaller than seen in fully marine conditions (Carmona *et al.,* 2009); (4) Traces develop robust, more complex structures (i.e. large *Teichichnus* or *Rhizocorallium*) as well as simple structures (i.e. *Planolites* and *Thalassinoides*), but are less abundant than in normal lower shoreface/upper offshore settings (Pemberton and MacEachern, 2006); and (5) the trace fossil assemblage is dominated by an impoverished *Cruziana* ichnofacies, displaying a range of fully marine traces (i.e. *Scolicia*, *Siphonichnus*, and *Rhizocorallium*). In summary, the trace-fossil suites developed in prodelta and lower delta front sediments show low to moderate diversities and moderate to high abundance of ichnofauna reflecting an impoverished *Cruziana* ichnofacies. Ichnodiversity levels within the tide-dominated deltaic Clearwater sediments are higher than those of a bay-head delta in a typical estuarine setting, which usually experiences strong salinity dilution (McIlroy, 2007; Carmona *et al.,* 2009). This suggests that this prograding, tidally dominated body was part of a deltaic system and not the bay-head delta of a transgressive estuarine system. The above characteristics form a preliminary ichnological framework, when used with caution as tide-dominated settings can be dynamic, can be applied to similar case studies.

Stratigraphic Framework

Clearwater sediments were deposited in the shallow Boreal Seaway during a period of overall third order eustatic sea-level rise called `The Aptian/Albian Clearwater Transgression' (Haq *et al.*, 1987; Hien and Cotterhill, 2006). Increased tectonism on the fold and thrust belt to the west resulted in episodic pulses of increased sedimentation rates during this period that were sufficient enough to overcome the effect of this major transgression. This resulted in a series of transgressive-regressive cycles of relative sea-level rise and fall, regression of the shoreline and progradation of deltaic sediments in the study area.

Chapter 4 redefines the stratigraphic framework and subdivides the

Clearwater Formation using a time-stratigraphic or allostratigraphic approach rather than stratigraphic schemes exclusively based on a lithostratigraphic correlation or sequence stratigraphy. The Clearwater Formation is subdivided into five allomembers - each allomember represents a genetically related package of interstratified sandstones, silts and shales separated by widespread bounding discontinuities (Trangressive Surfaces of Erosion/Sequence Boundaries; NACSN, 1983). Each allomember also takes into consideration eustatic sea-level change. Each allomember represents a regressional cycle of deposition of tide-dominated deltaic sediment that accumulated when sediment influx exceeded that of relative sea-level rise. A3 reflects the preserved trangressional cycle following the A2 regression, whereas between other regressional cycles, transgression is marked by a transgressive surface of erosion. Each transgressive-regressive cycle most likely represents a smaller scale 4th order relative sea-level fluctuation superimposed on the larger scale 3rd order rise in sea-level. Moreover, each succeeding cycle indicates successive progradation of deltaic deposits into the Boreal Sea, despite that deposition of the Clearwater Formation occurred during a long-term relative sea-level rise.

Modern Analogue for the Clearwater Formation

The Fly River delta in Papua New Guinea provides an excellent modern analogue for this study, in terms of geological setting, mineralogy and sedimentology (Dalymple *et al.,* 2003). Dalyrmple *et al.* (2003) detailed the geomorphology and sedimentology of the Fly River delta and concluded that it is tidally dominated. Similar to the deposition of the Clearwater sediment, Fly River delta sediments are sourced from a fold- and thrust belt and are deposited in a low gradient, foreland basin. Mineralogy is thought to be also similar as Fly River is dominated by immature quartz, lithic fragments, plagioclase feldspar, pyroxene, and hornblende (Dalyrmple *et al.*, 2003). Moreover, as possibly more consequential, is the similarity in facies and facies association descriptions provided by Dalrymple *et al.* (2003) in the subaqueous portion of the Fly River delta. Their descriptions and interpretations of mouth bar sands, delta front, and prodelta regions of the Fly River Delta are analogous to facies associations 2-4 in the Clearwater Formation. The stratigraphic evolution of the Fly River Delta is also comparable, as most allomembers identified in the Clearwater Formation were formed during a transgressive systems tract/early highstand, presumably due to high sediment discharge which initiated progradation.

Conclusion

The Clearwater Formation within the Cold Lake oil sands area has a proven vast resource potential of 672 million barrels (http://www.imperialoil.ca/Canada-English/about_what_upstream_produce.aspx). The distribution of the hydrocarbons within the Clearwater Formation is, for the most part, related to primary facies distribution of the reservoir quality sandstones. Sandstone geometry and quality are related to the primary depositional, and to a lesser extent, post-depositional processes. These depositional processes directly affected the distribution of facies and reservoir properties of the different depositional facies. The recognition of cyclic tide-dominated deltaic sedimentation driven by a combination of allocyclic and autocyclic processes significantly increases the predictability of depositional environments and distribution of reservoir quality sandstone. A thorough understanding of this dynamic environment and the complex distribution of the facies and ichnology present within tide-dominated deltaic systems will facilitate more accurate models to effectively develop the vast resource potential contained within the strata of the Clearwater Formation.

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Multifaceted Ichnology. SEPM Special Publication, vol. 88, pp. 195–211.

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APPENDIX A

LEGEND

LITHOLOGY

- sand/sandstone
- silty sand
- shale/mudstone
- sandy shale
- silty shale
- lost core

CONTACTS

- sharp
- uncertain
- erosional
- bioturbated

PHYSICAL SEDIMENTARY STRUCTURES

- current ripples
- low angle bedding
- flaser bedding
- oscillatory ripples
- fault
- planar tabular bedding
- wavy parallel bedding
- climbing ripples
- high angle tabular beding
- hummocky cross-strat.
- trough cross-bedding
- double mud-drapes
- herringbone cross-strat.
- convolute bedding
- biogenically homogenized
- synaeresis cracks
- xxxxxx tight zone

LITHOLOGICAL ACCESSORIES

- sand lamina
- silt lamina
- shale lamina
- Sid siderite
- rip-up clasts
- coal fragments
- pebbles/granules
- Gl glauconite
- Wd wood fragments
- coal lamina
- breccia horizon
- shell fragments
- Py pyrite

TRACE FOSSILS

- *Paleophycus*
- *Cylindrichnus*
- *Rosselia*
- *Teichichnus*
- *Skolithos*
- *Diplocraterion*
- bioturbation
- *Siphonichnus*
- *Thalassinoides*
- *Zoophycus*
- *Planolites*
- *Helminthopsis*
- *Arenicolites*
- *Rhizocorrallium*
- *Asterosoma*
- *Chondrites*
- *Scolicia*
- *Phycosiphon*

STAIN

- Excellent
- Very Good
- Good
- Fair
- Poor
- Nil

BIOTURBATION

- Abundant
- Common
- Moderate
- Rare
- Barren

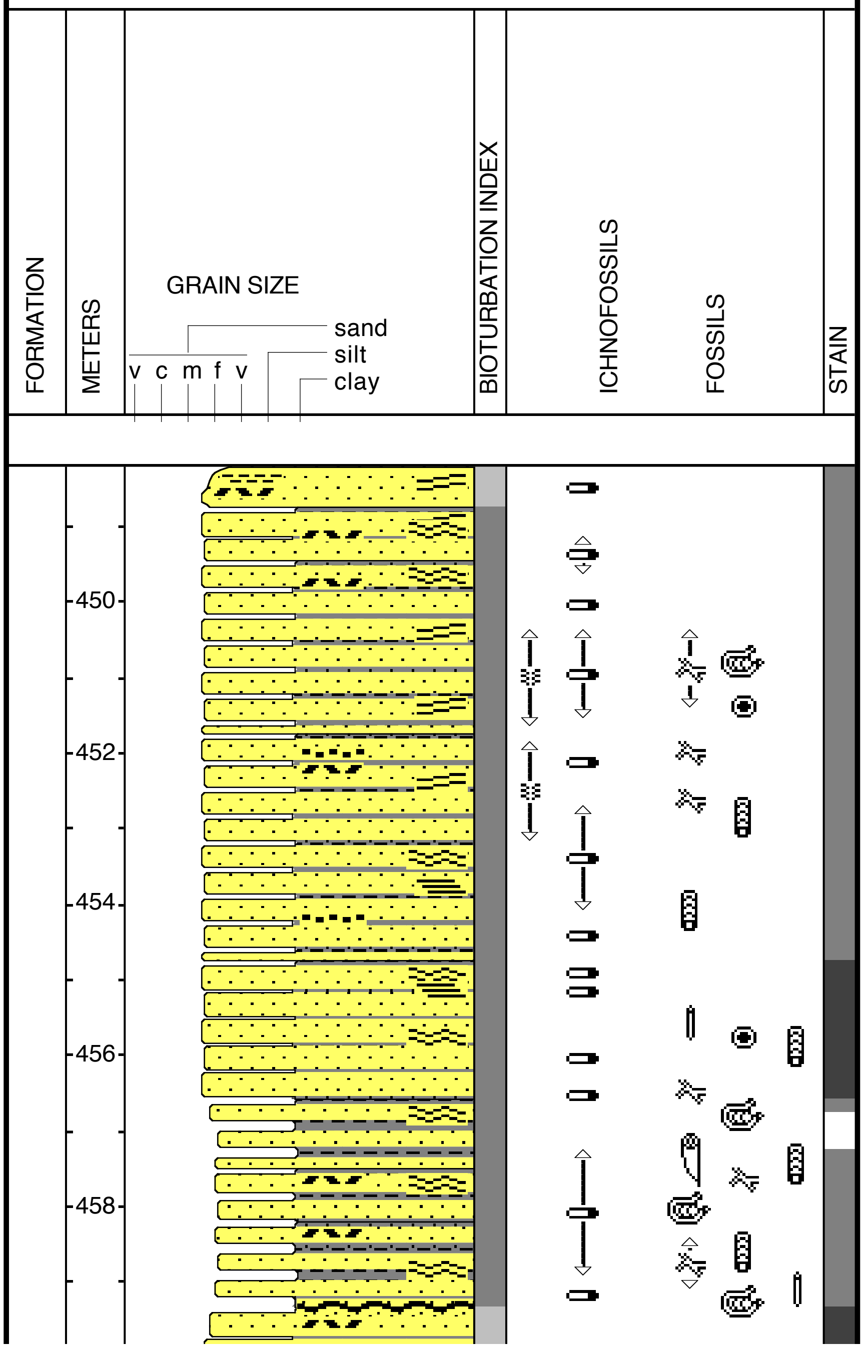
IMP 03 OV COLD LK

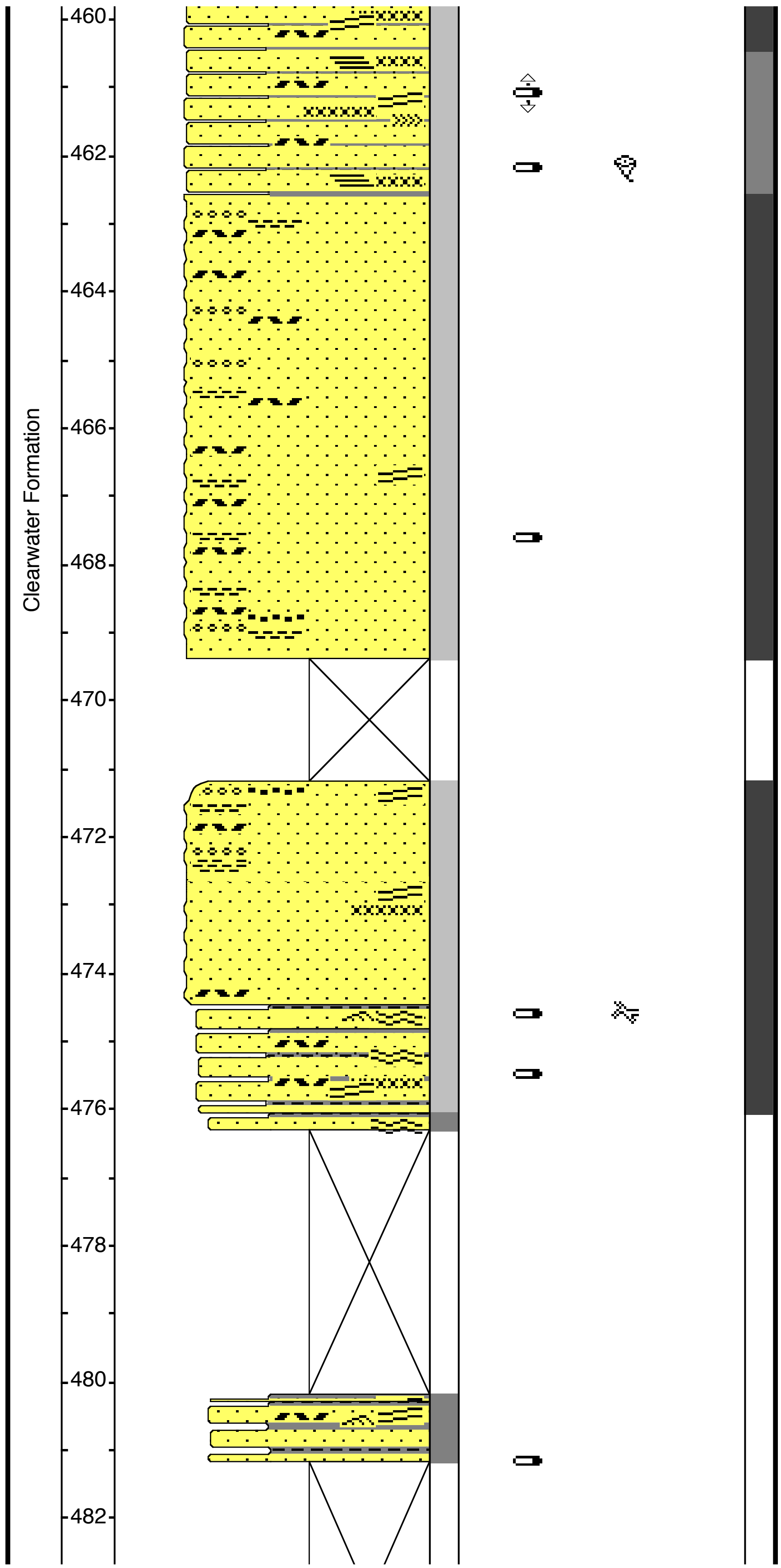
01-11-065-03w4

Date Logged: October 7th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, recovery ok, missing core 4 and 5 and core 7 box 3




Clearwater Formation
460
462
464
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474
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478
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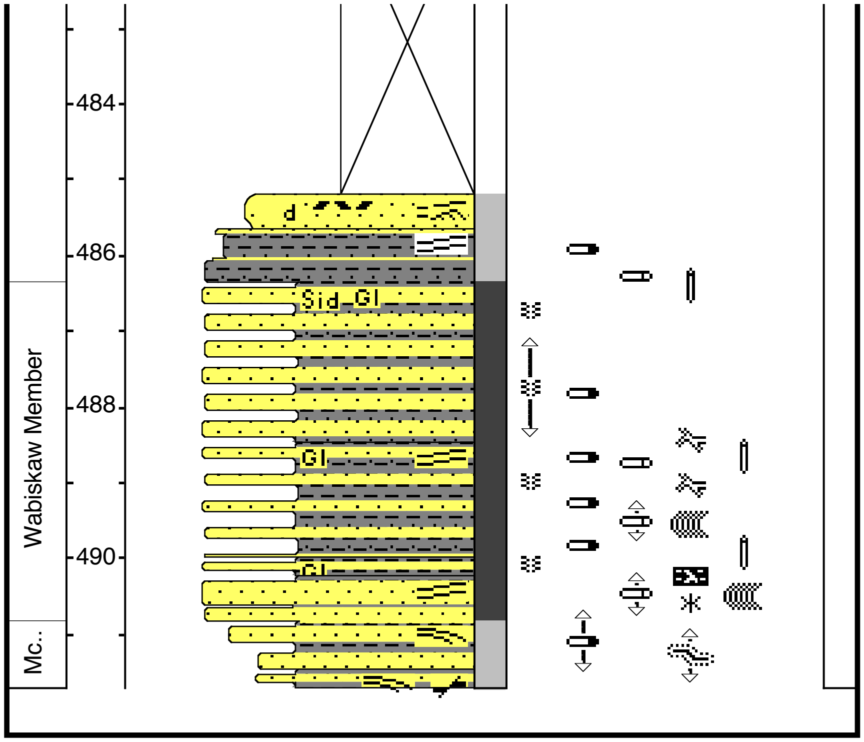
482



484
486
488
490
Wabiskaw Member
Mc..
Sid Gl
Gl

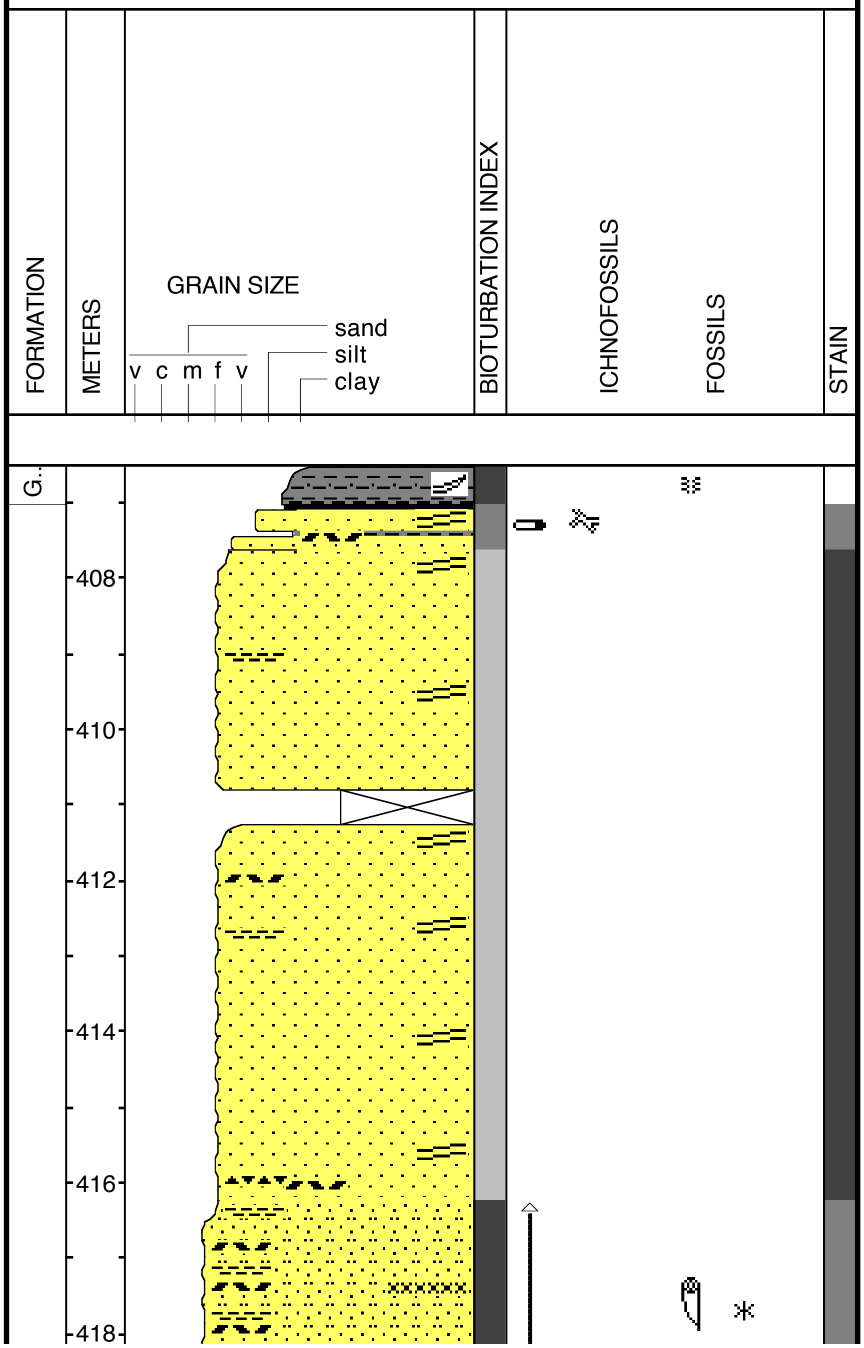
IMP 06 OV COLD LK

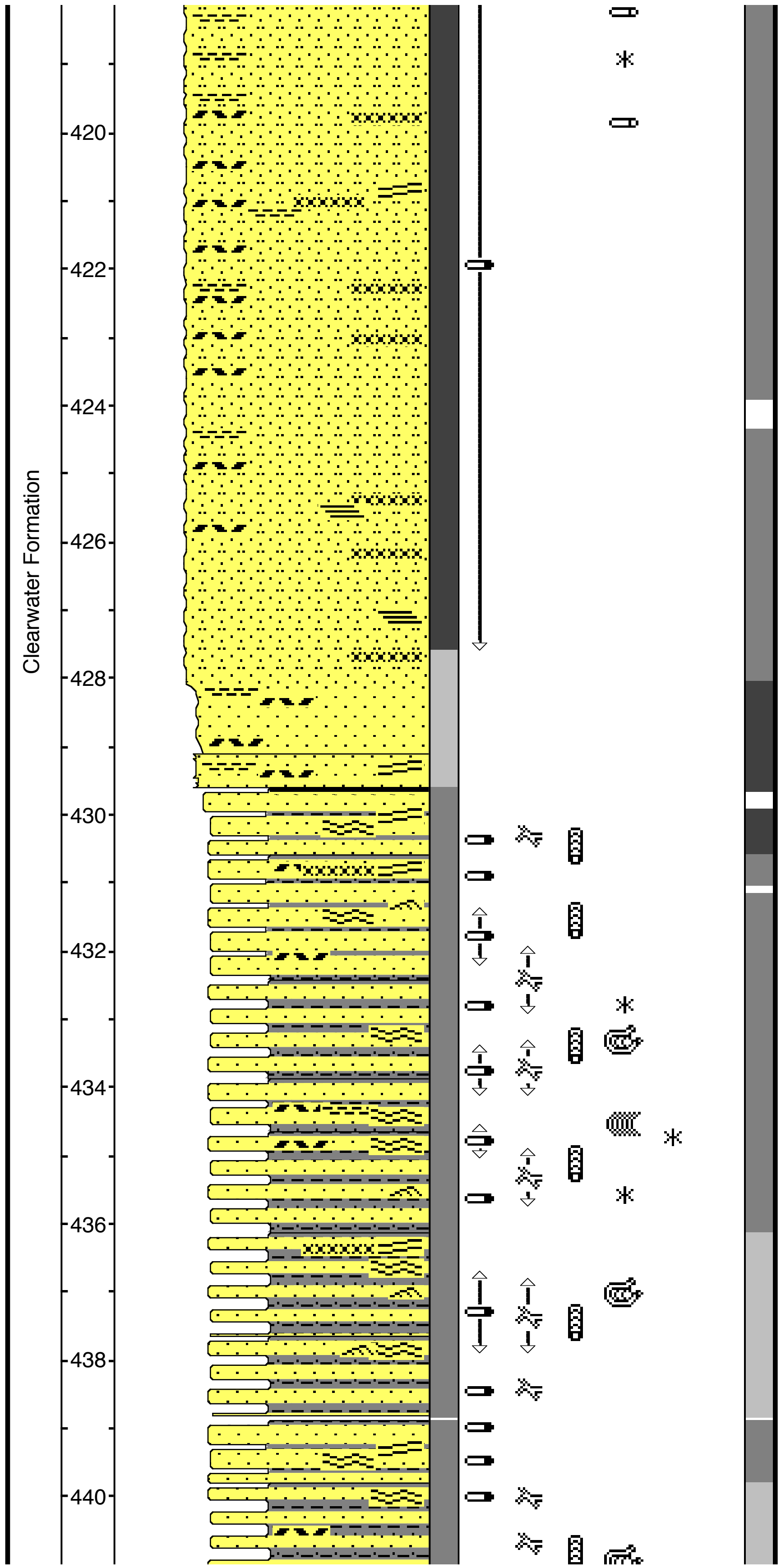
01-29-065-03w4

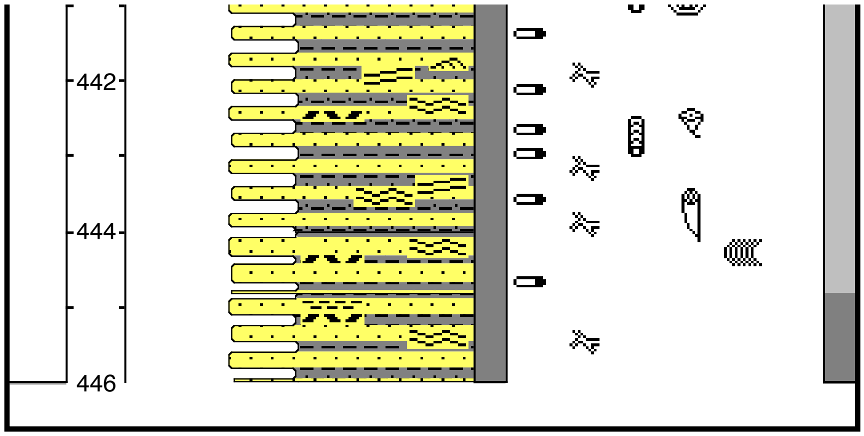
Date Logged: October 1st, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, good recovery.




Clearwater Formation
420
422
424
426
428
430
432
434
436
438
440


442
444
446

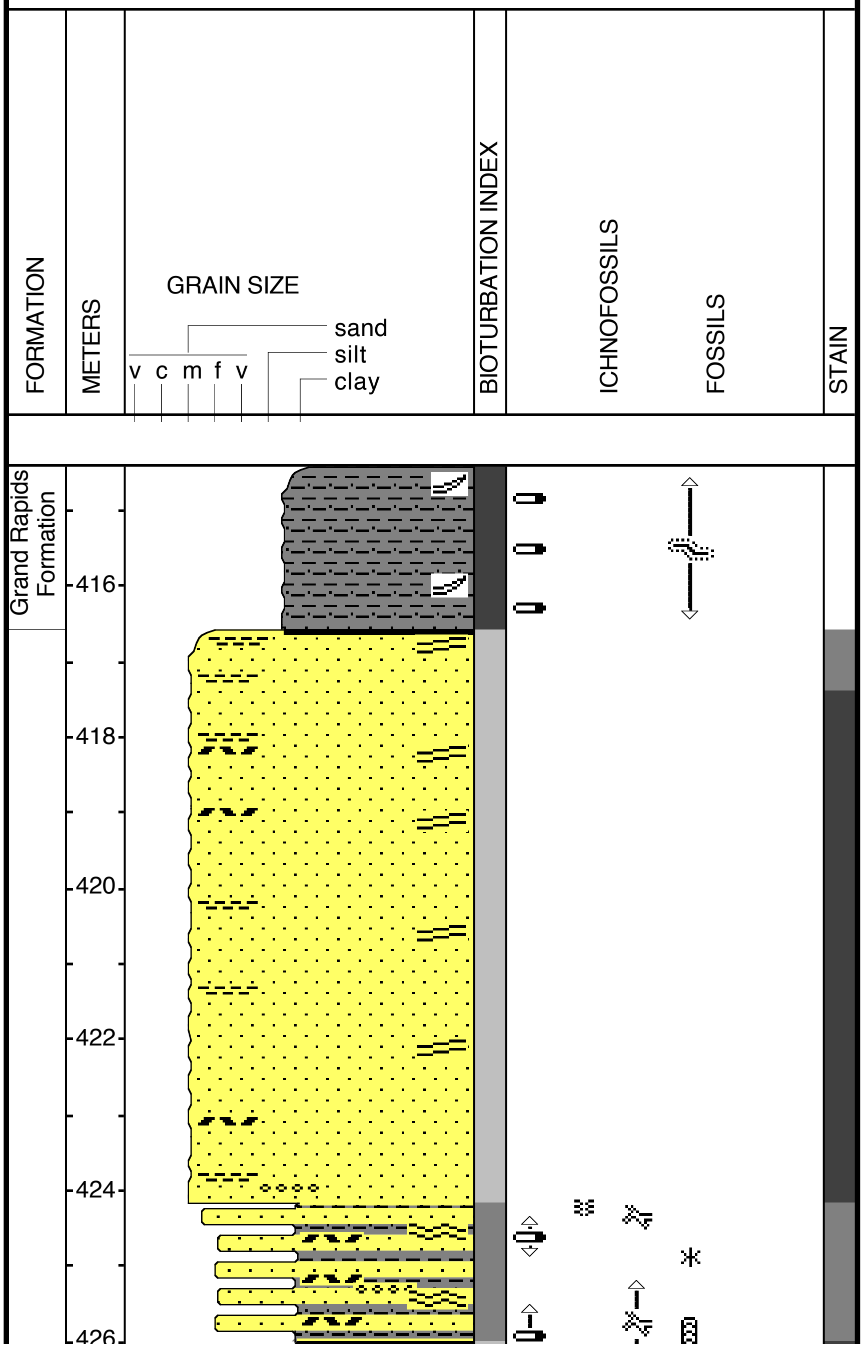
IMP 06 OV COLD LK

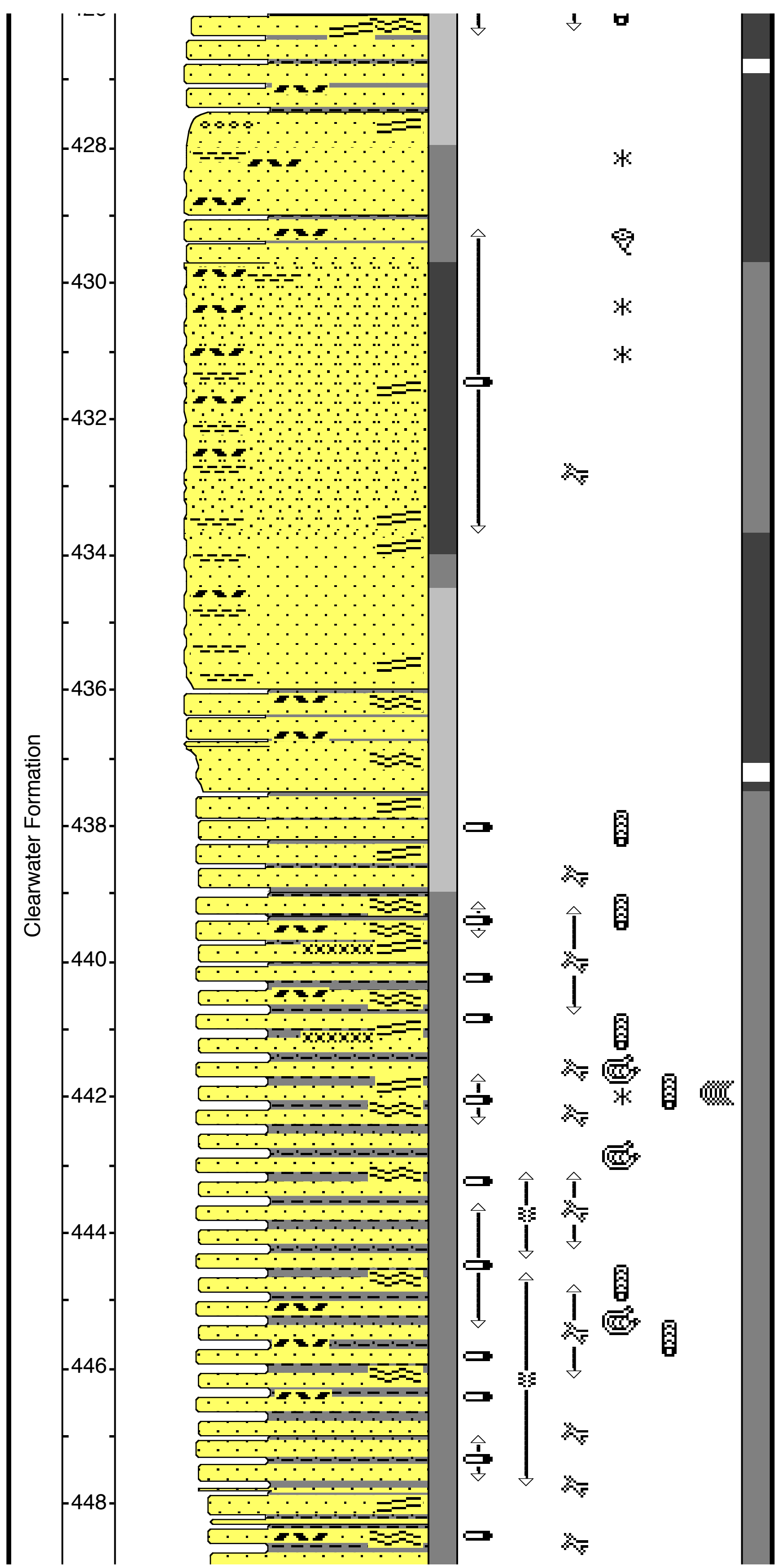
01-30-065-03w4

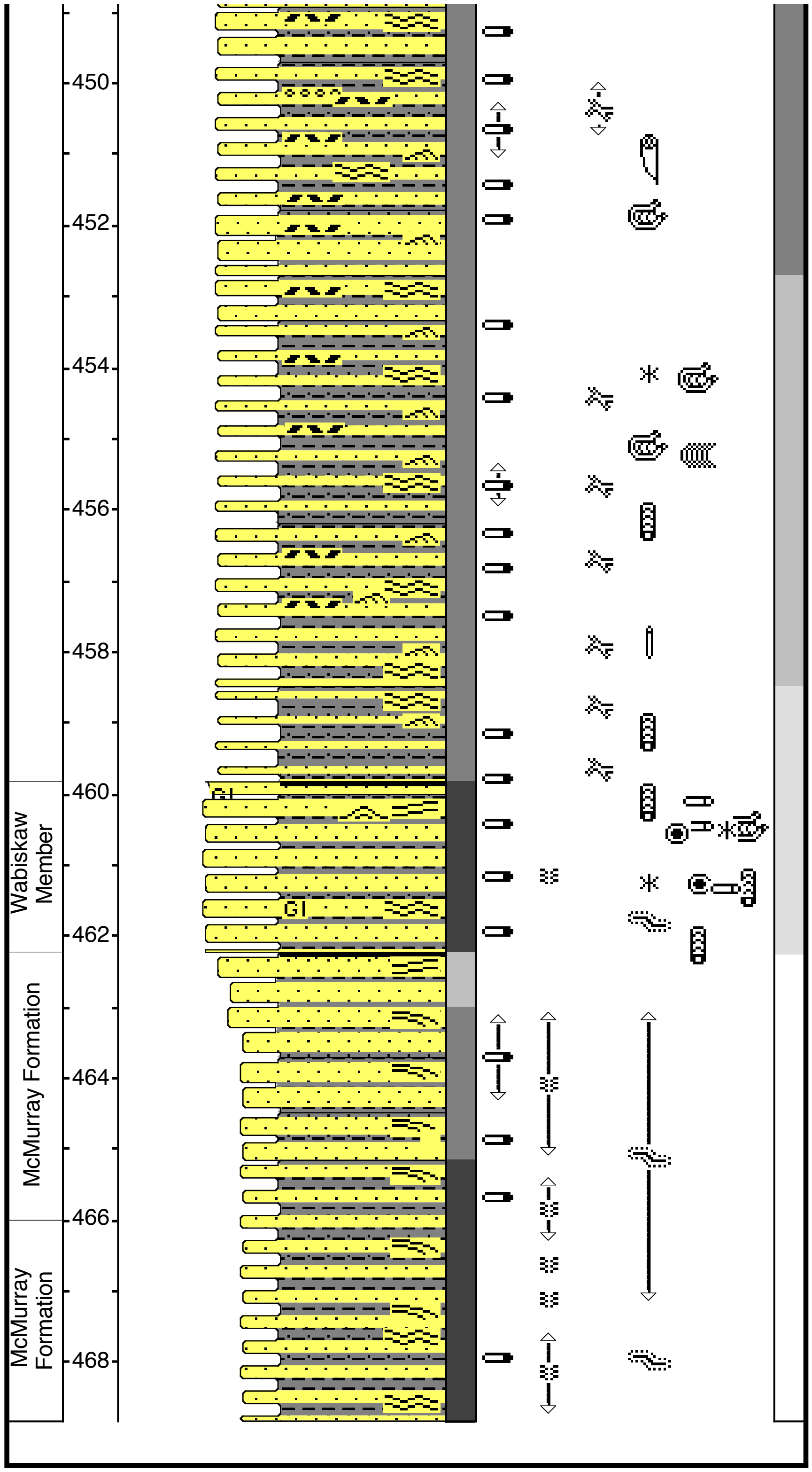
Date Logged: October 2nd, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery




Clearwater Formation
-428
-430
-432
-434
-436
-438
-440
-442
-444
-446
-448


450
452
454
456
458
460
462
464
466
468
GI
Wabiskaw Member
McMurray Formation
McMurray Formation

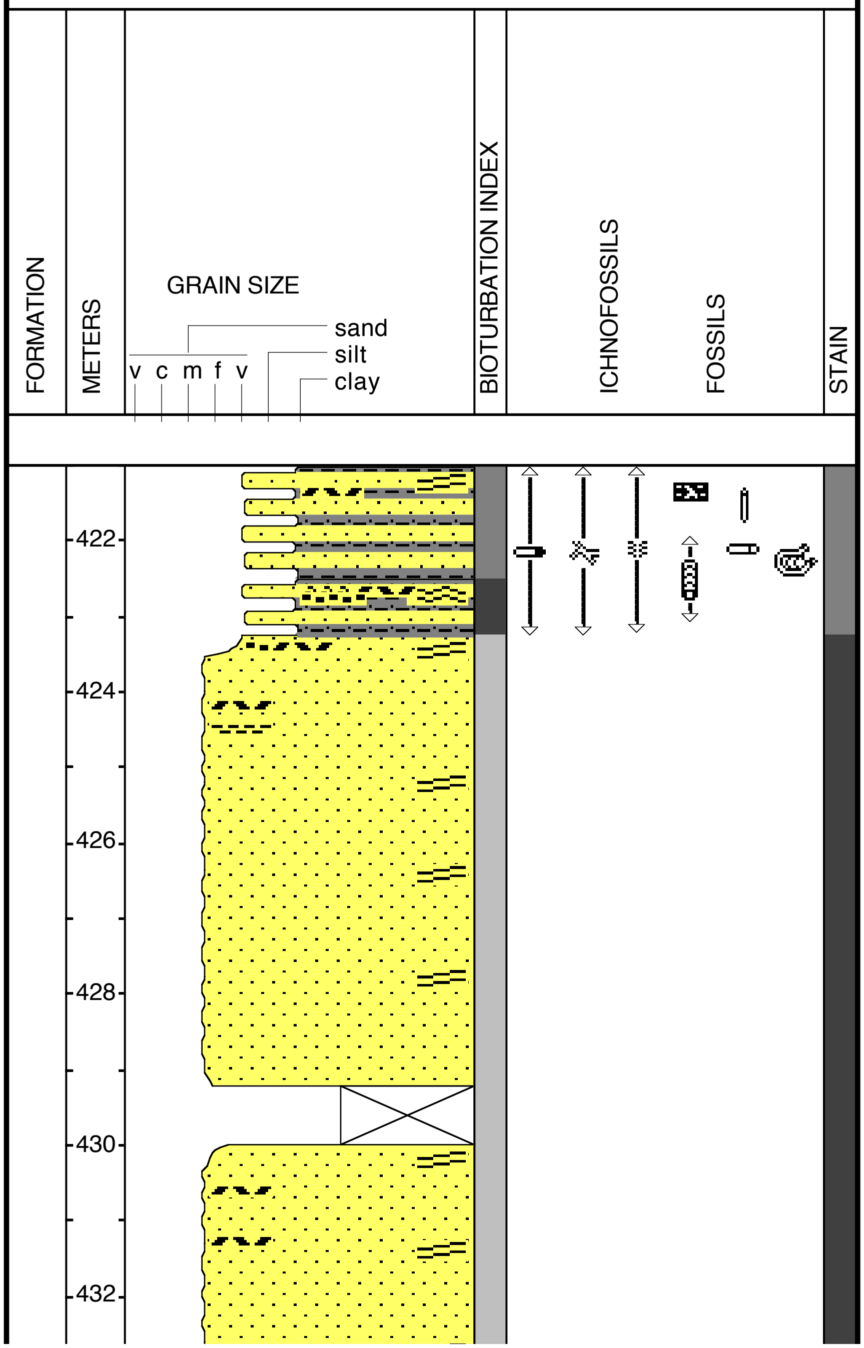
ESSO 87 COLD LK OV 3-23

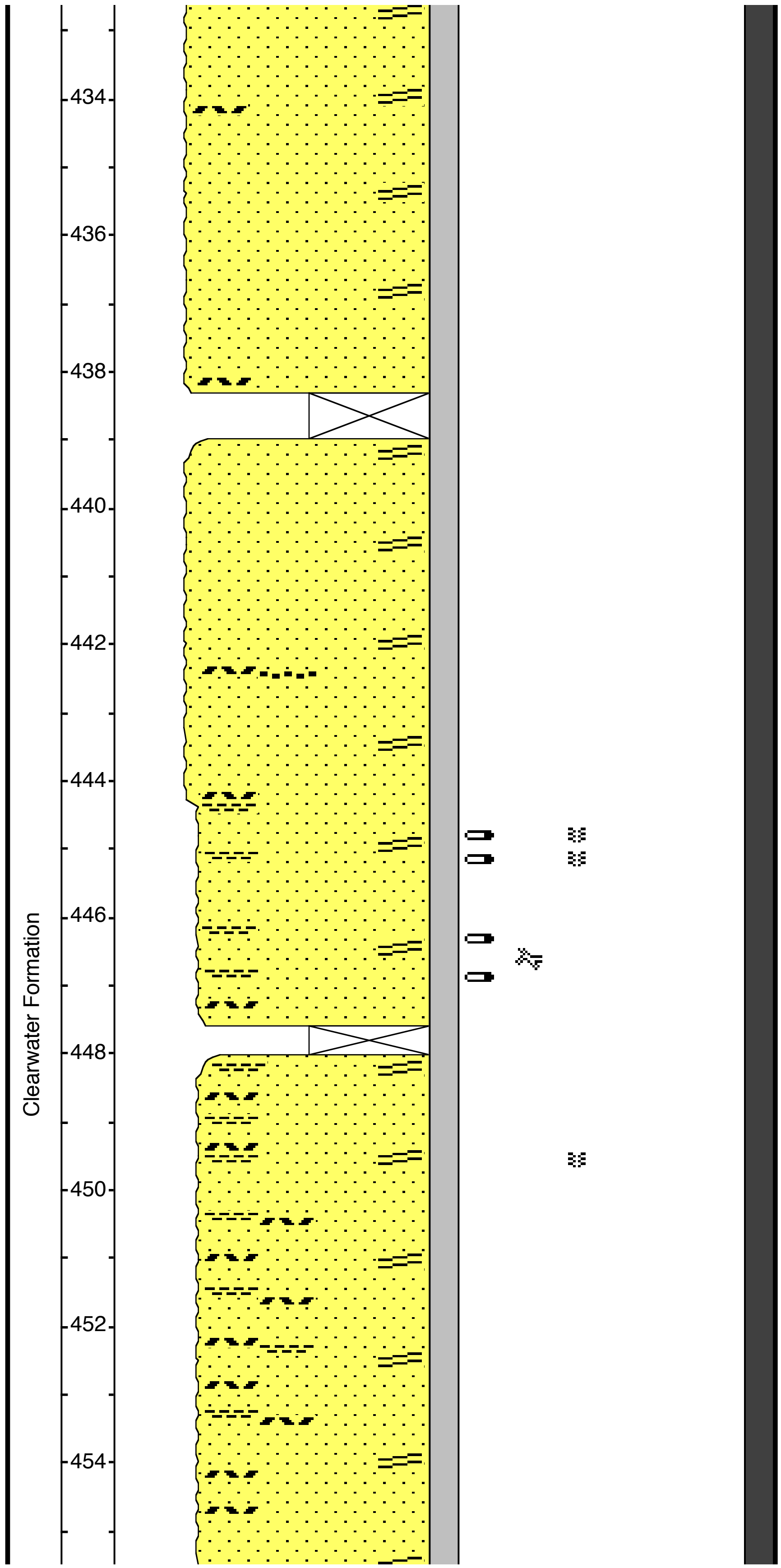
03-23-065-04w4

Date Logged: November 25th, 2009

Logged by: Carolyn Currie

Remarks: 2.5" slabbed core, oil saturated, good recovery, no Mc Murray or Grand Rapids above




Clearwater Formation
434
436
438
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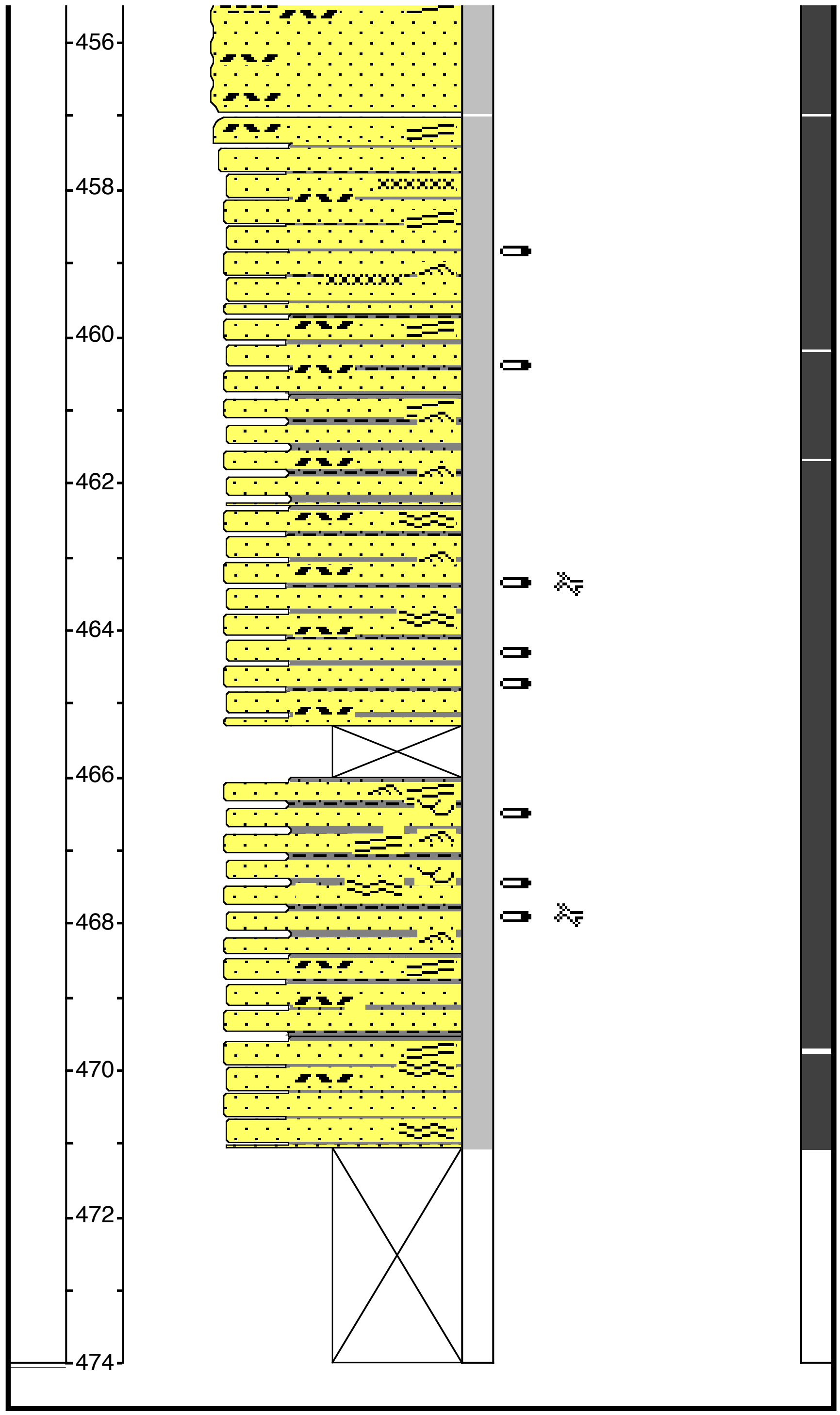
448
450
452
454


456
458
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462
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466
468
470
472
474

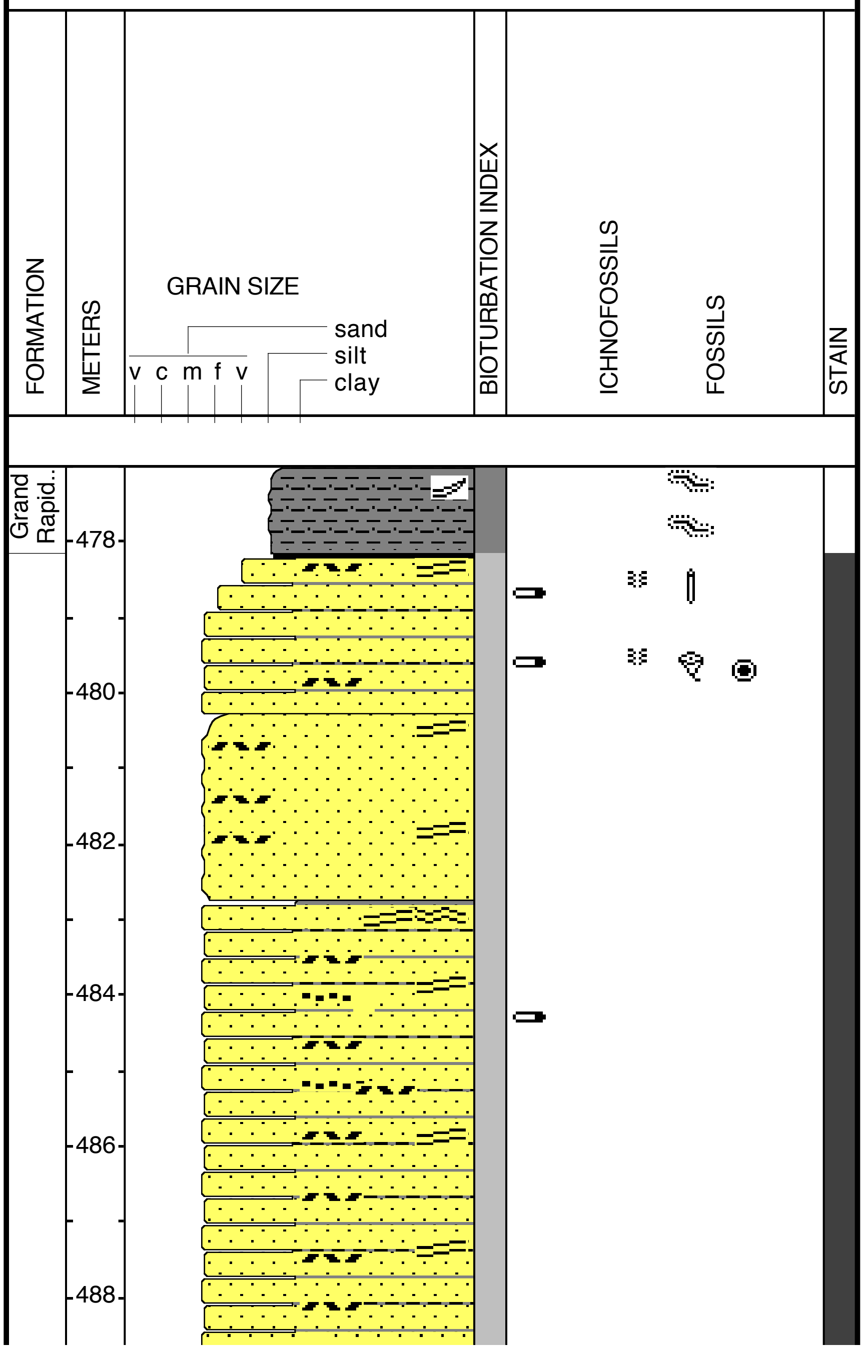
IMP 95 OV COLD LK

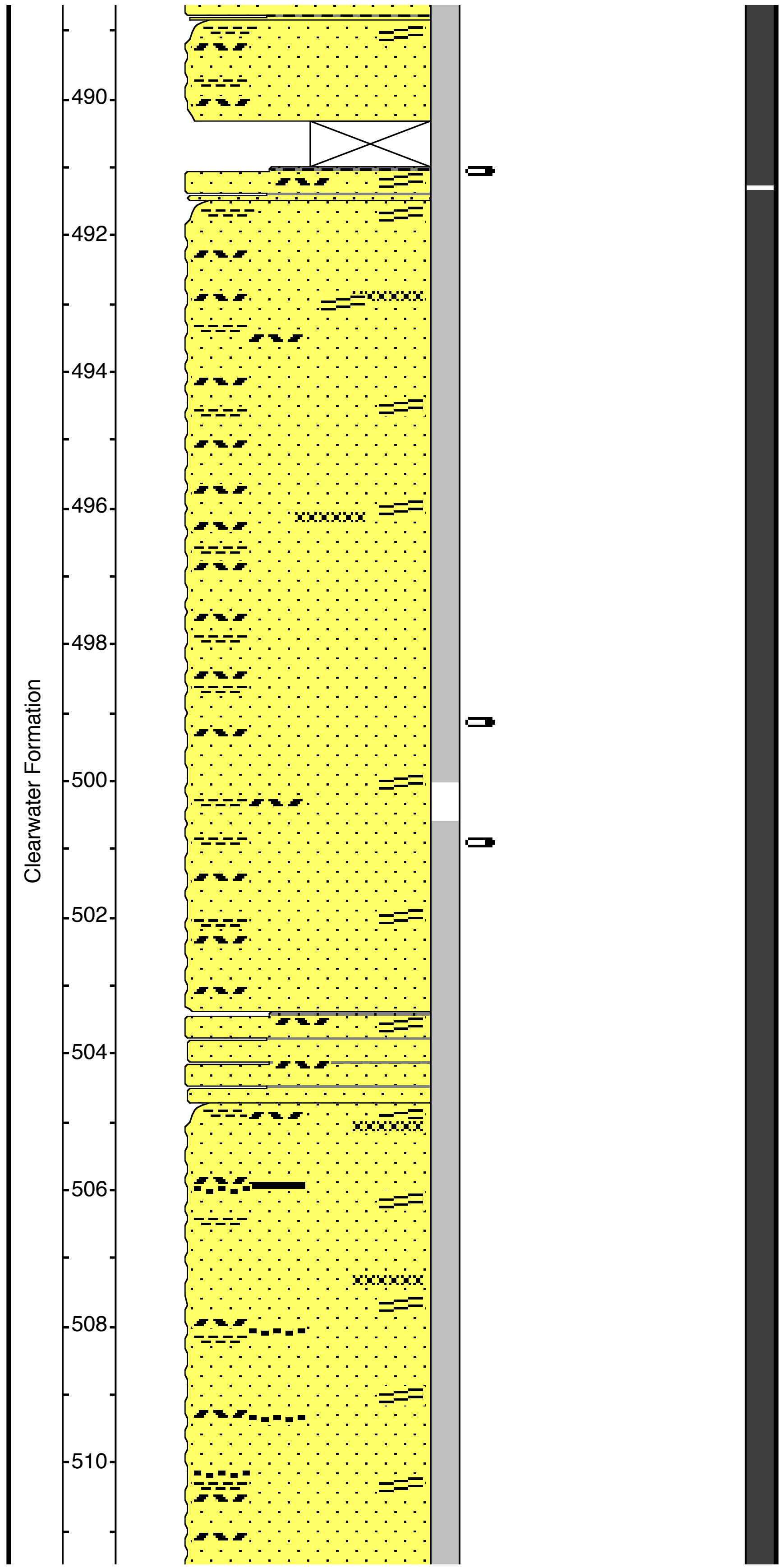
04-03-065-03w4

Date Logged: November 5th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery.




Clearwater Formation
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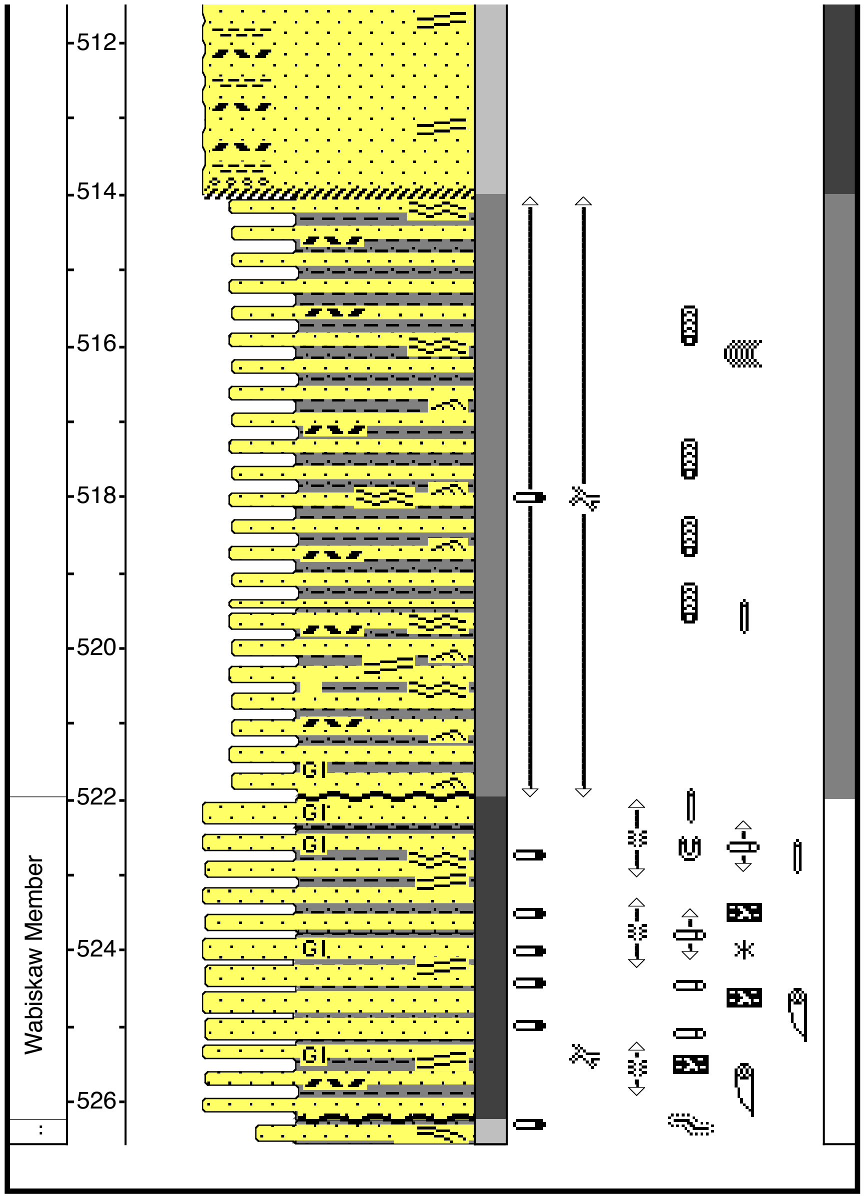
510


512
514
516
518
520
522
524
526
Wabiskaw Member
GI

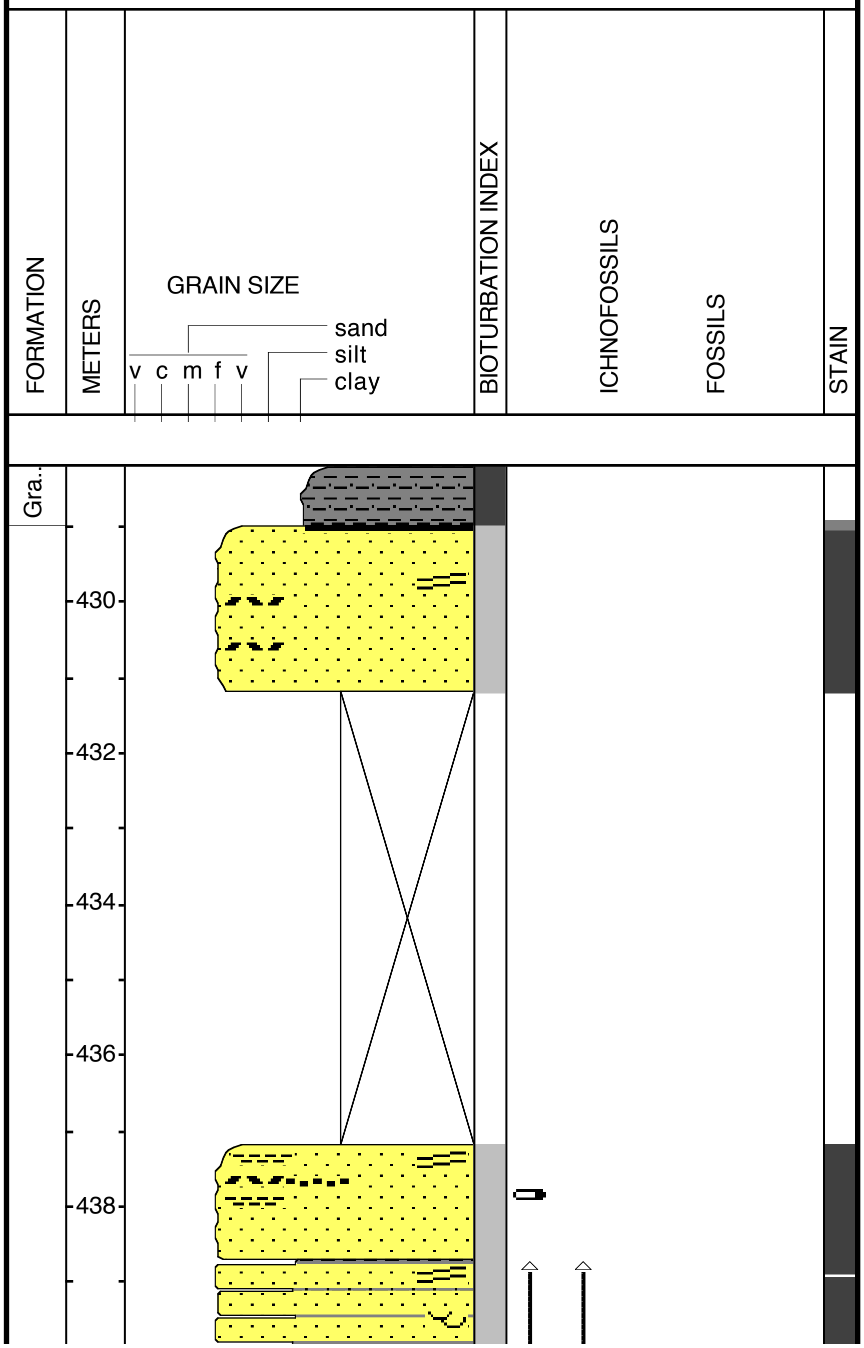
IMP 1-78 COLD LK OV

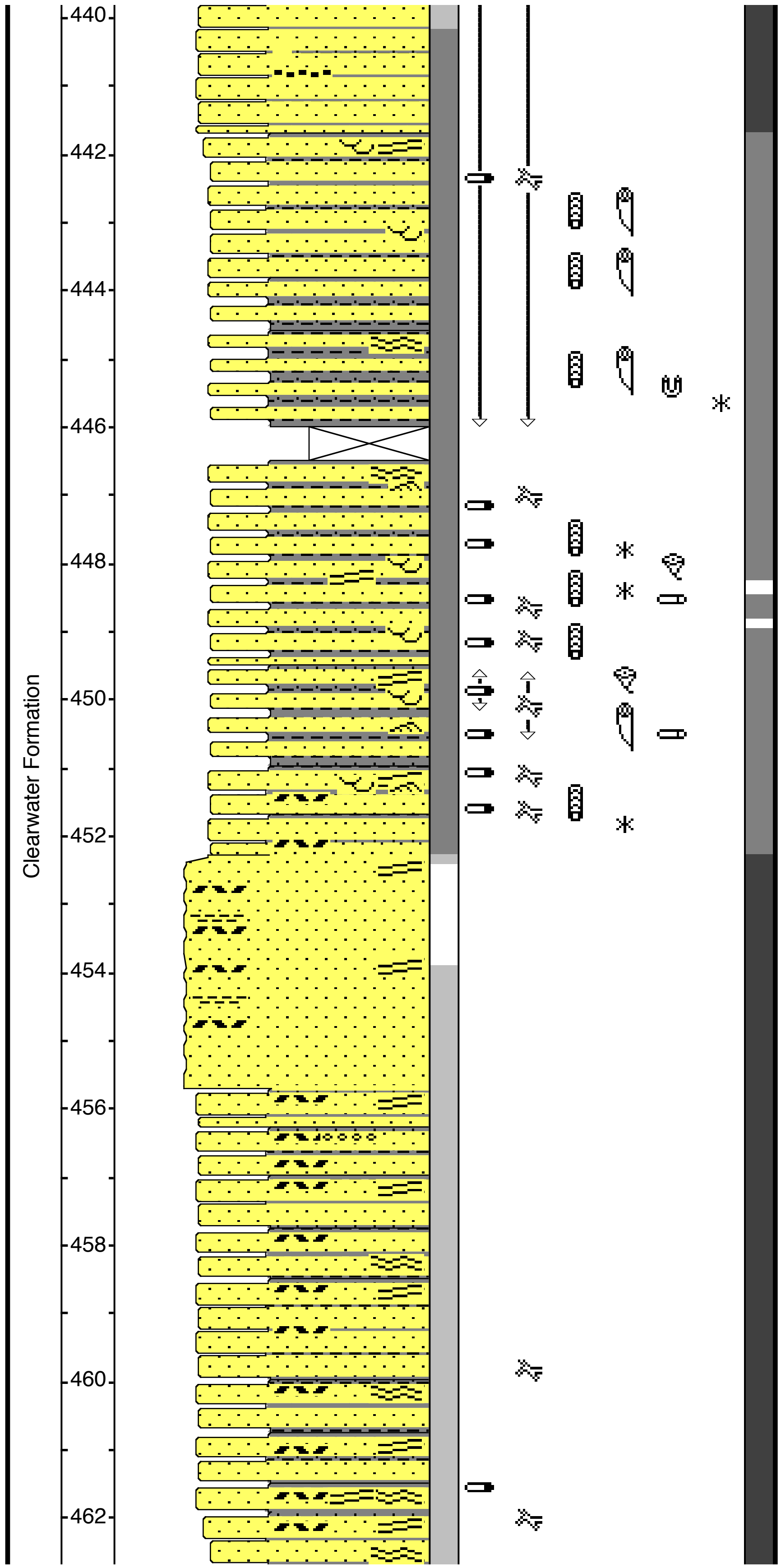
04-15-065-03w4

Date Logged: October 21st, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery




Clearwater Formation
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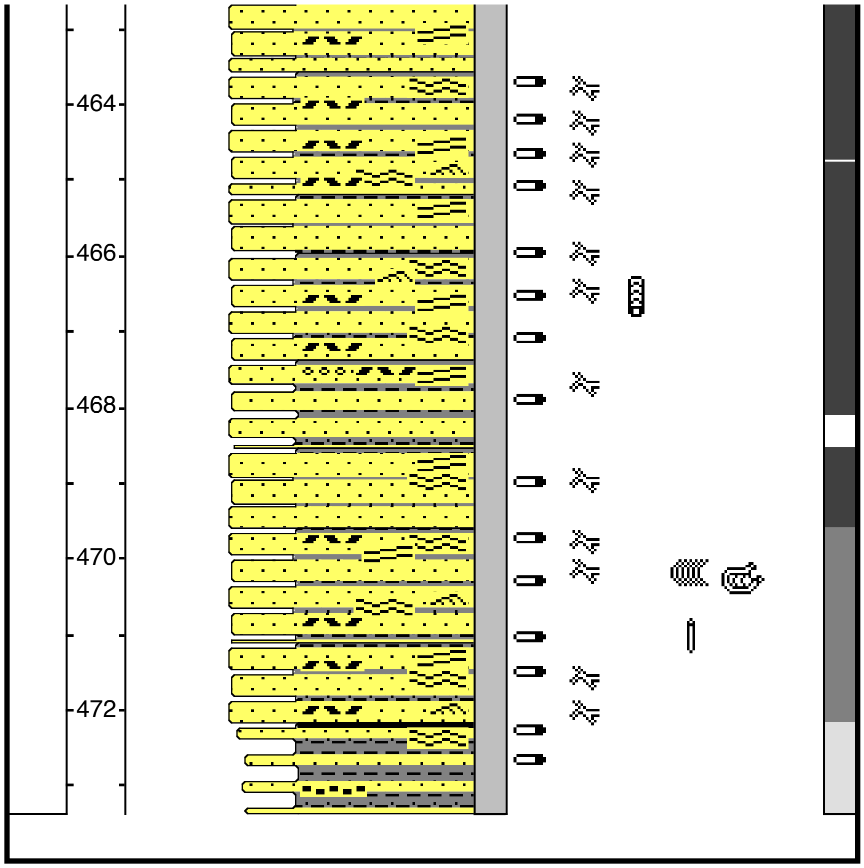


464
466
468
470
472

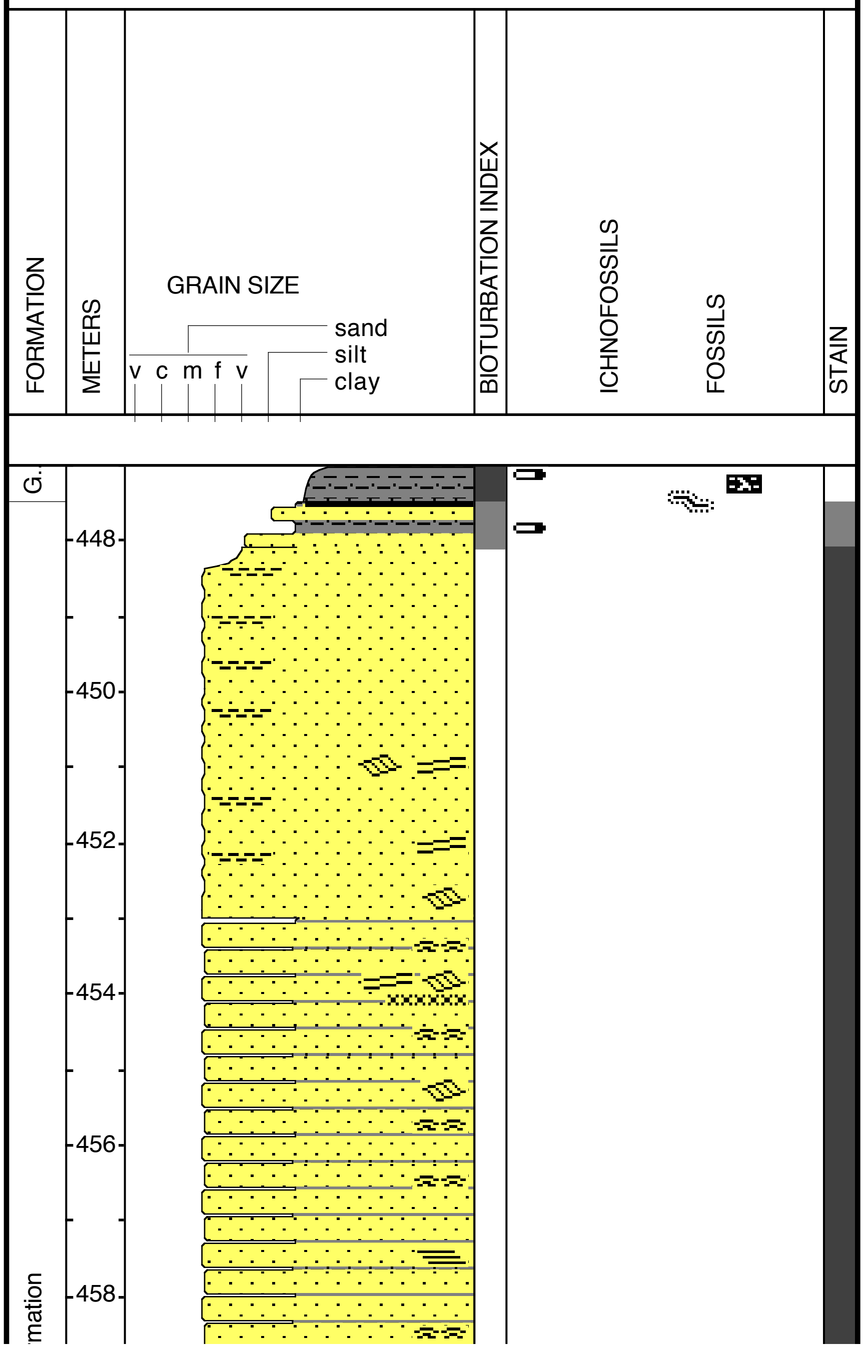
IMPERIAL COLD LAKE

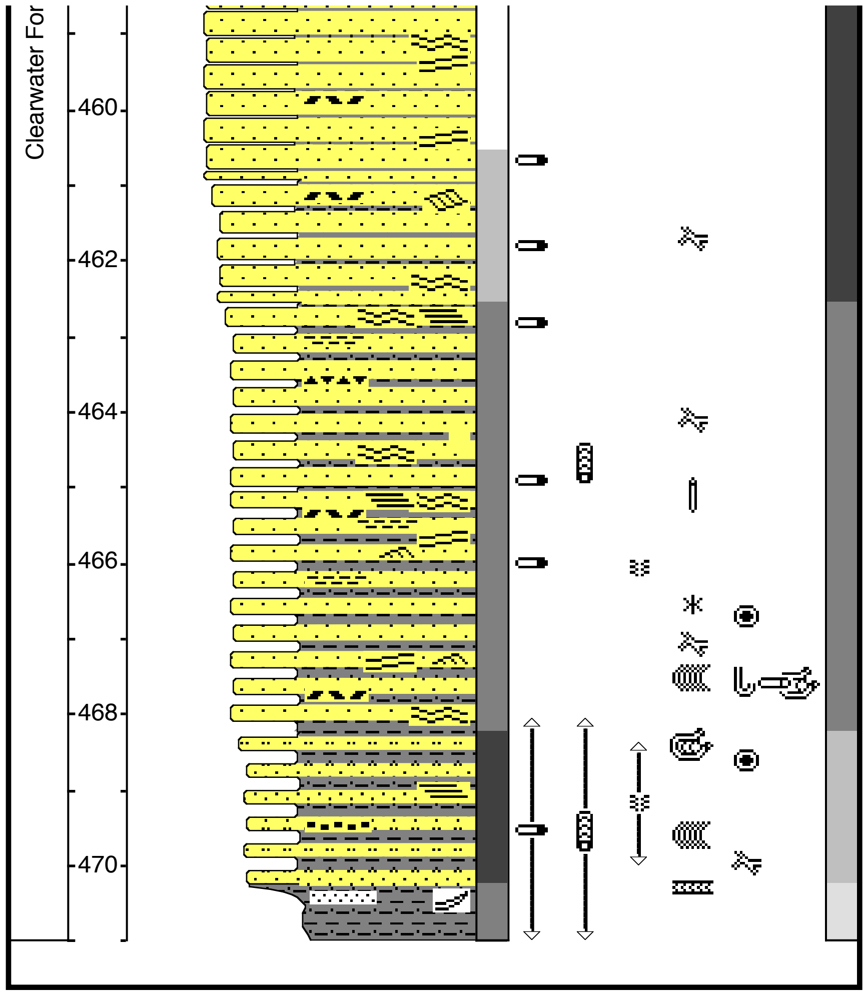
05-24-66-03w4

Date Logged: January 30, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, v. good recovery, oil stained




Clearwater For
460
462
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470

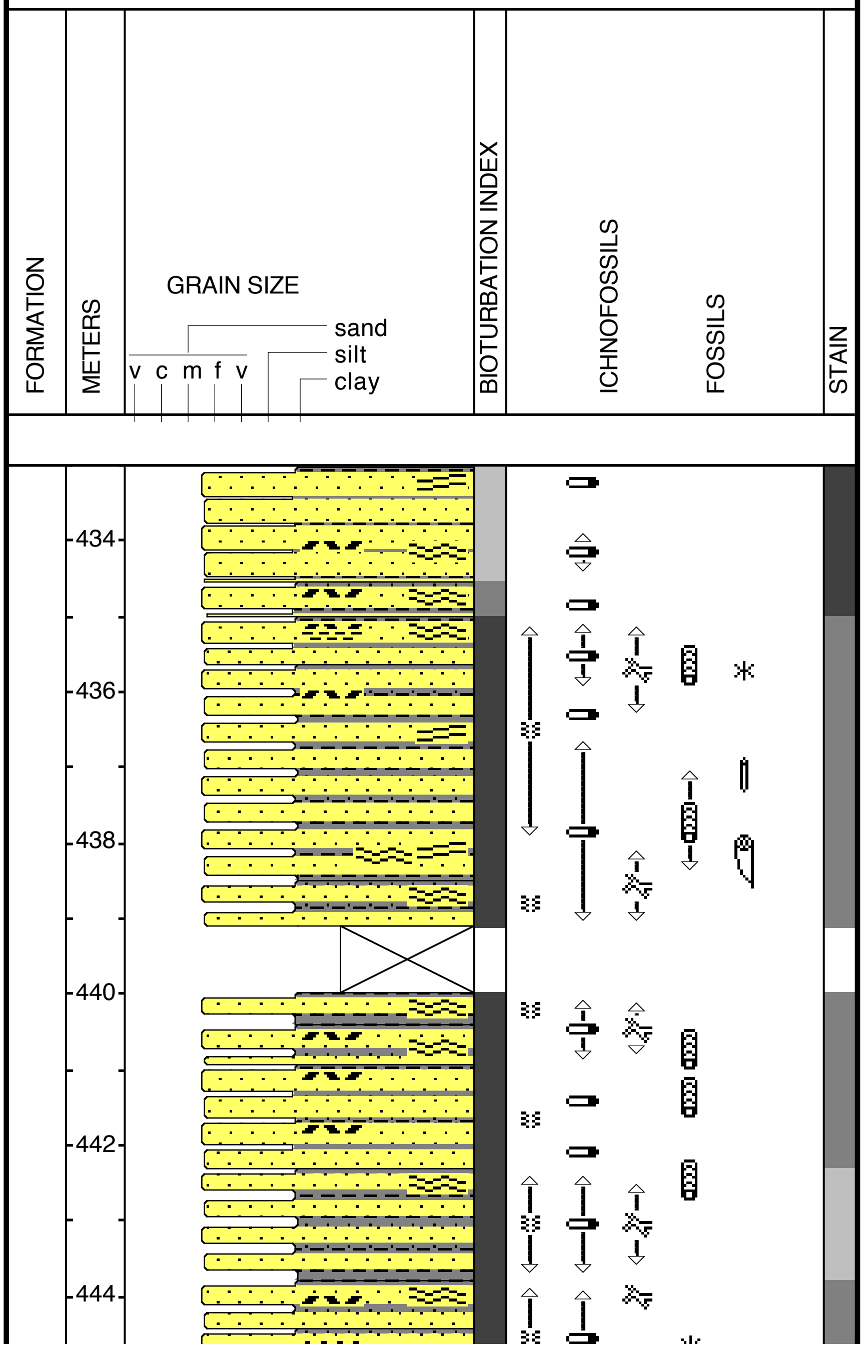
IMP 07 OV WOLF LK

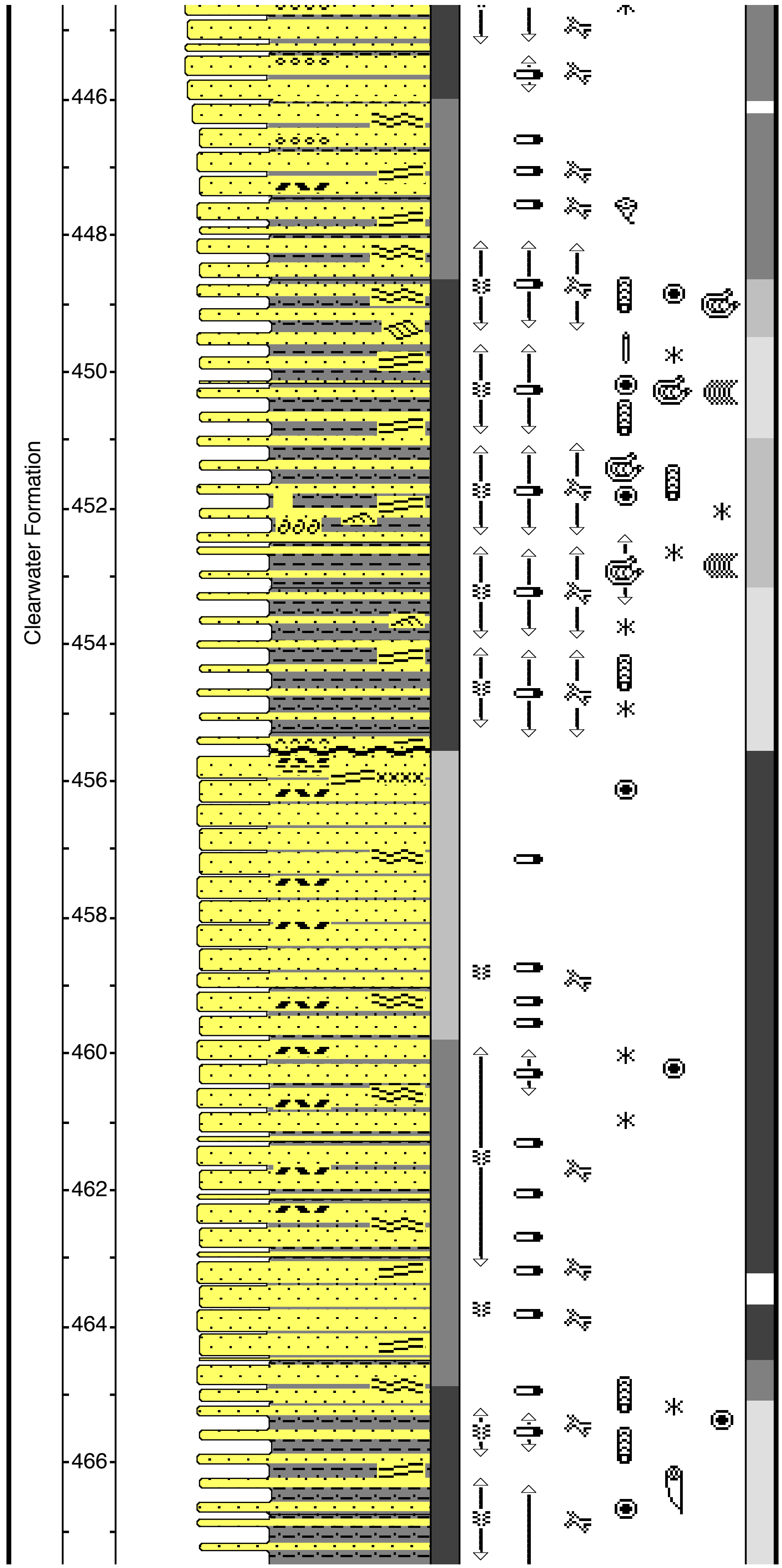
06-03-066-03w4

Date Logged: September 30th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, good recovery.




Clearwater Formation
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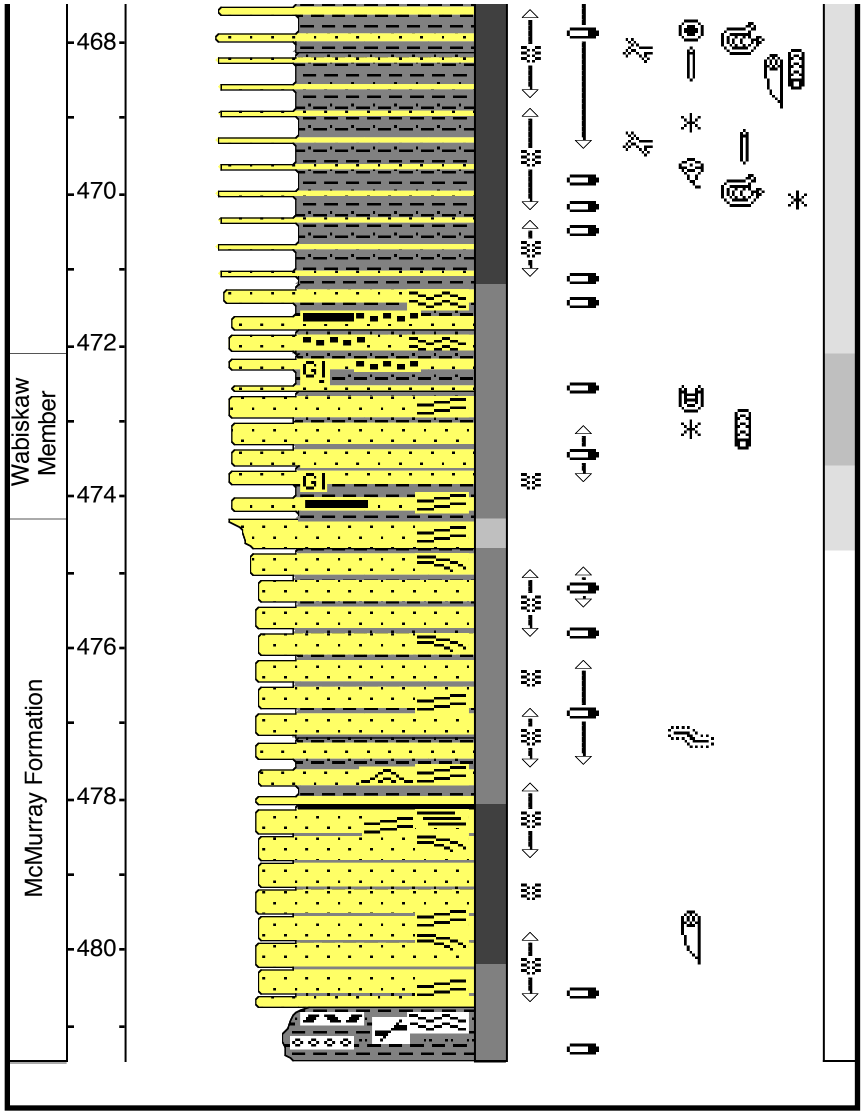
Wabiskaw Member
McMurray Formation
468
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472
474
476
478
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GI
GI

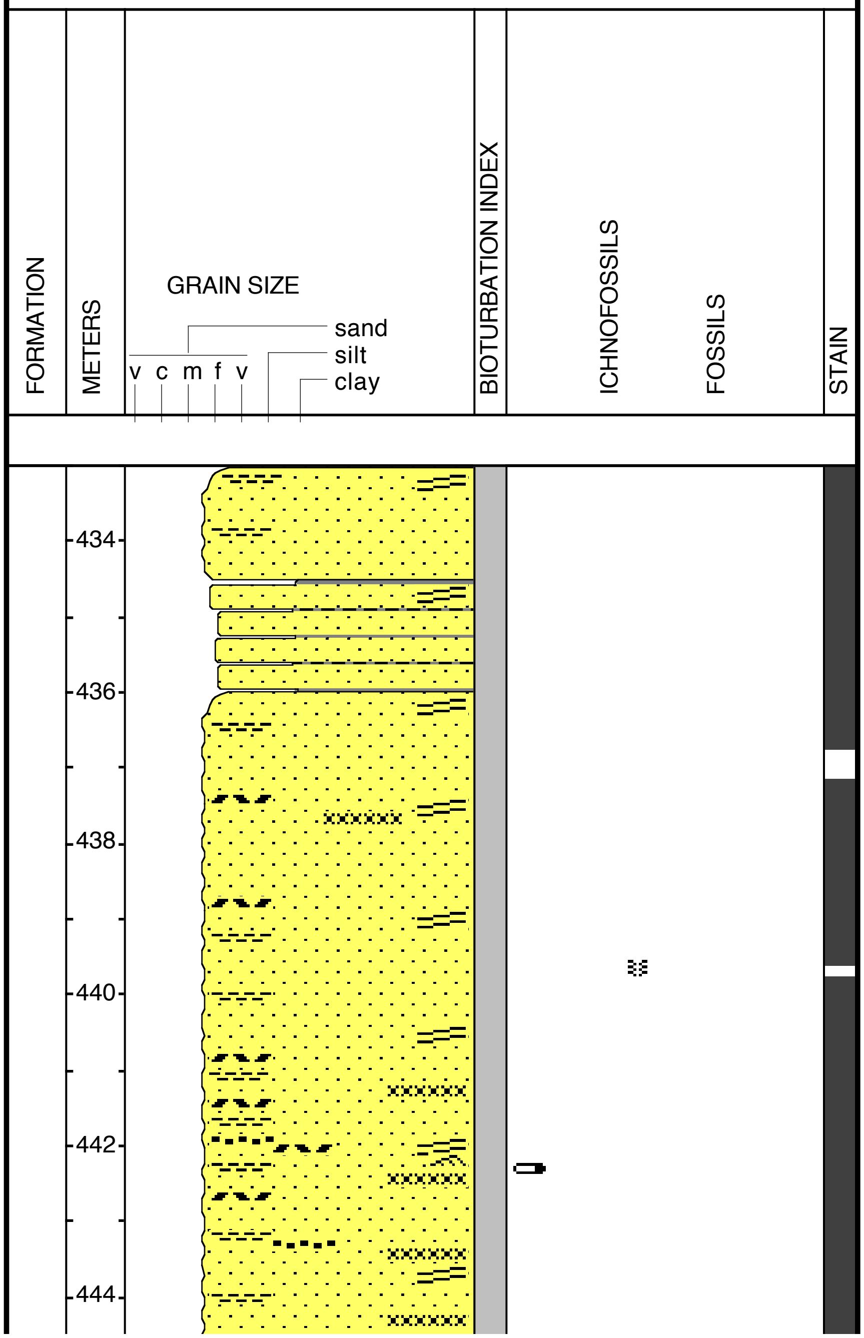
ESSO COLD LK OV

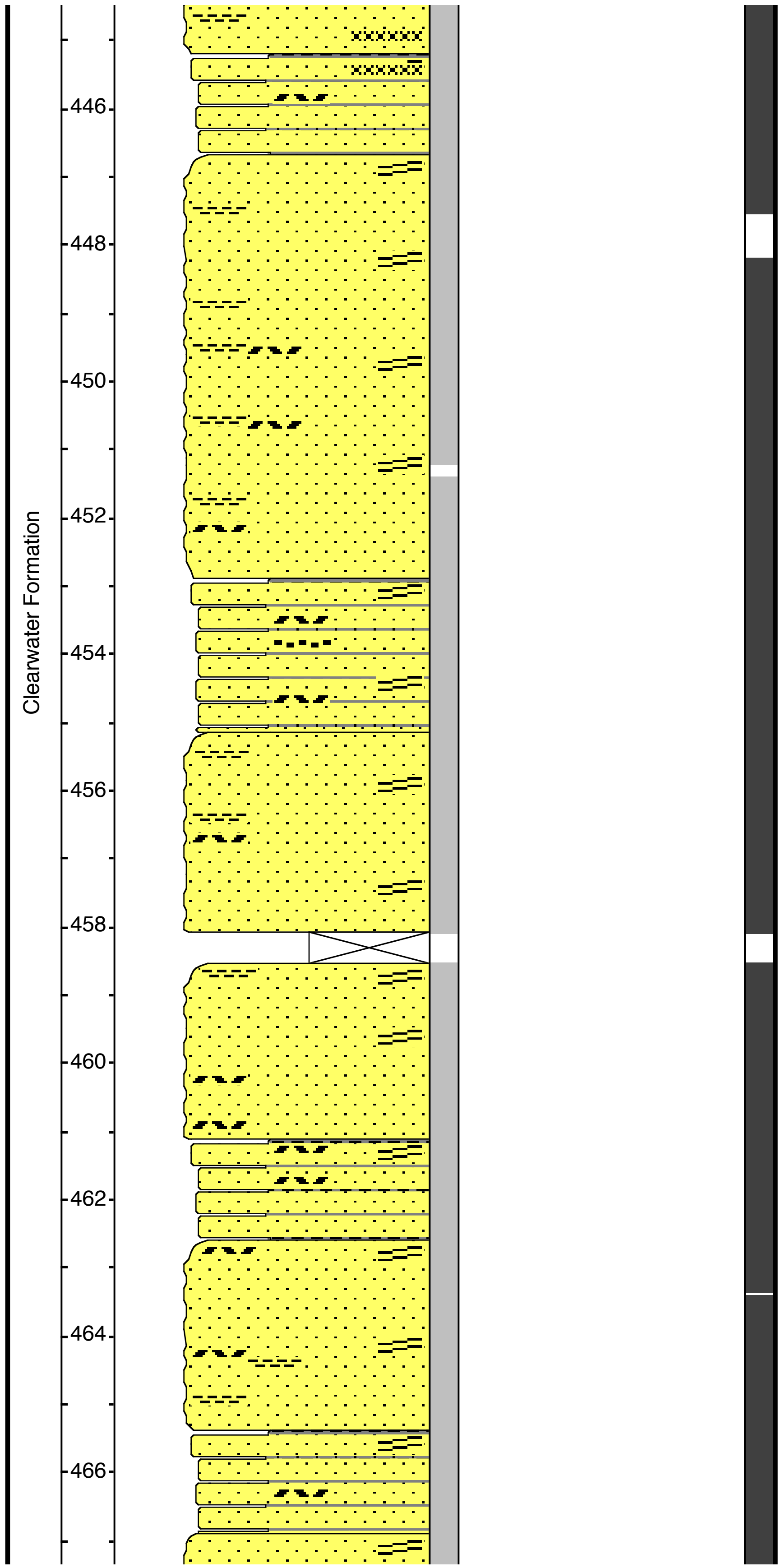
06-08-065-04w4

Date Logged: December 2nd, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery, contains McMurray and Wabiskaw at the base, no Grand Rapids above




Clearwater Formation
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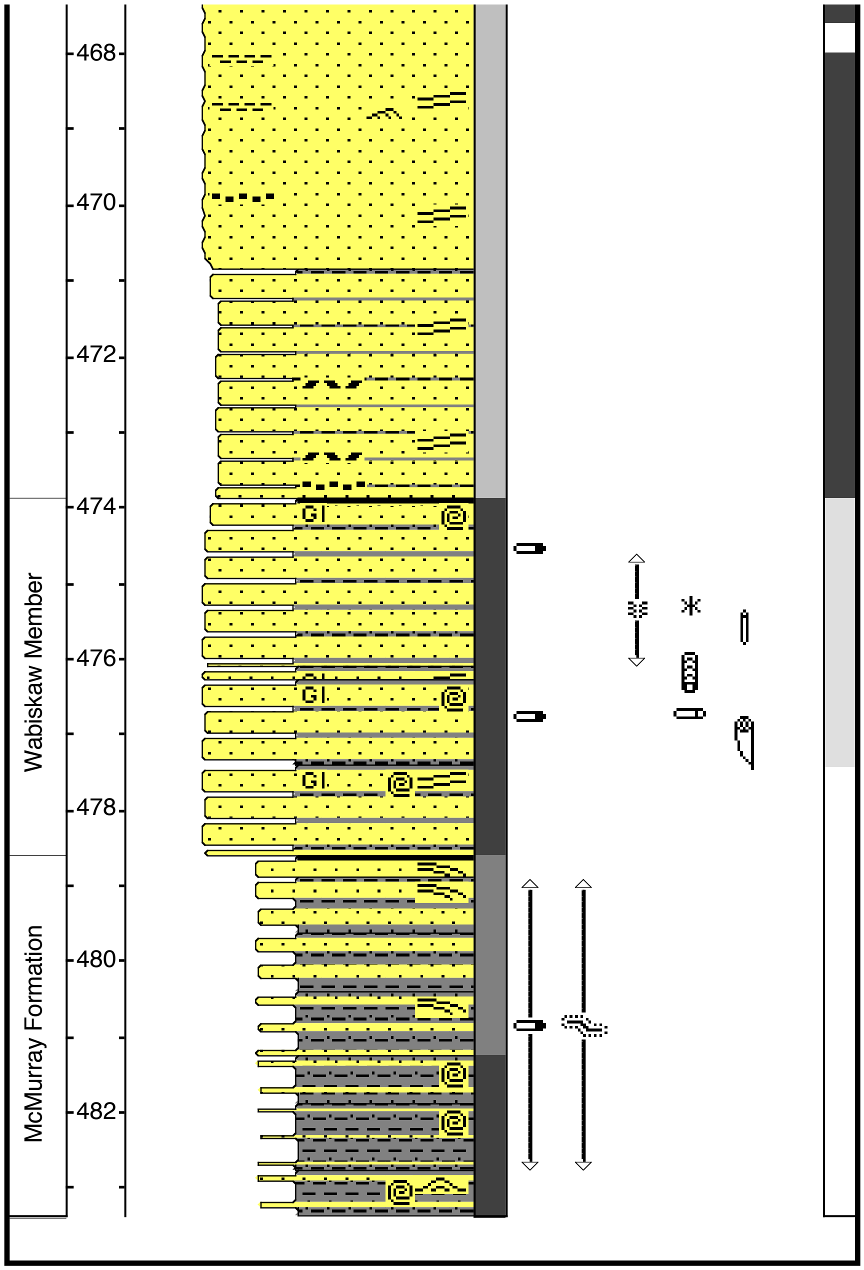
468
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474
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482
Wabiskaw Member
McMurray Formation
Gl
Gl
Gl

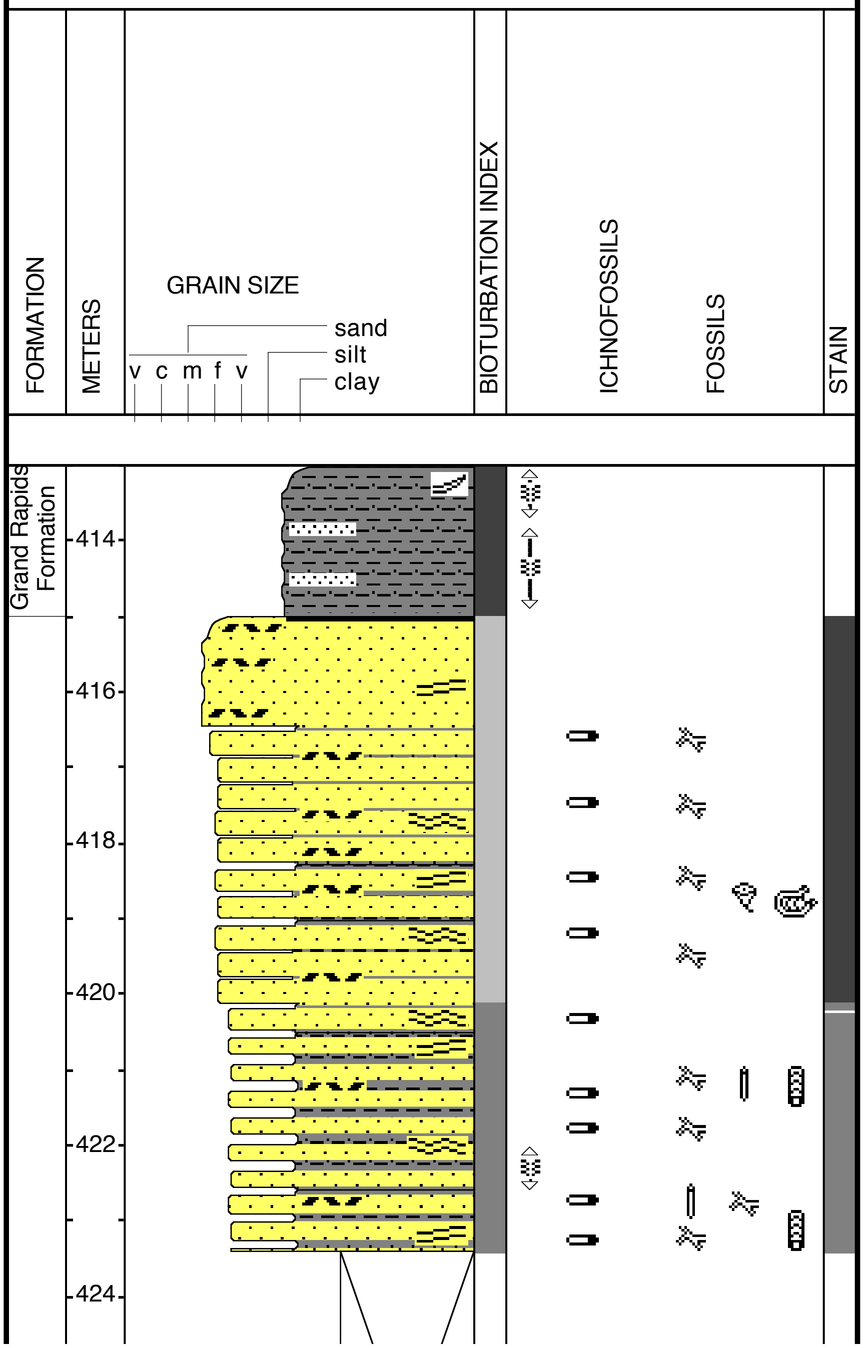
IMP 05 OV COLD LK

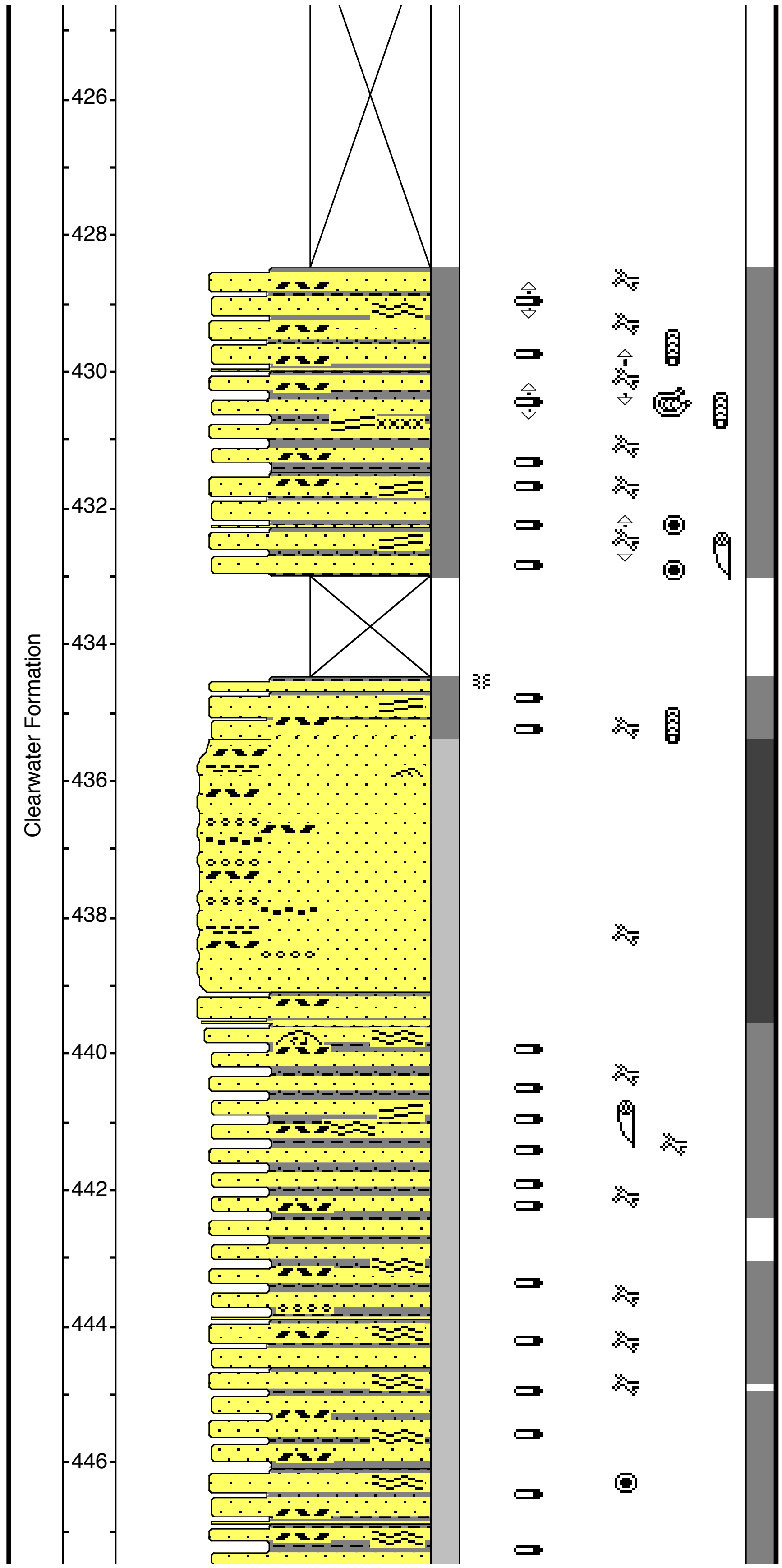
06-20-065-03w4

Date Logged: October 7th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, ok recovery




Clearwater Formation
426
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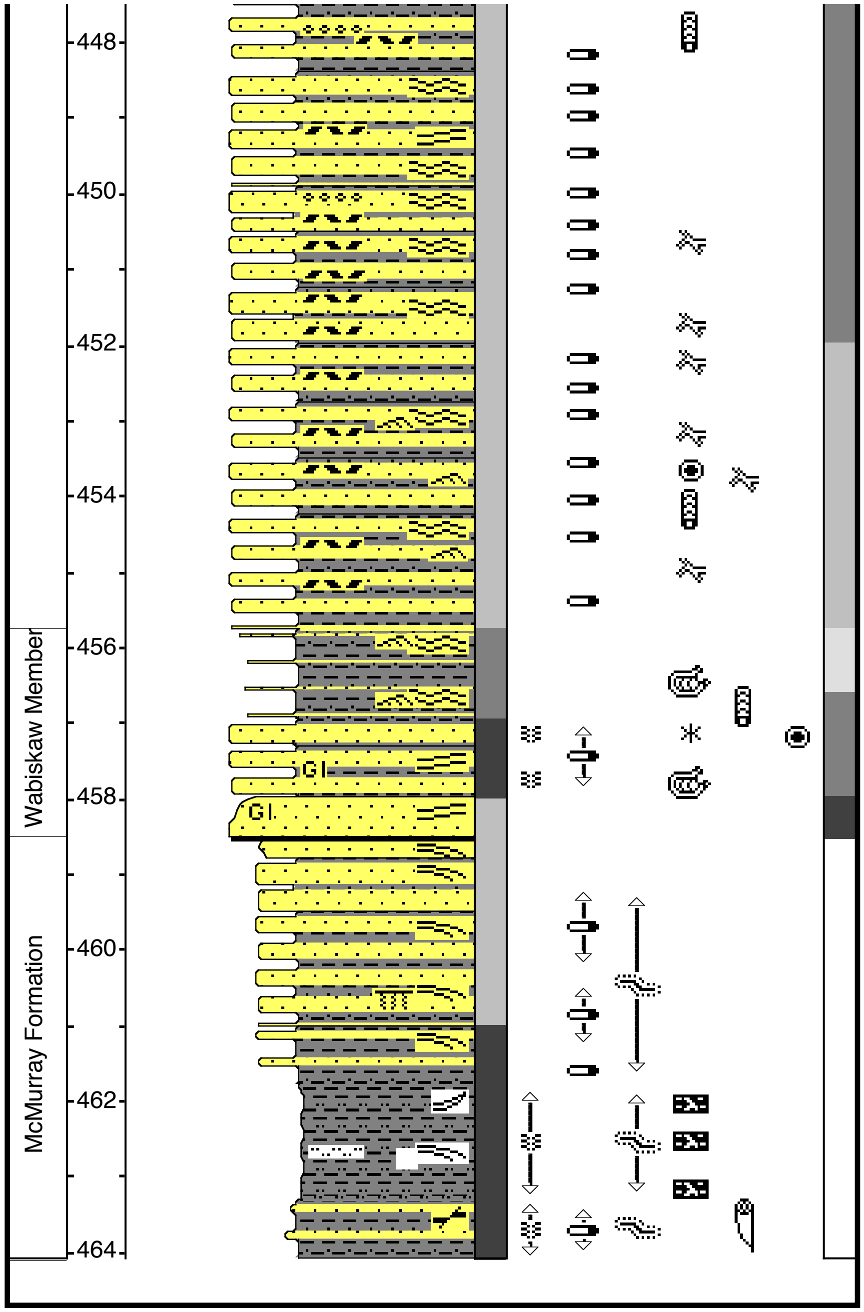
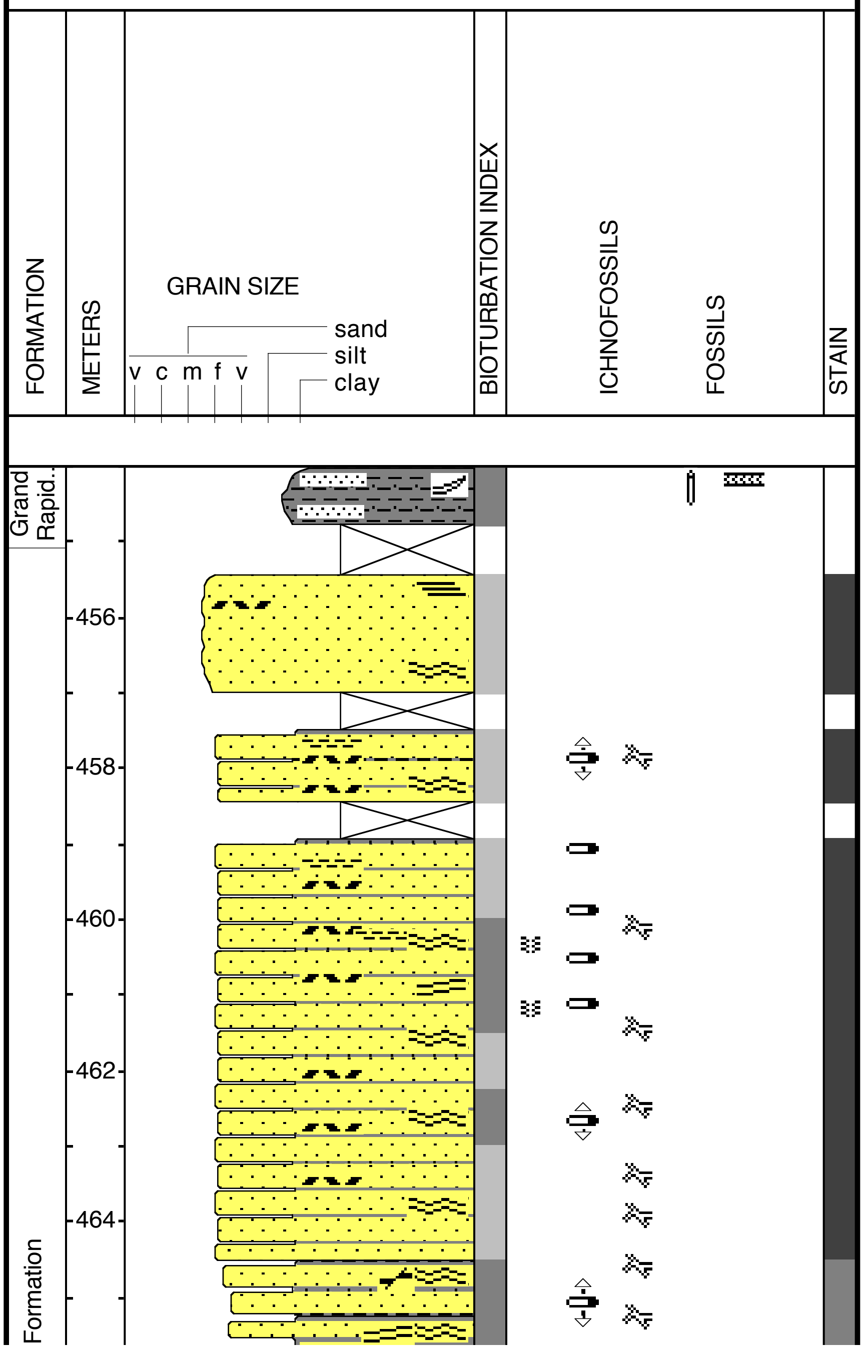

448
450
452
454
456
458
460
462
464
Wabiskaw Member
McMurray Formation
GI
GI

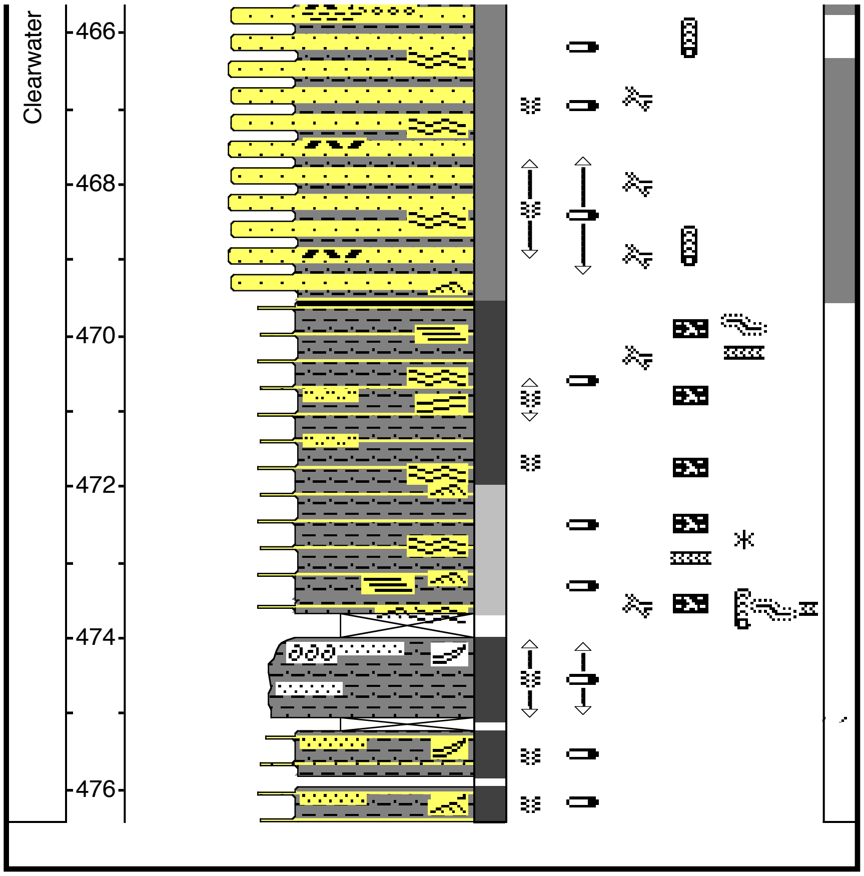
IMPERIAL 99/00 OV COLD LAKE
06-20-66-02w4

Date Logged: May 15th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, ok recovery, oil saturated





Clearwater
466
468
470
472
474
476

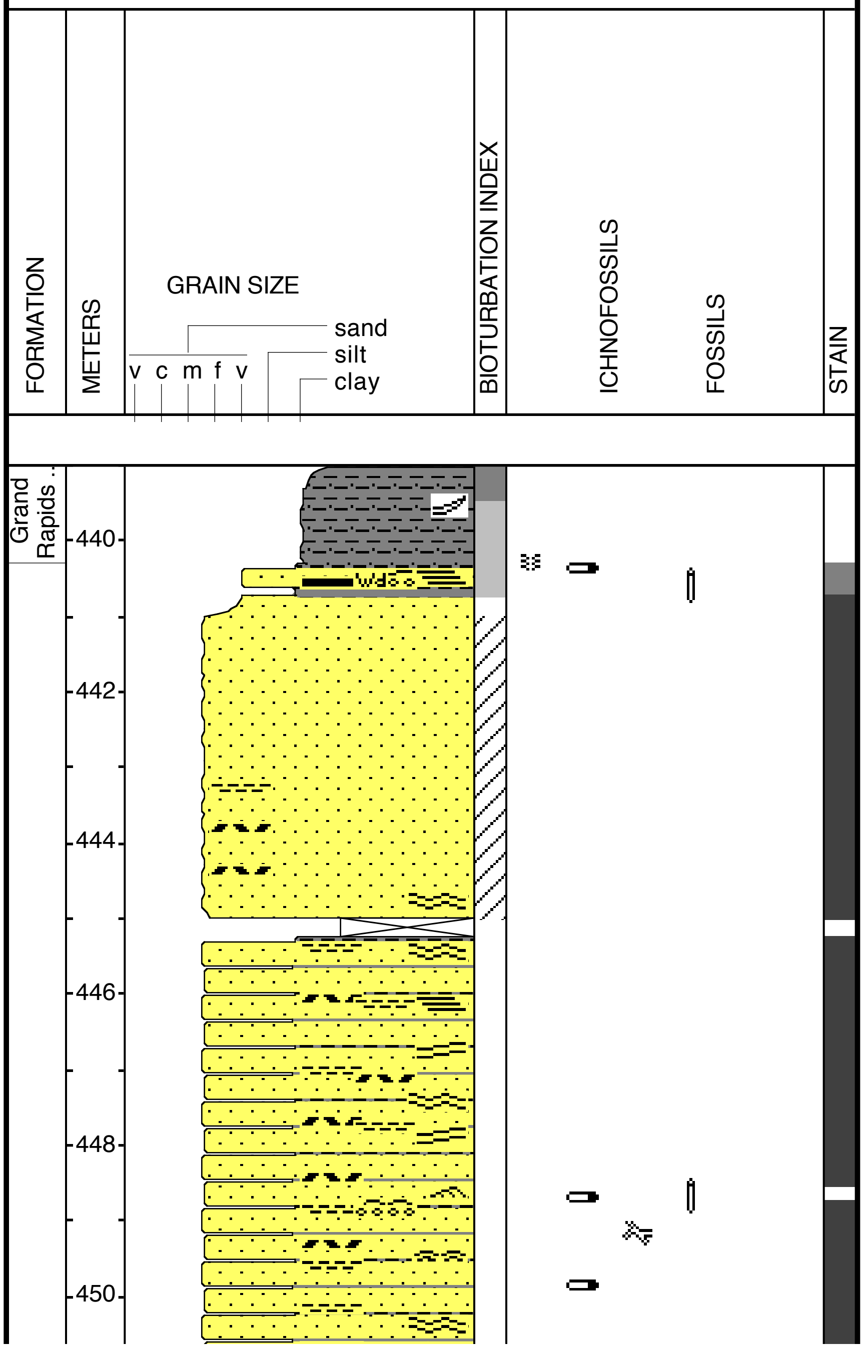
ESSO 86 MARIE 6-24

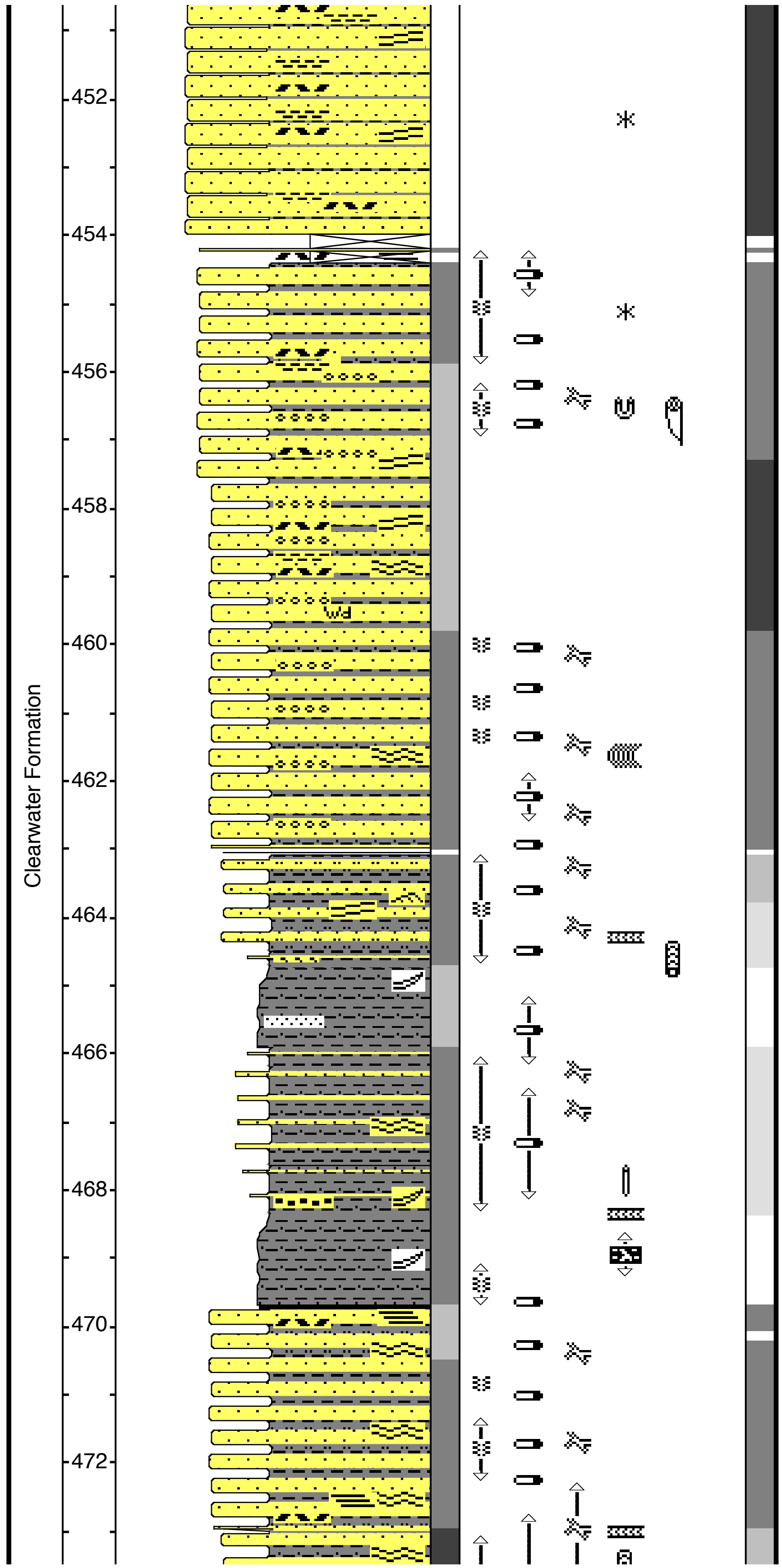
6-24-66-3w4

Date Logged: May 8th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil stained, recovery good




Clearwater Formation
452
454
456
458
460
462
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466
468
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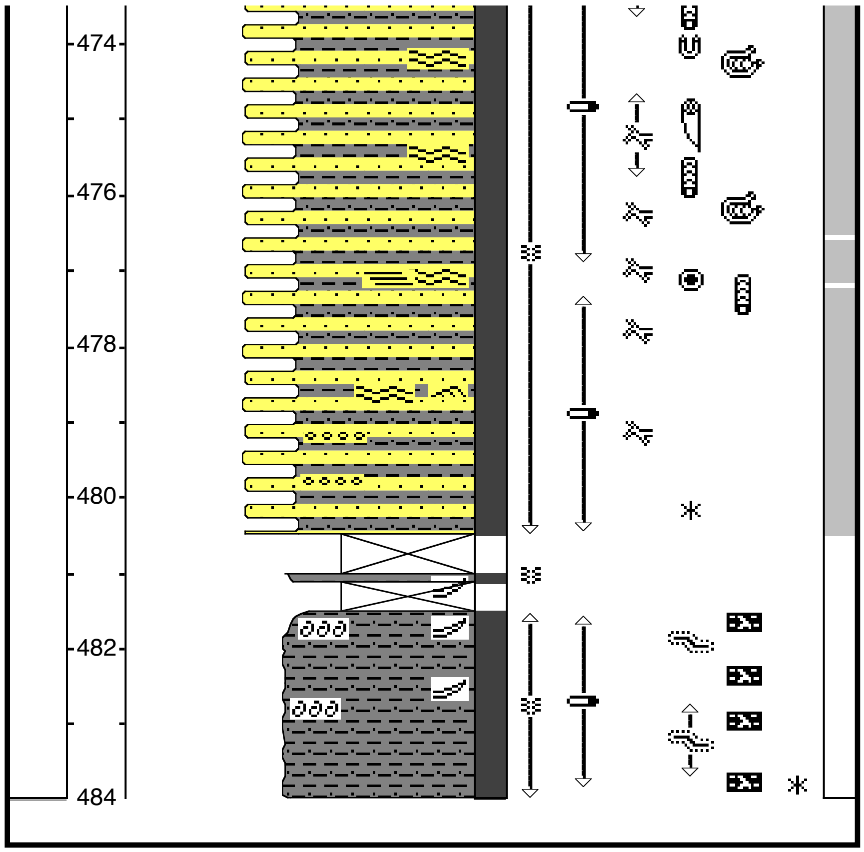
472


474
476
478
480
482
484

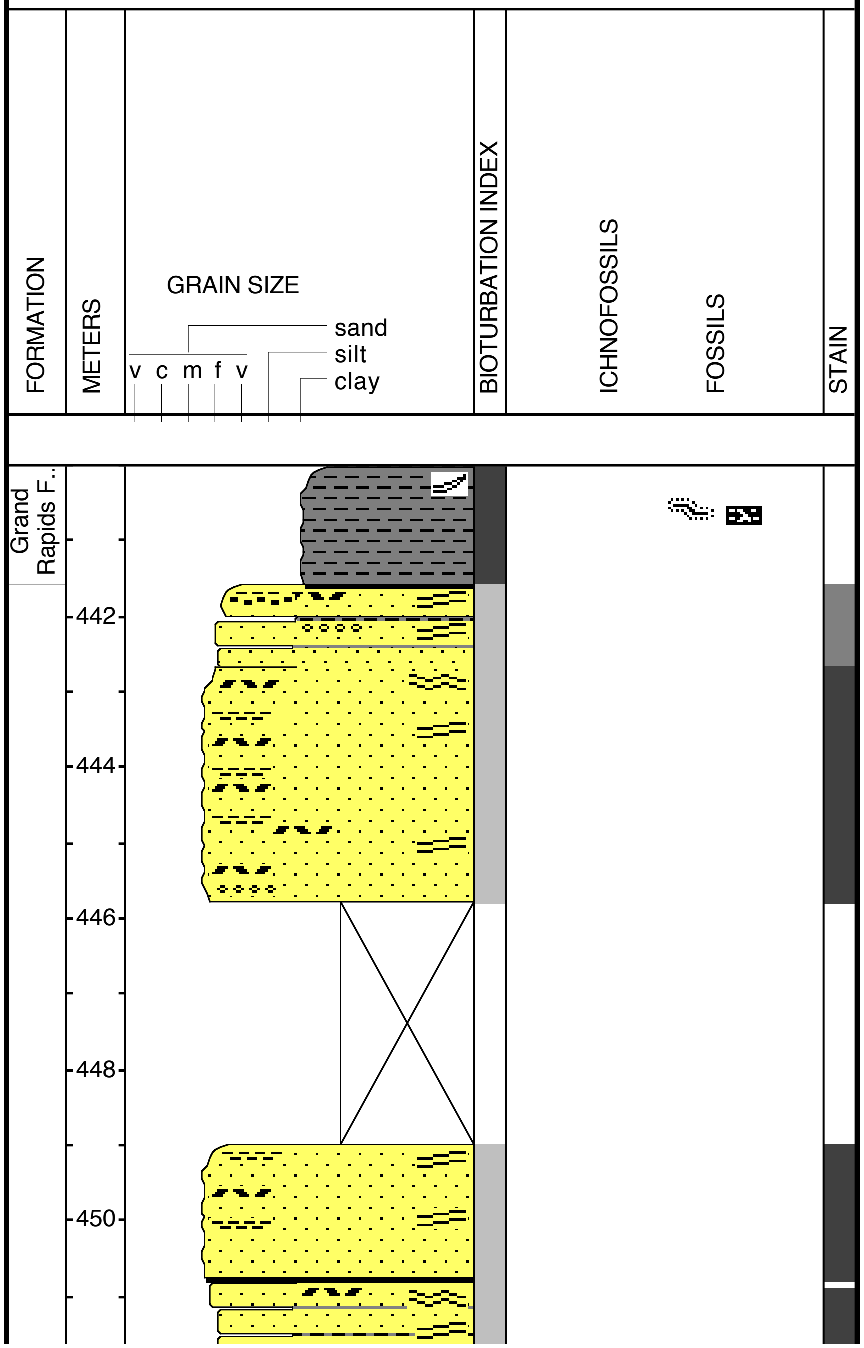
IMPERIAL 99/00 OV COLD LAKE

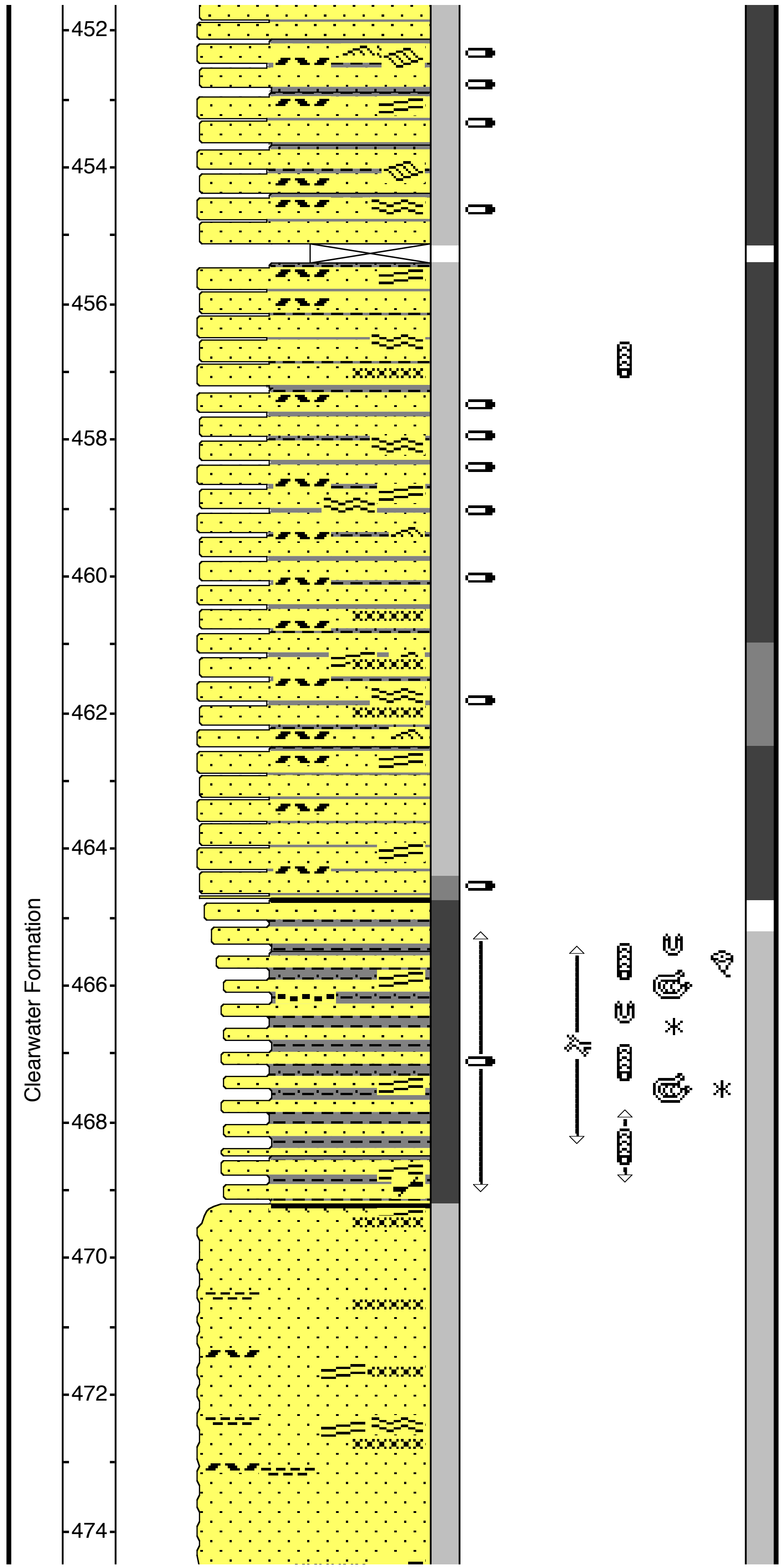
07-01-066-03w4

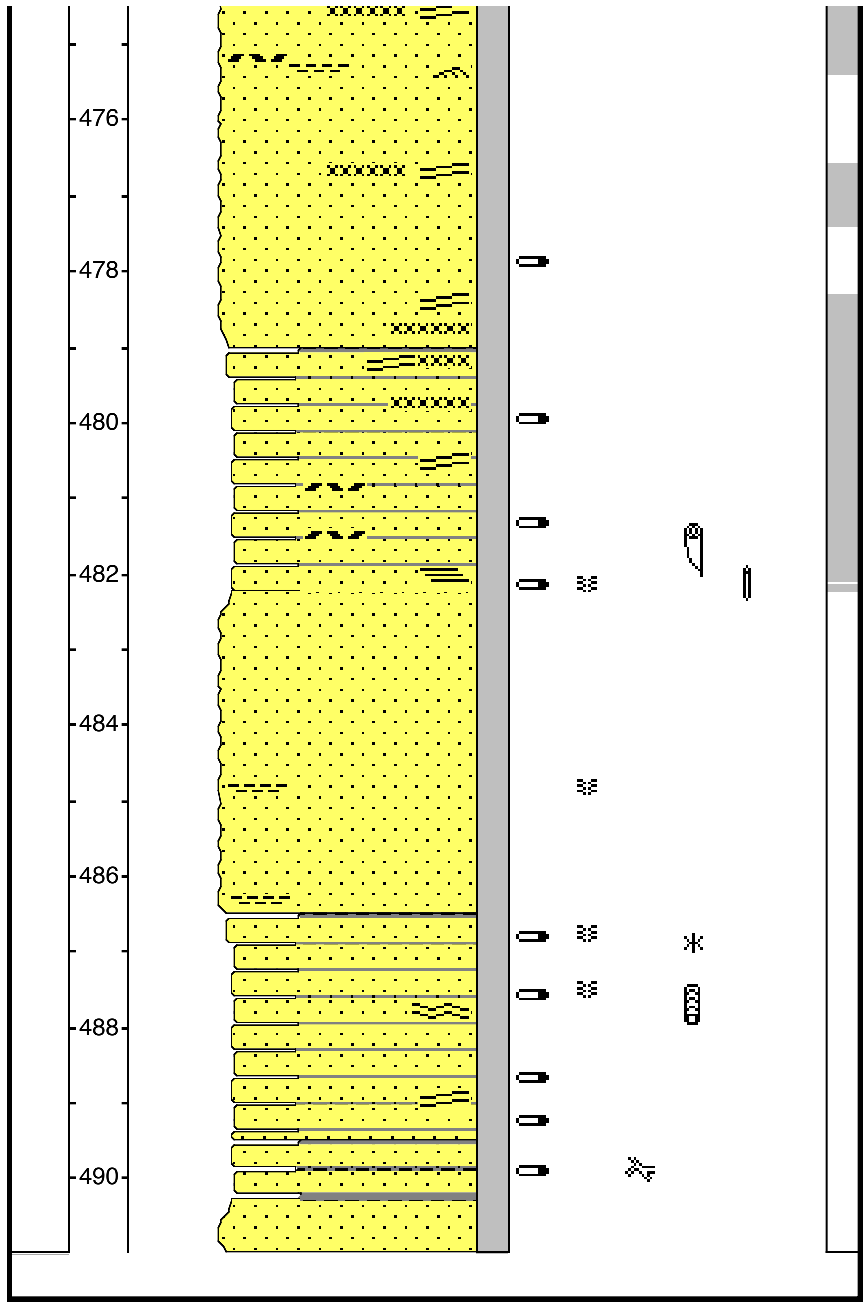
Date Logged: October 15th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery




Clearwater Formation
452
454
456
458
460
462
464
466
468
470
472
474


476
478
480
482
484
486
488
490

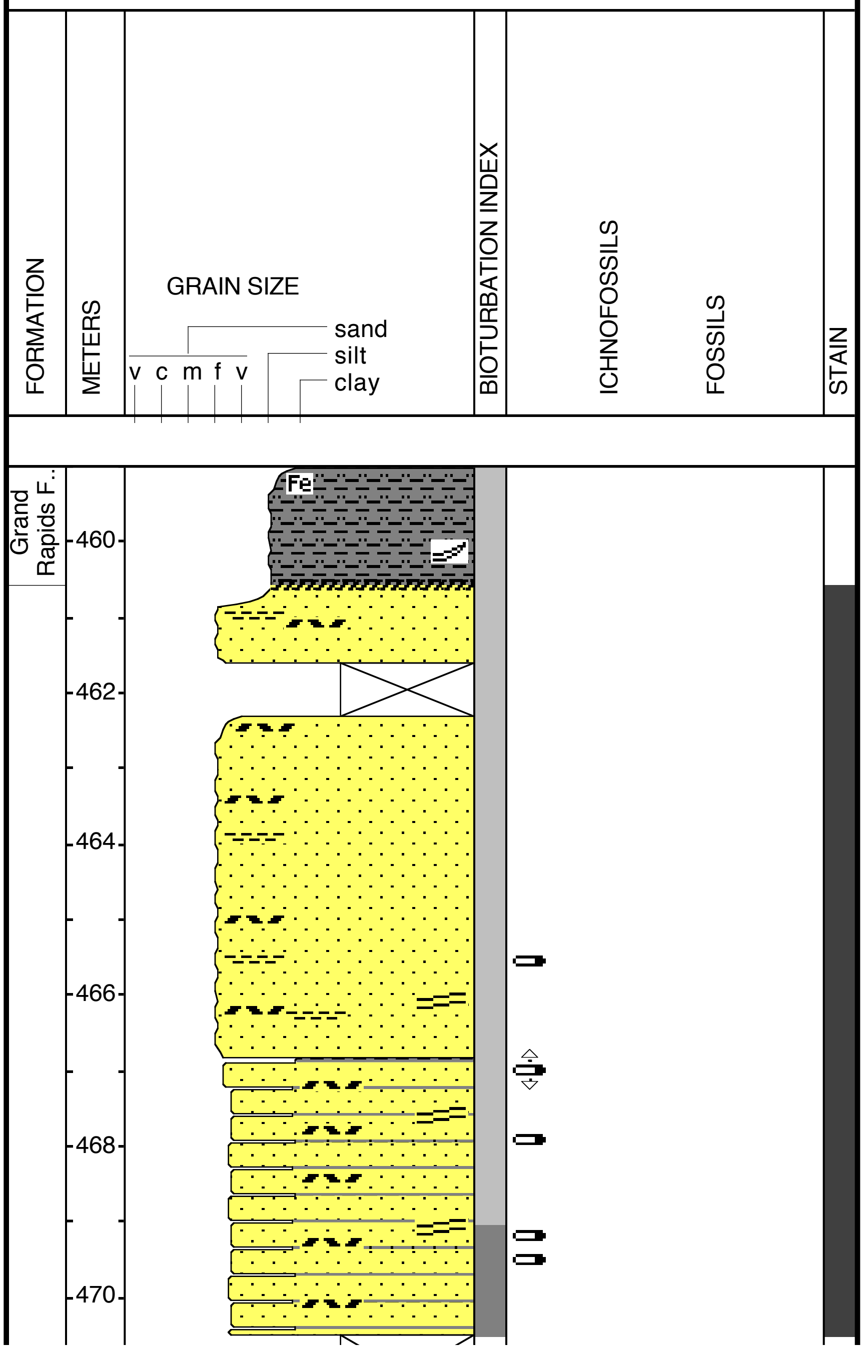
ESSO 85 COLD LK OV 7-22

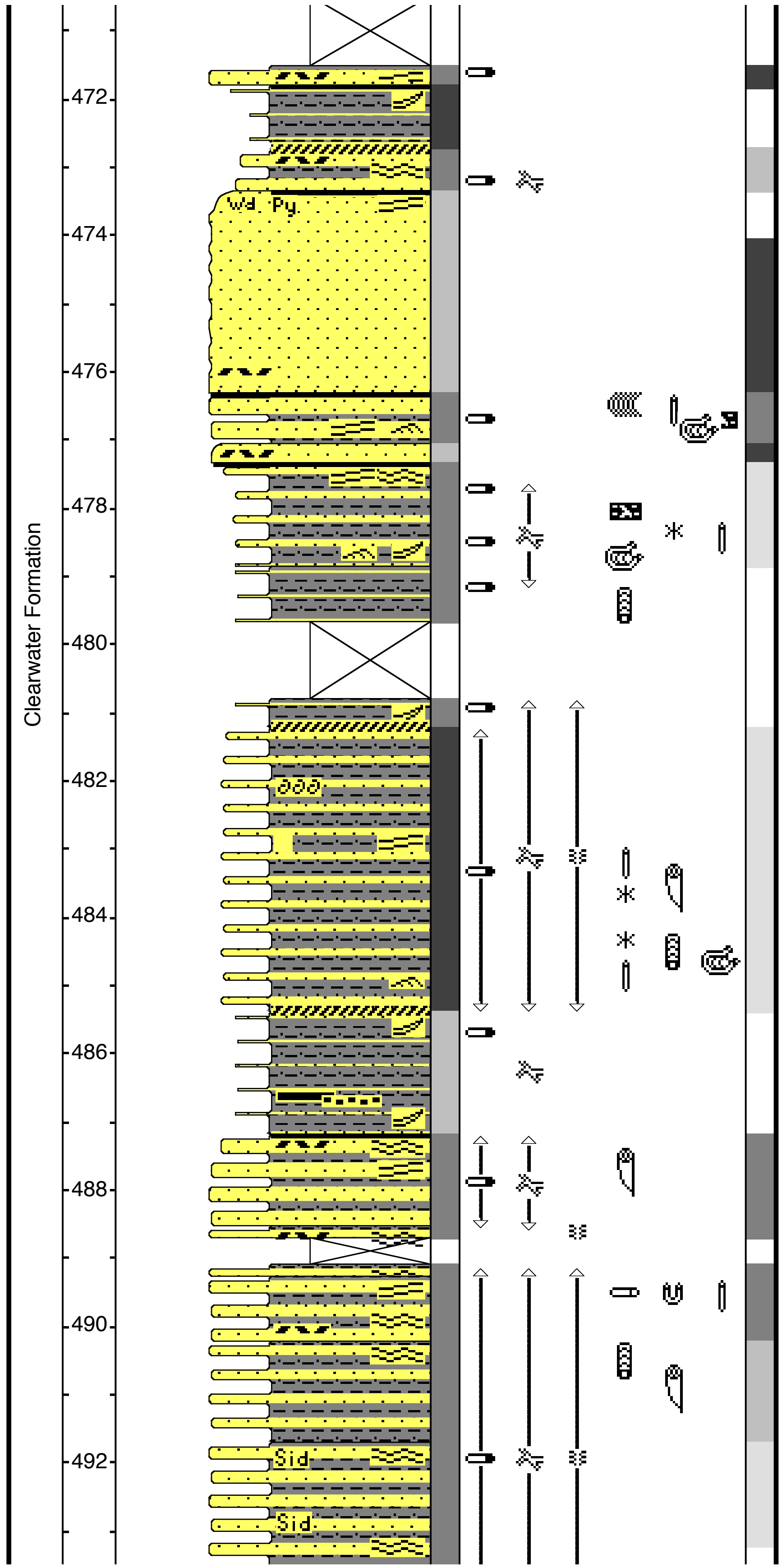
07-22-066-03w4

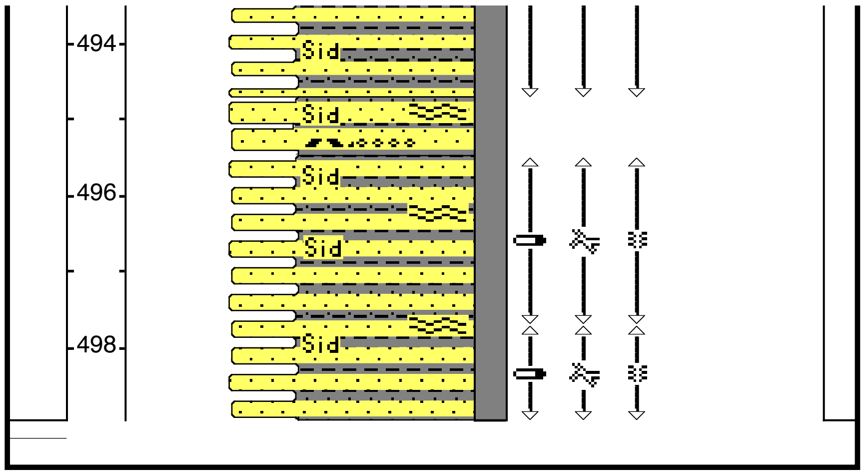
Date Logged: October 29, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated middle, damage being an older core, v. good recovery.




Clearwater Formation
472
474
476
478
480
482
484
486
488
490
492
Wd Py
Sid
Sid


494
Sid
Sid
496
Sid
Sid
498
Sid

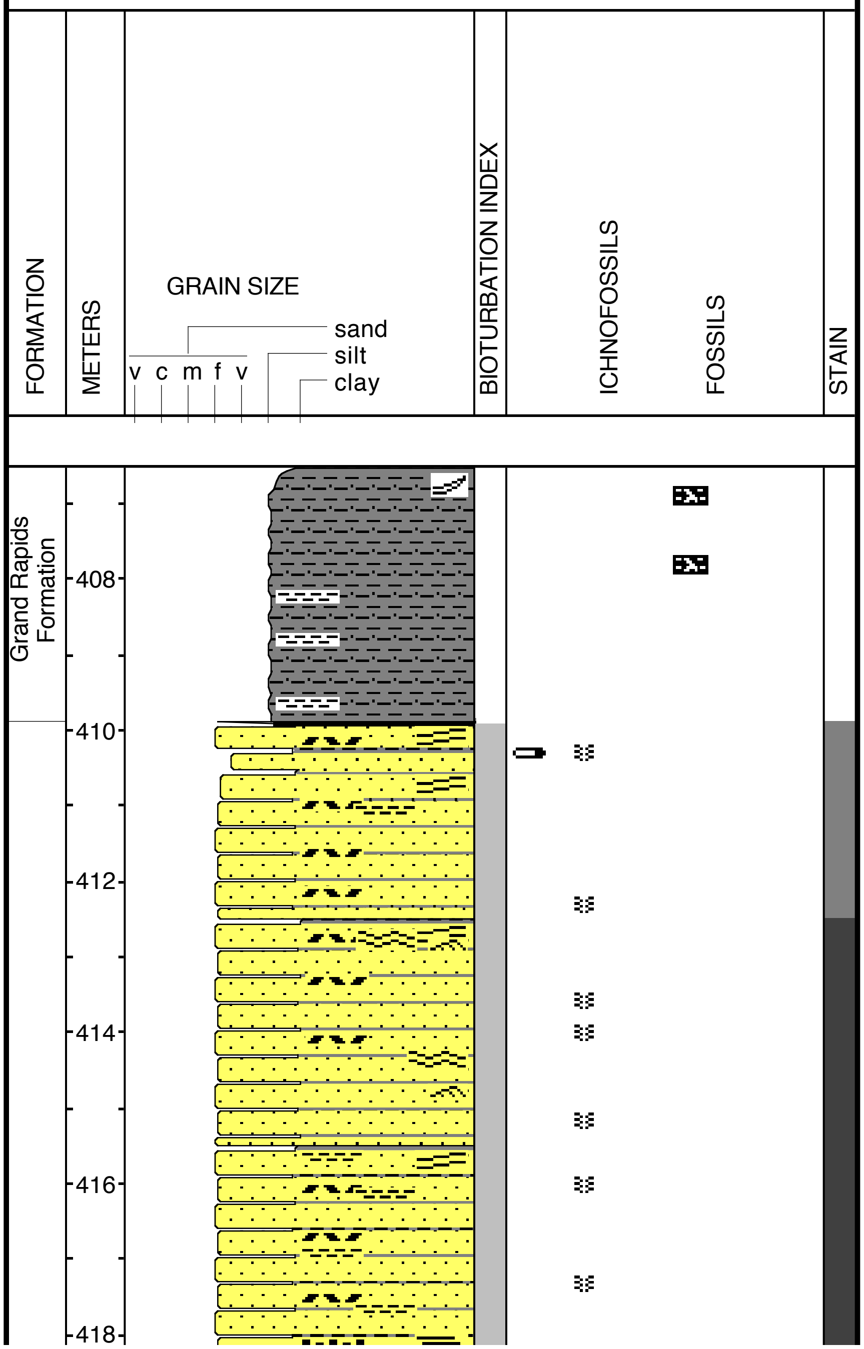
IMPERIAL COLD LAKE

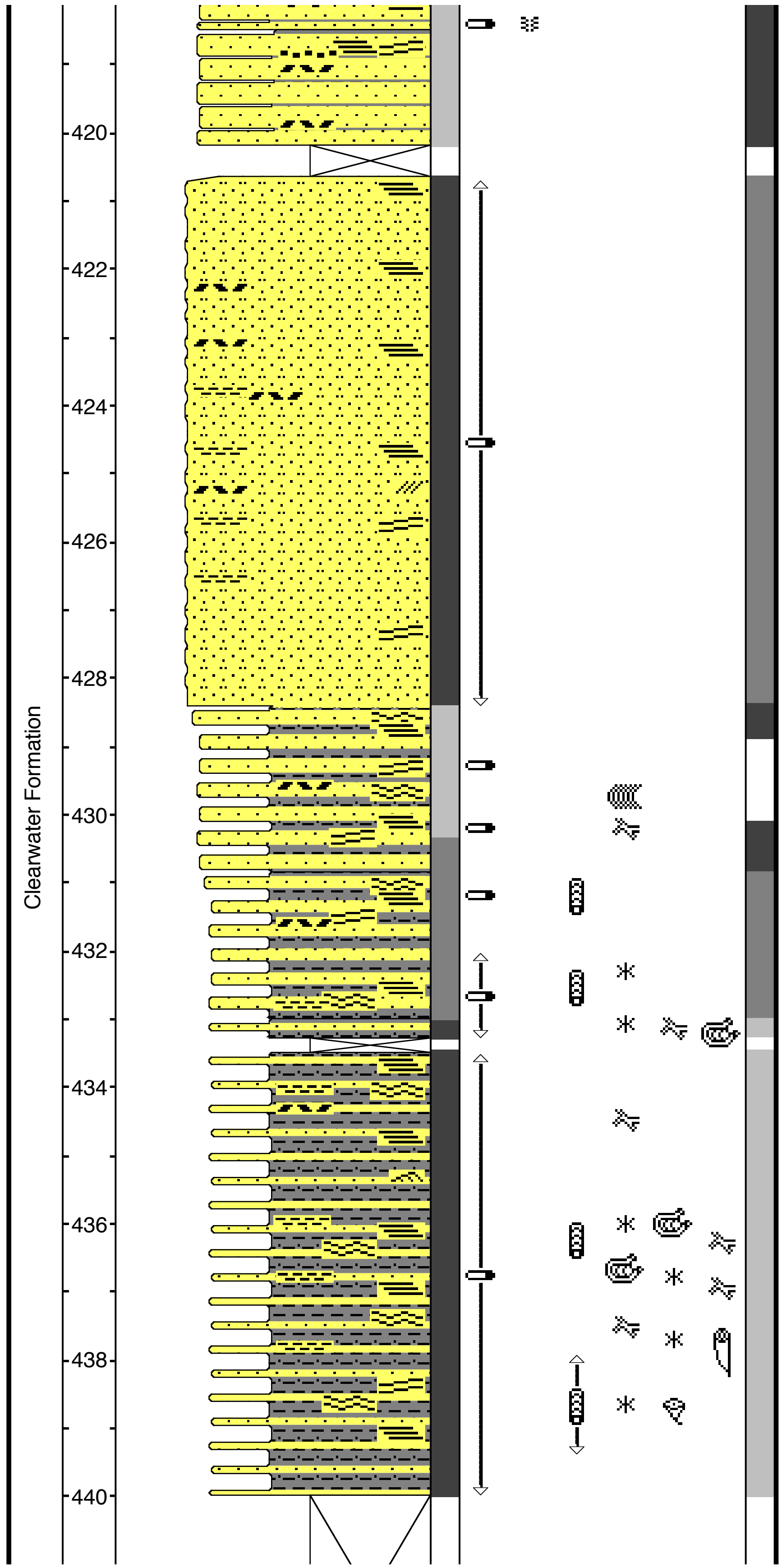
07-28-065-03w4

Date Logged: January 30, 2009

Logged by: Carolyn Currie

Remarks: 3.5" core, slabbed, good recovery, oil stained




Clearwater Formation
420
422
424
426
428
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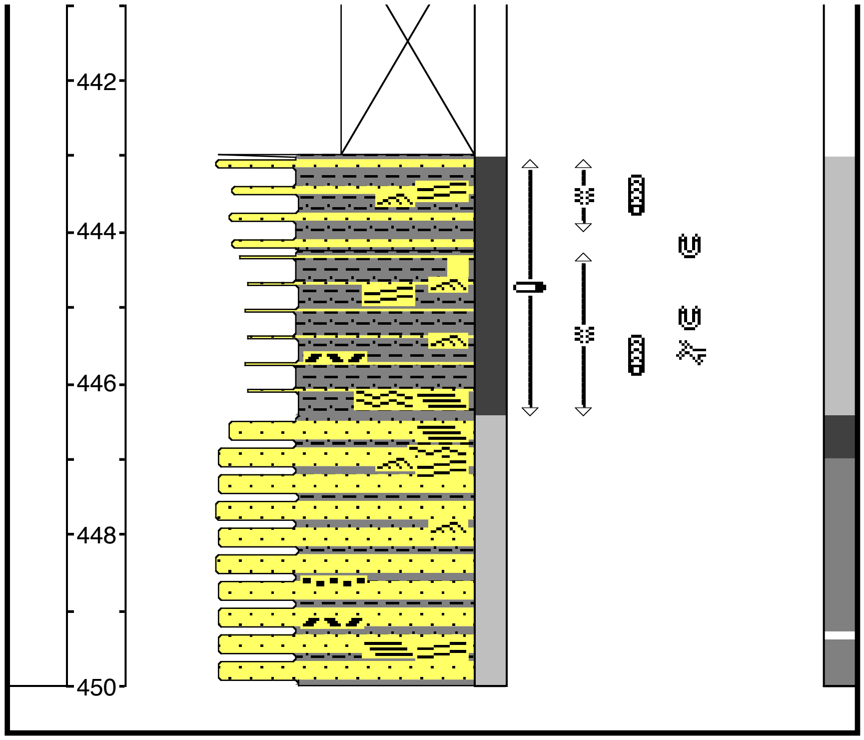
438
440



442
444
446
448
450

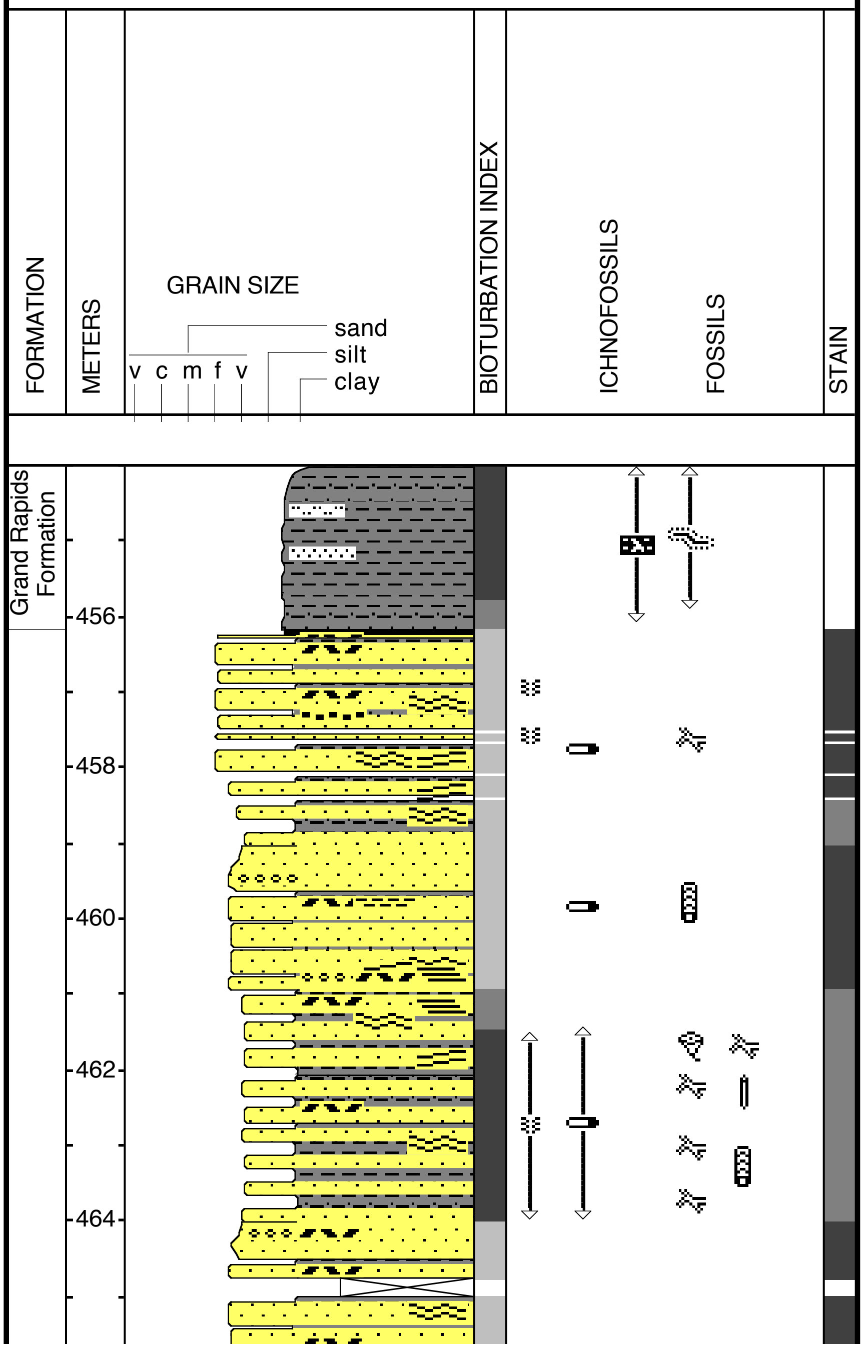
IMP 77 MARIE OV

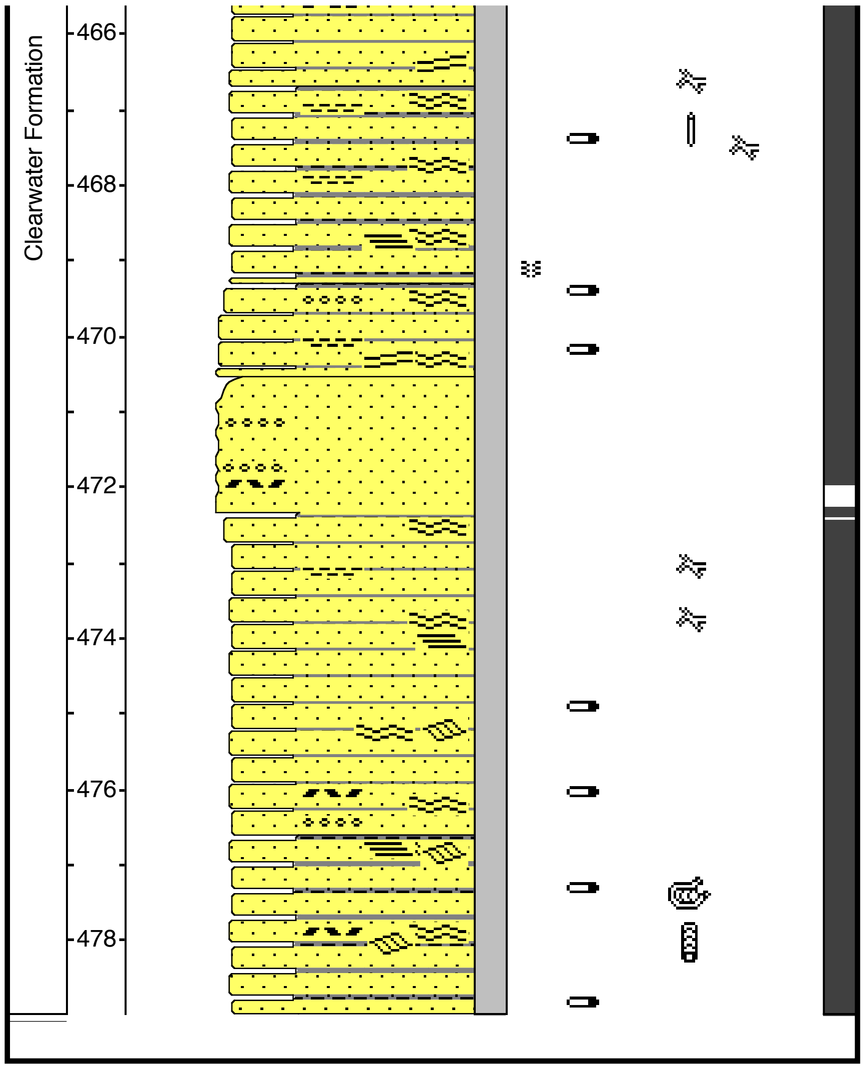
07-36-65-03w4

Date Logged: August 21, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, excellent recovery, only bottom half of core is oil saturated.




Clearwater Formation
466
468
470
472
474
476
478

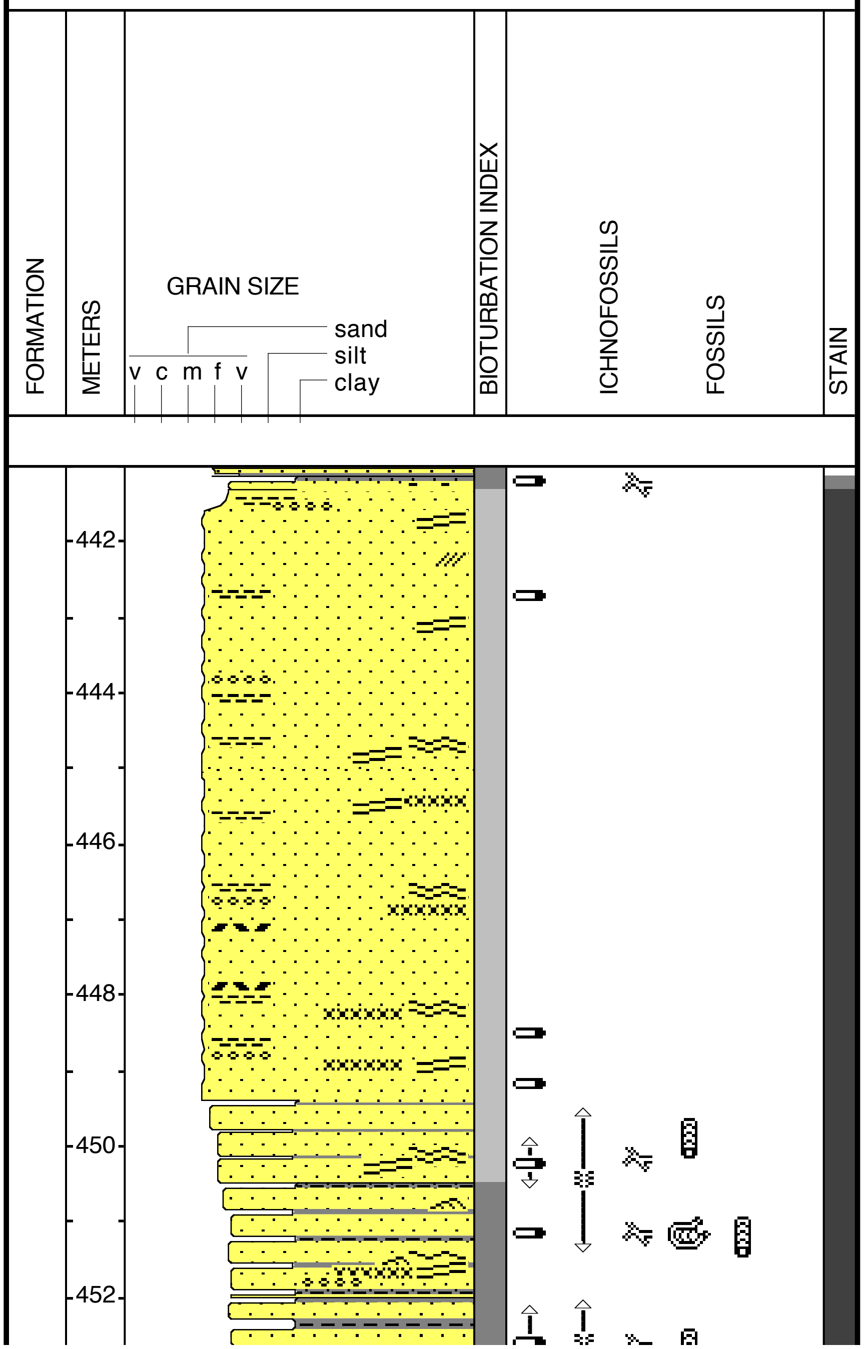
IMP 95 OV COLDLK

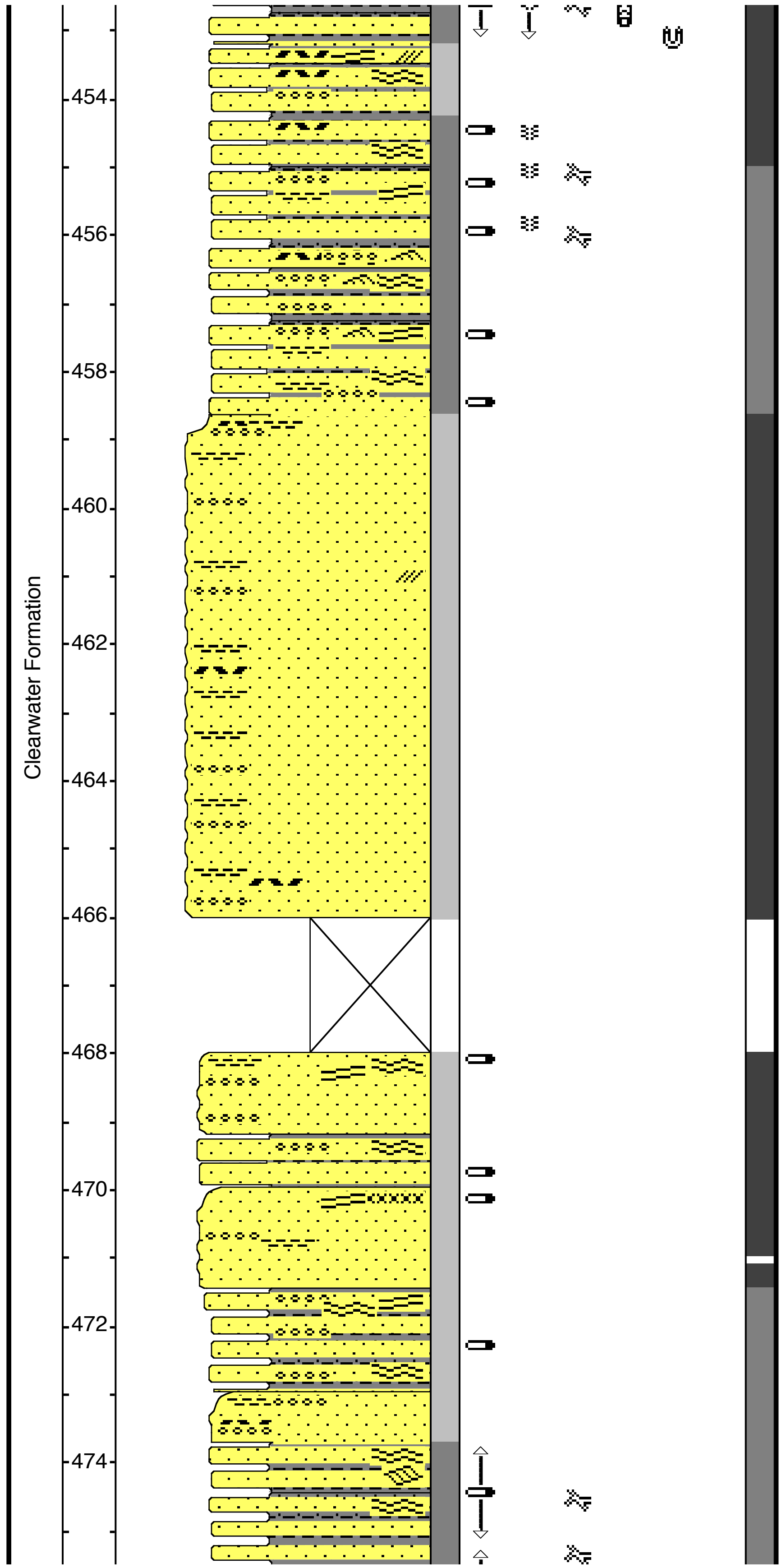
08-02-065-03w4

Date Logged: September 25th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery.




Clearwater Formation
454
456
458
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462
464
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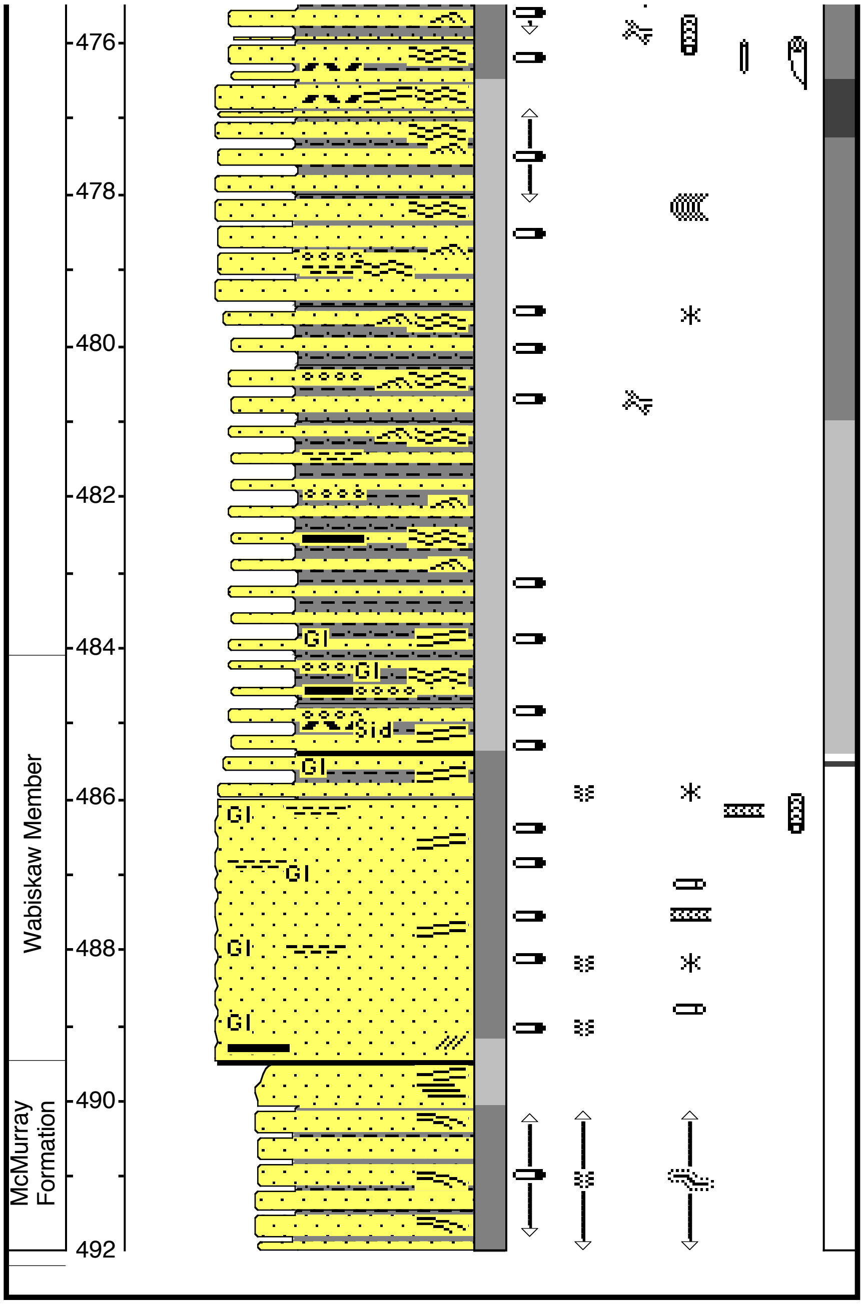
472
474


476
478
480
482
484
486
488
490
492
Wabiskaw Member
McMurray Formation
Gl
Sid

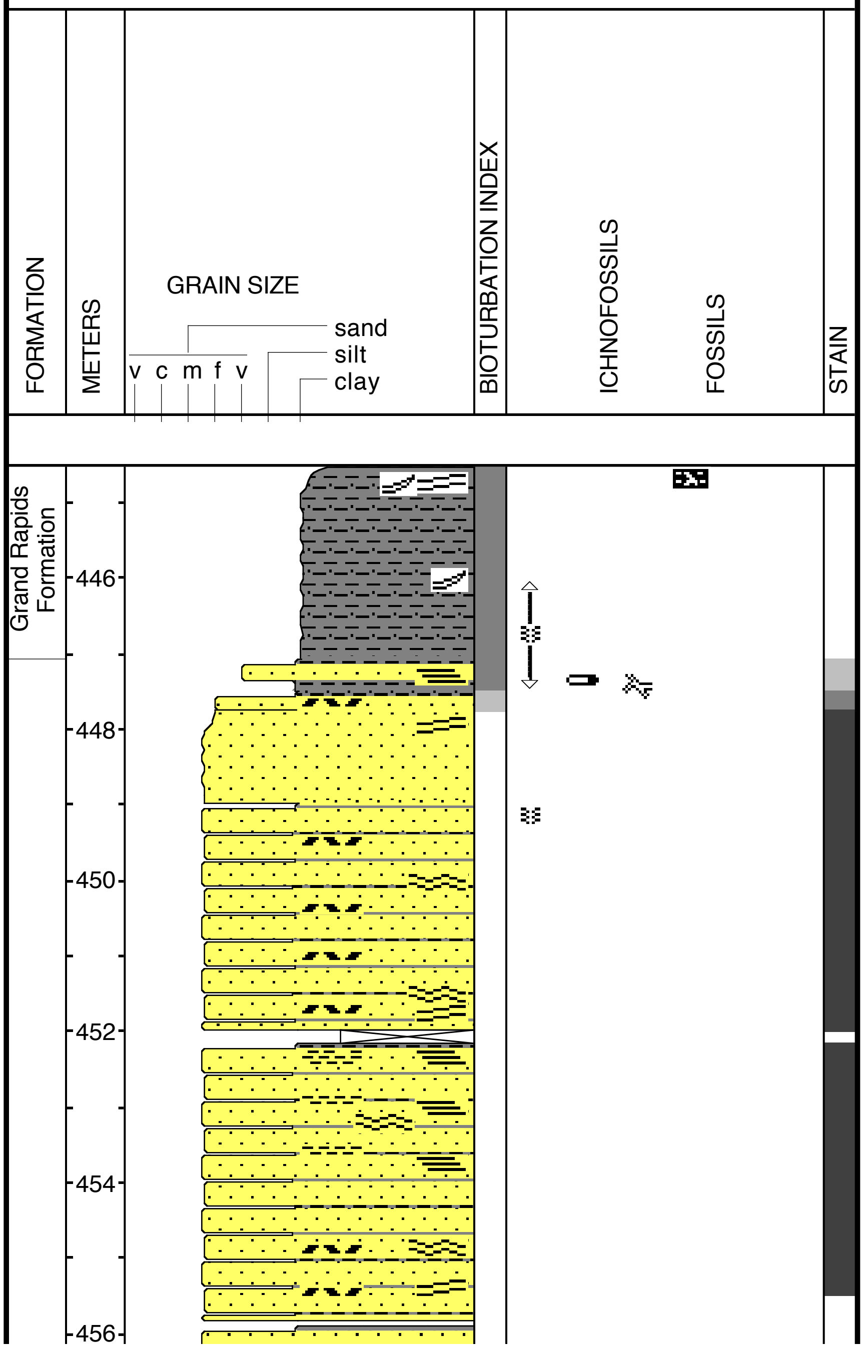
ESSO 86 MARIE 8-19

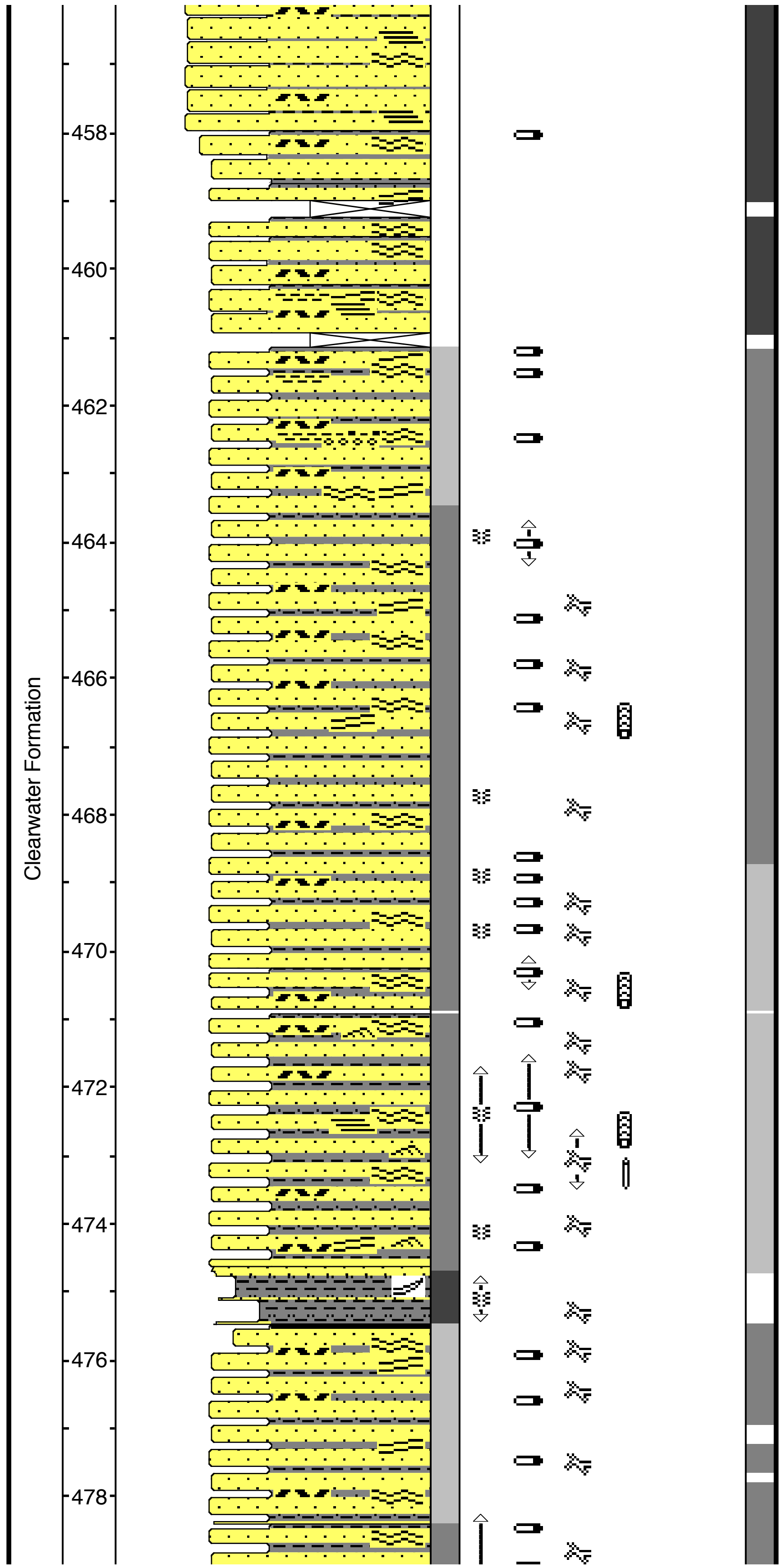
8-19-66-2w4

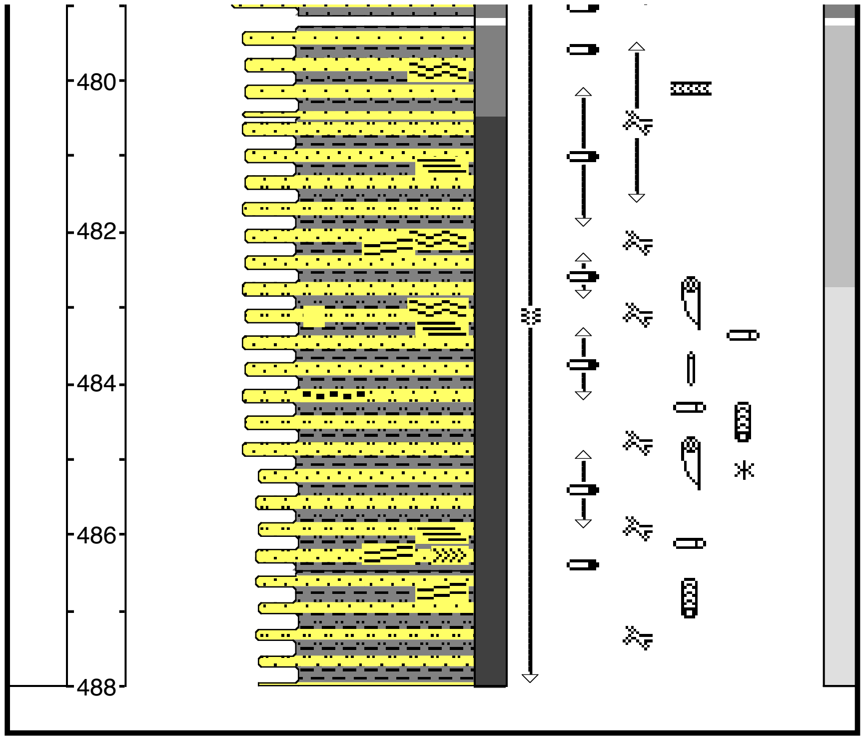
Date Logged: May 13, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, good recovery




Clearwater Formation
458
460
462
464
466
468
470
472
474
476
478


480
482
484
486
488

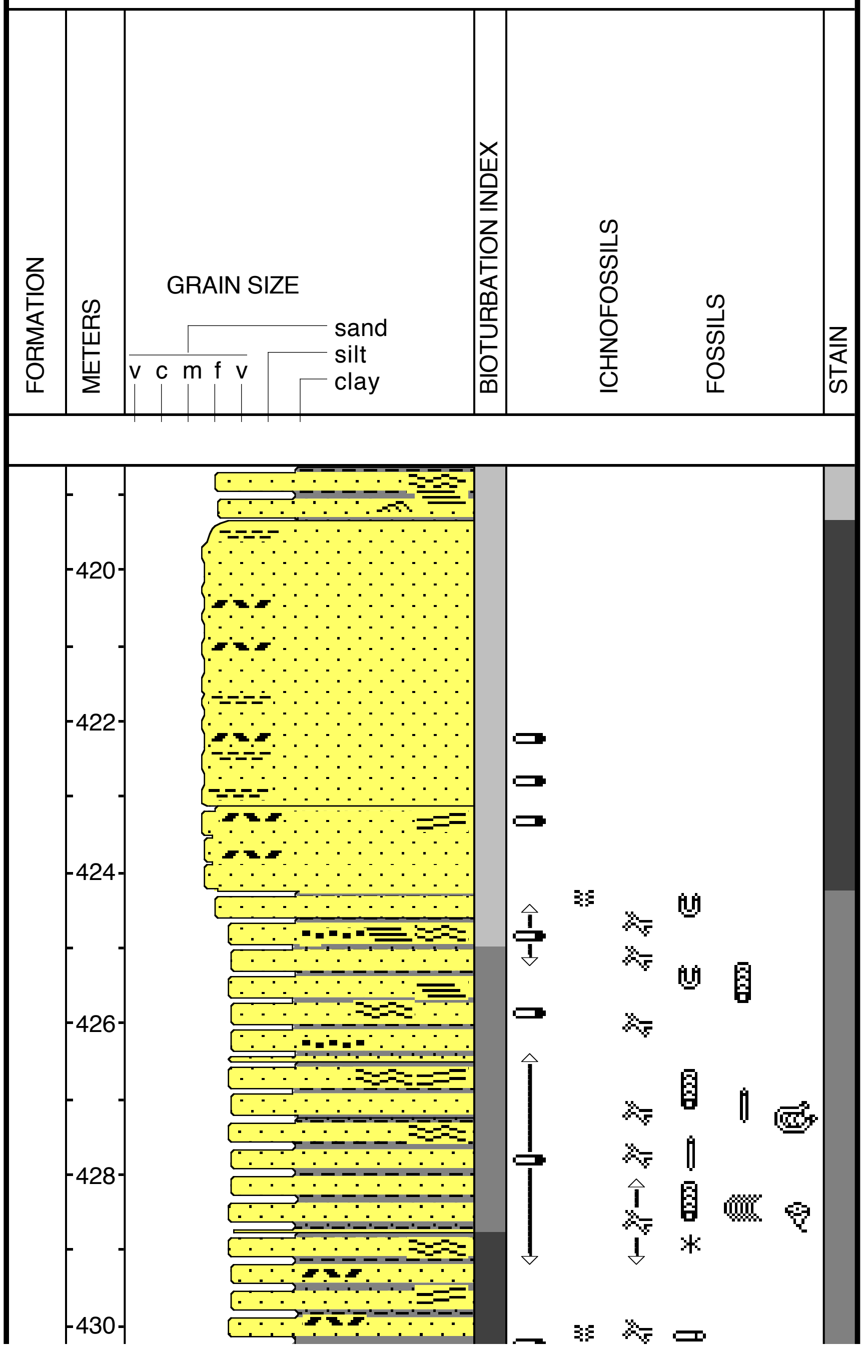
IMPERIAL 99/00 OV COLDLAKE

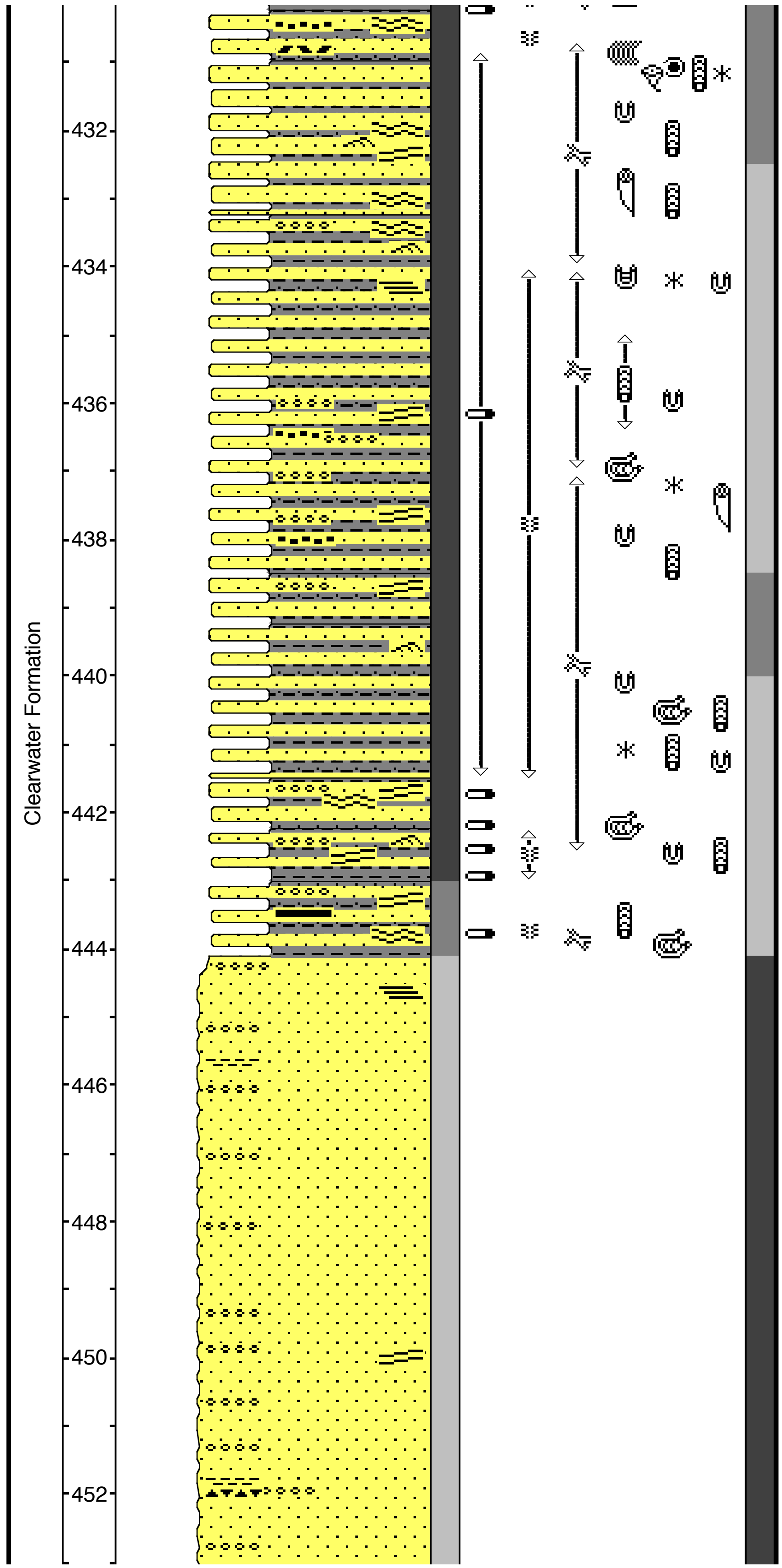
08-24-065-04w4

Date Logged: September 24th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery




Clearwater Formation
432
434
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438
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442
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448
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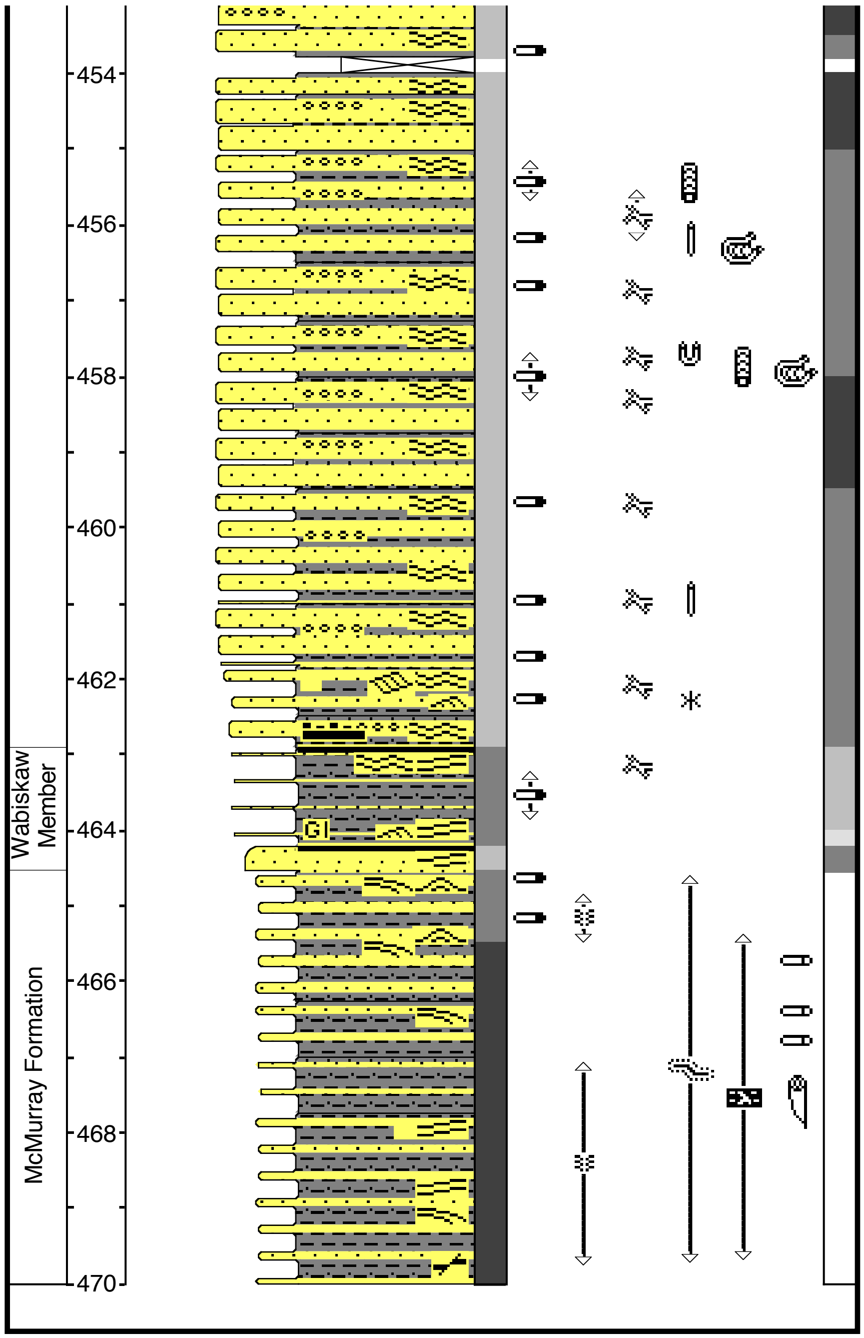
452



454
456
458
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462
464
466
468
470
Wabiskaw Member
McMurray Formation
GI

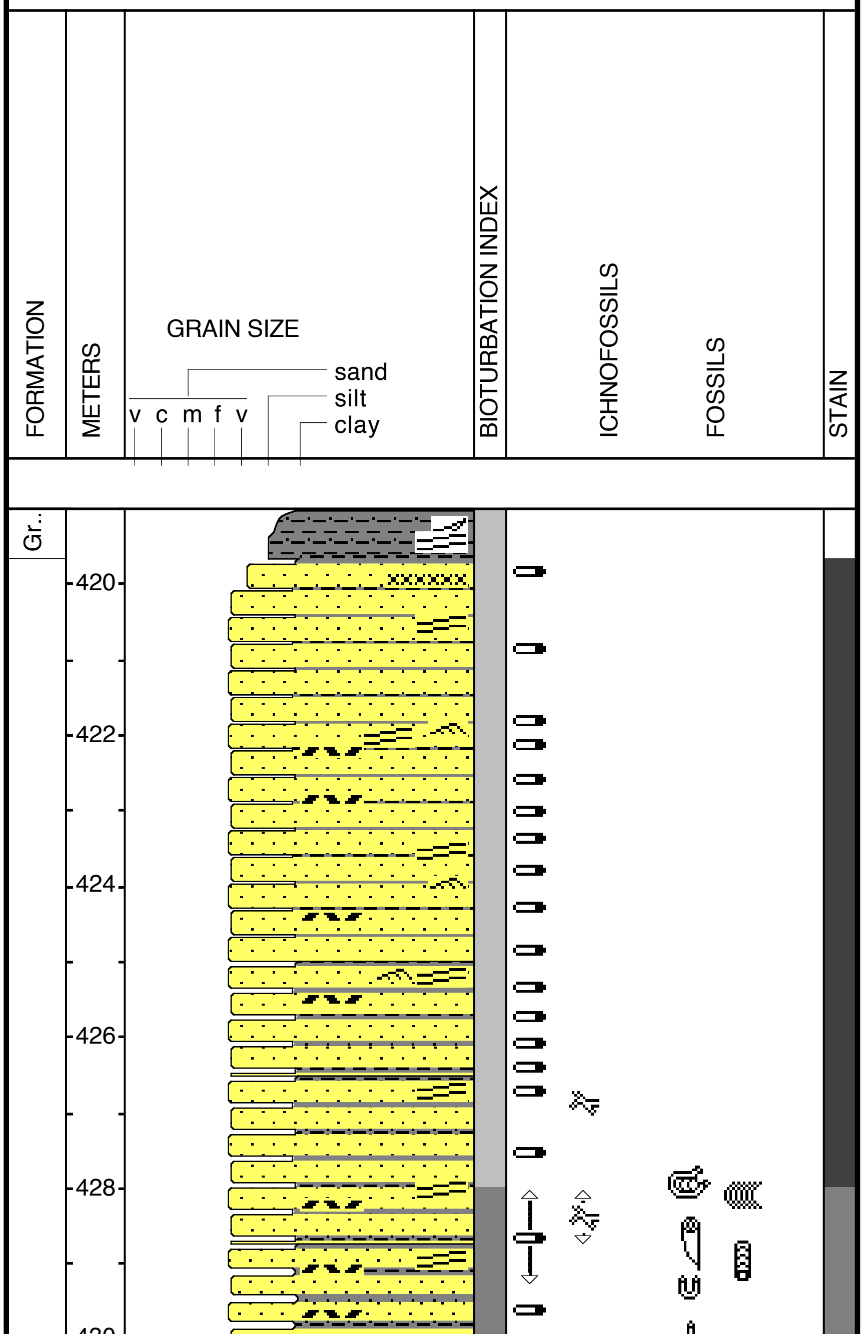
ESSO 86 COLDLK OV 10-04

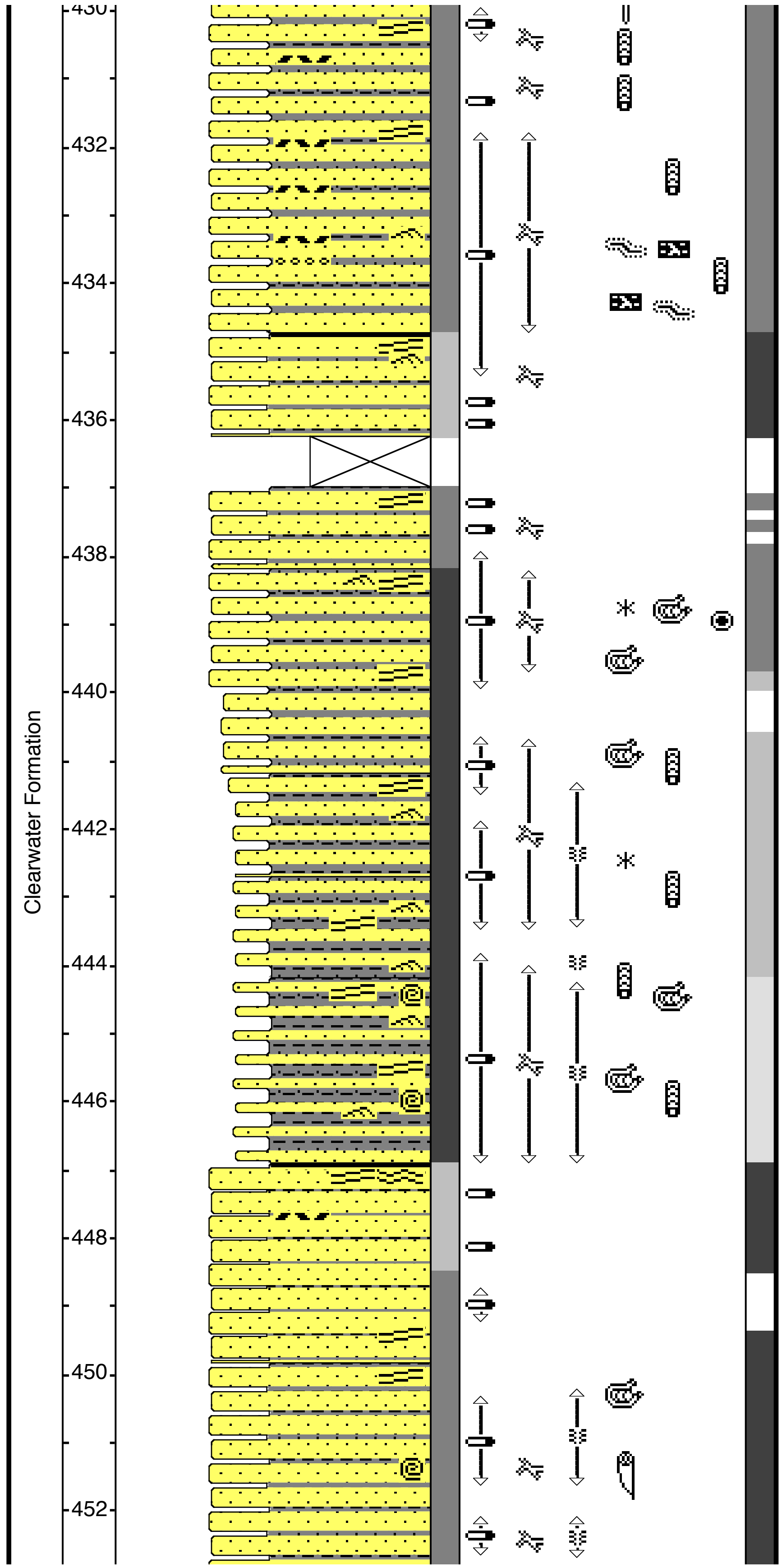
10-04-066-03w4

Date Logged: December 9th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery, contains McMurray and Wabiskaw below and a portion of the Grand Rapids above




Clearwater Formation
430
432
434
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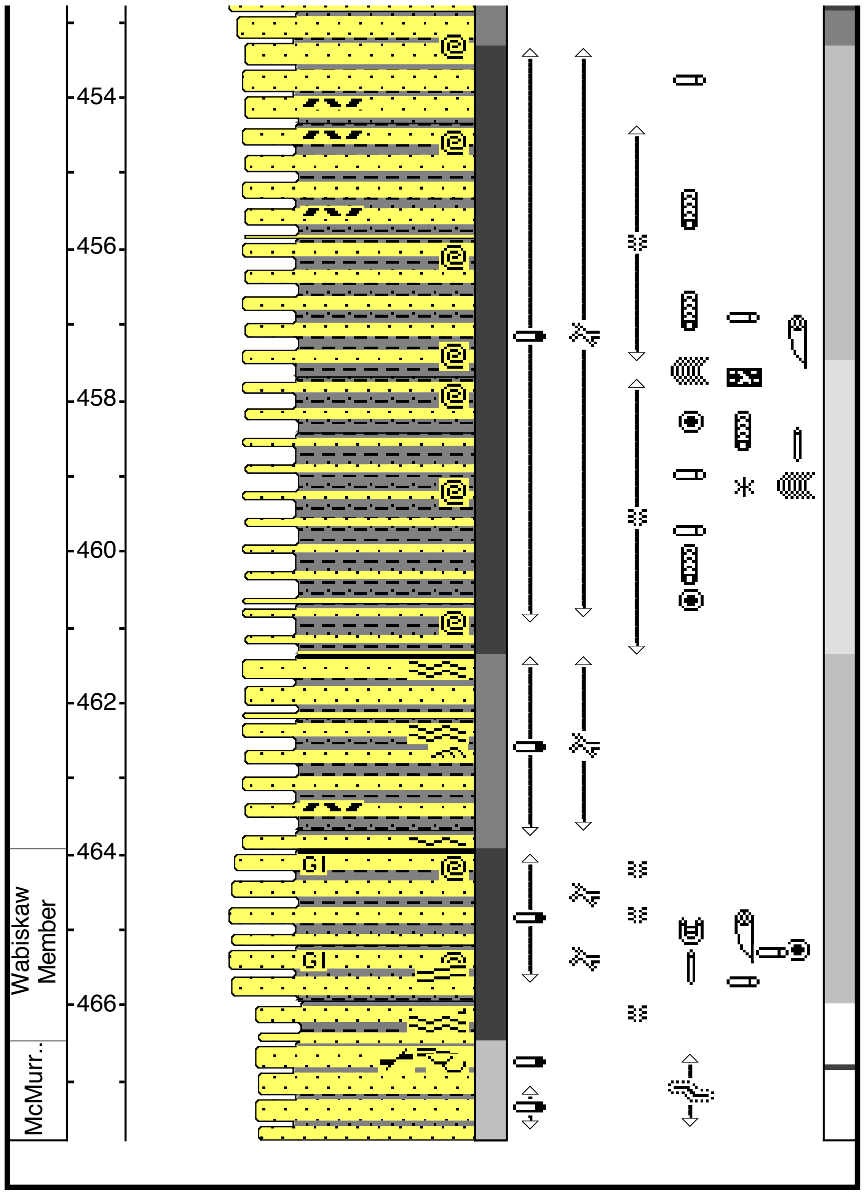
452


454
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464
466
Wabiskaw Member
McMurr..
GI
GI

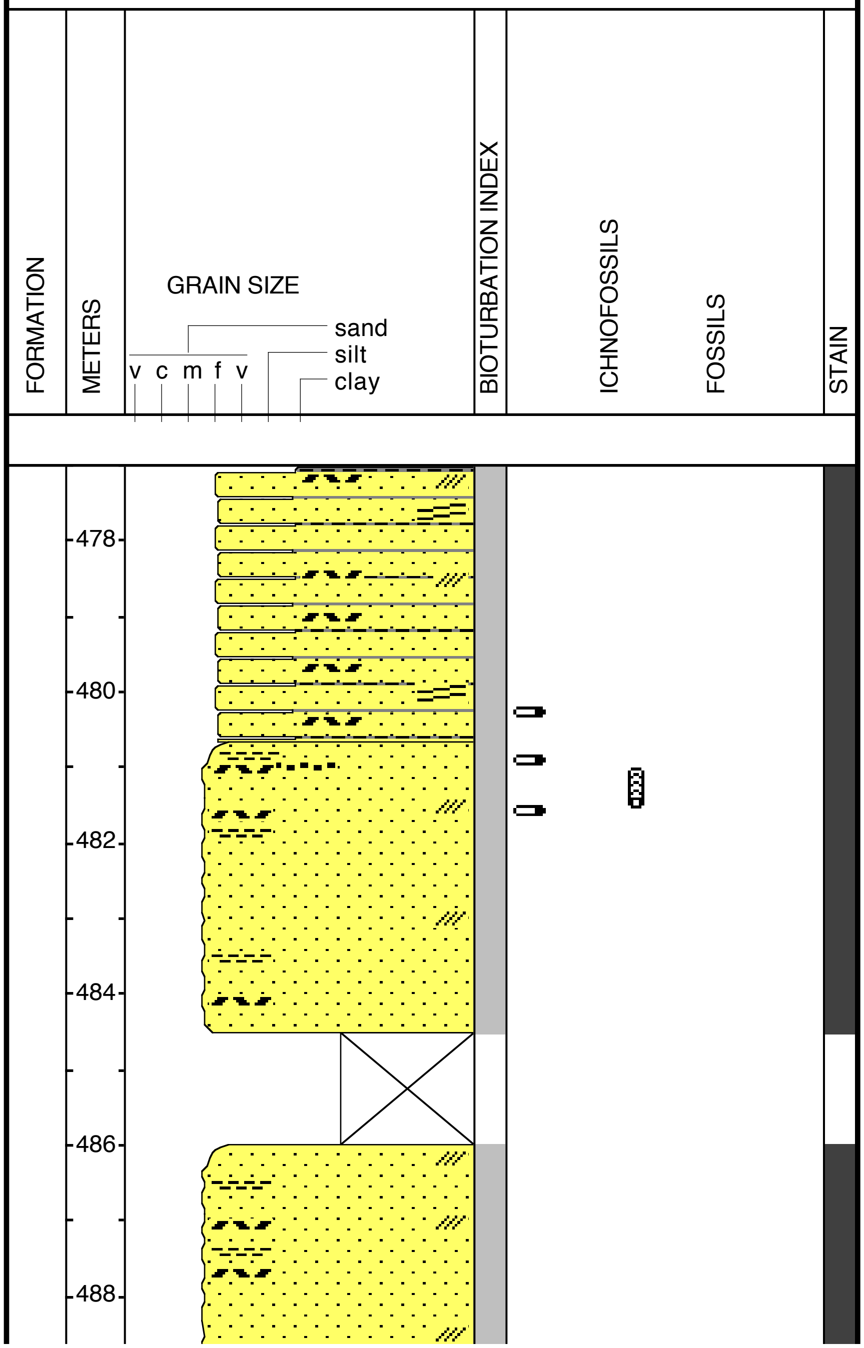
ESSO U 10 LEMING ETHEL LK. EX

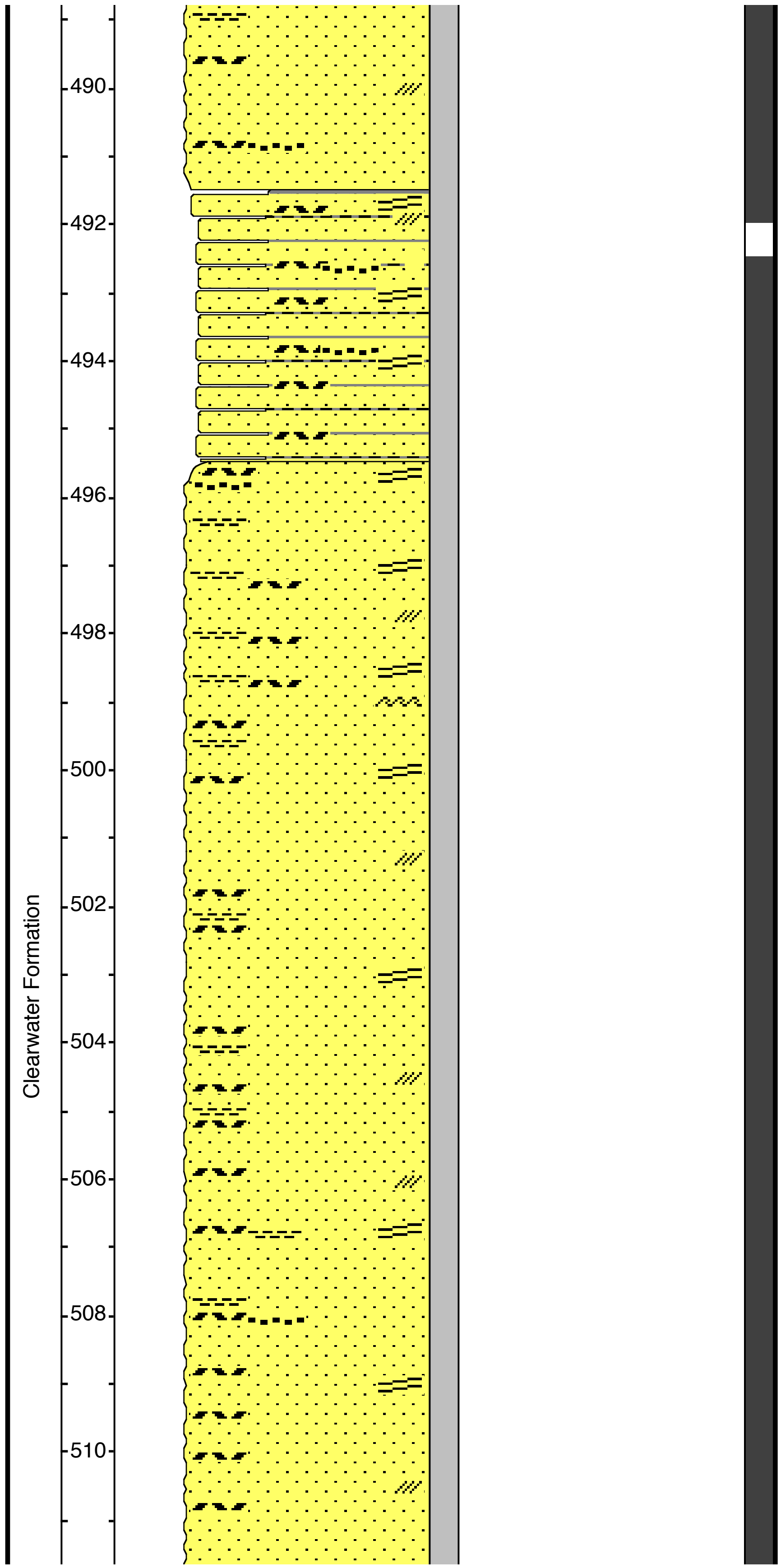
10-08-065-03w4

Date Logged: November 18th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery




Clearwater Formation
490
492
494
496
498
500
502
504
506
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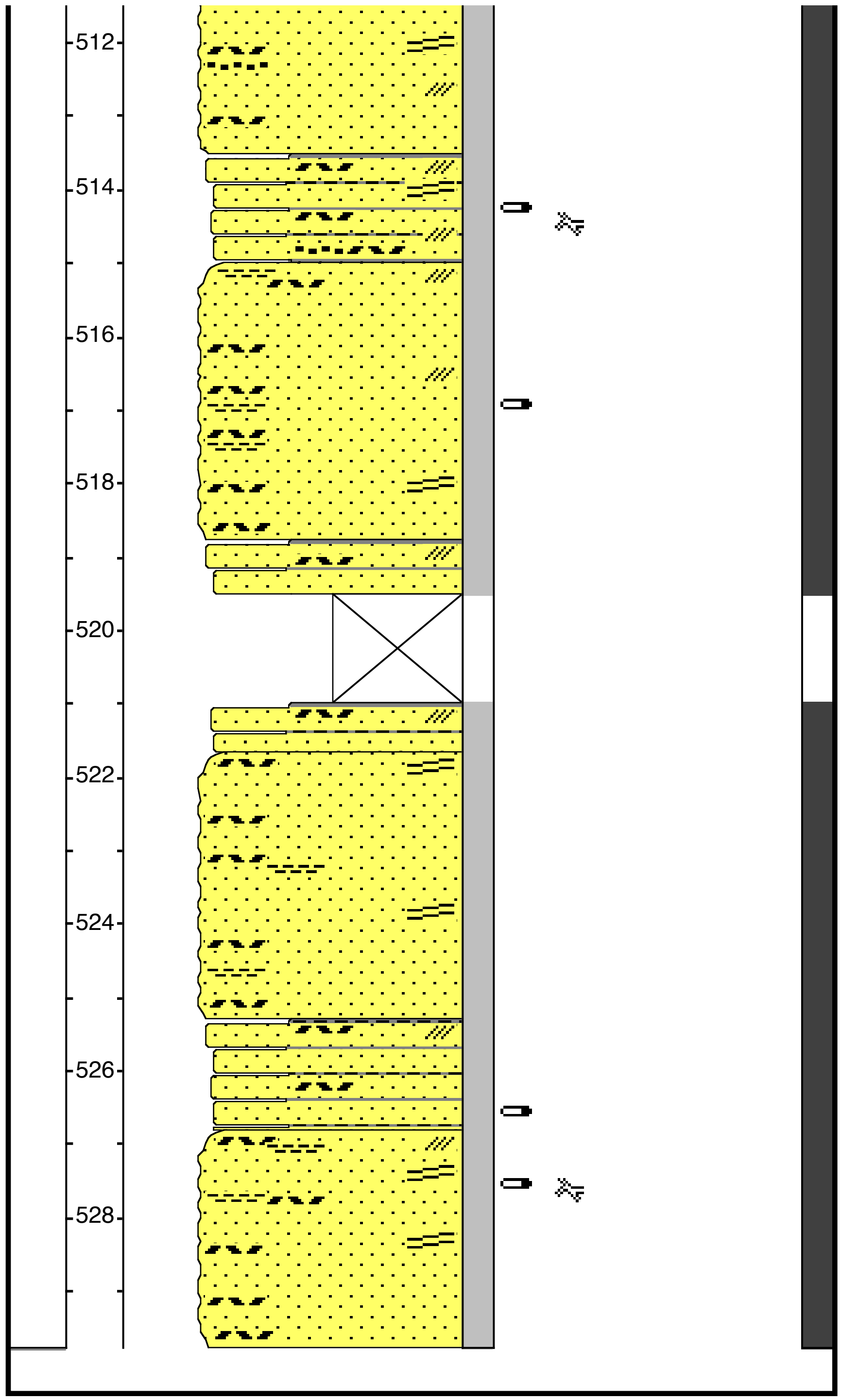
510



512
514
516
518
520
522
524
526
528

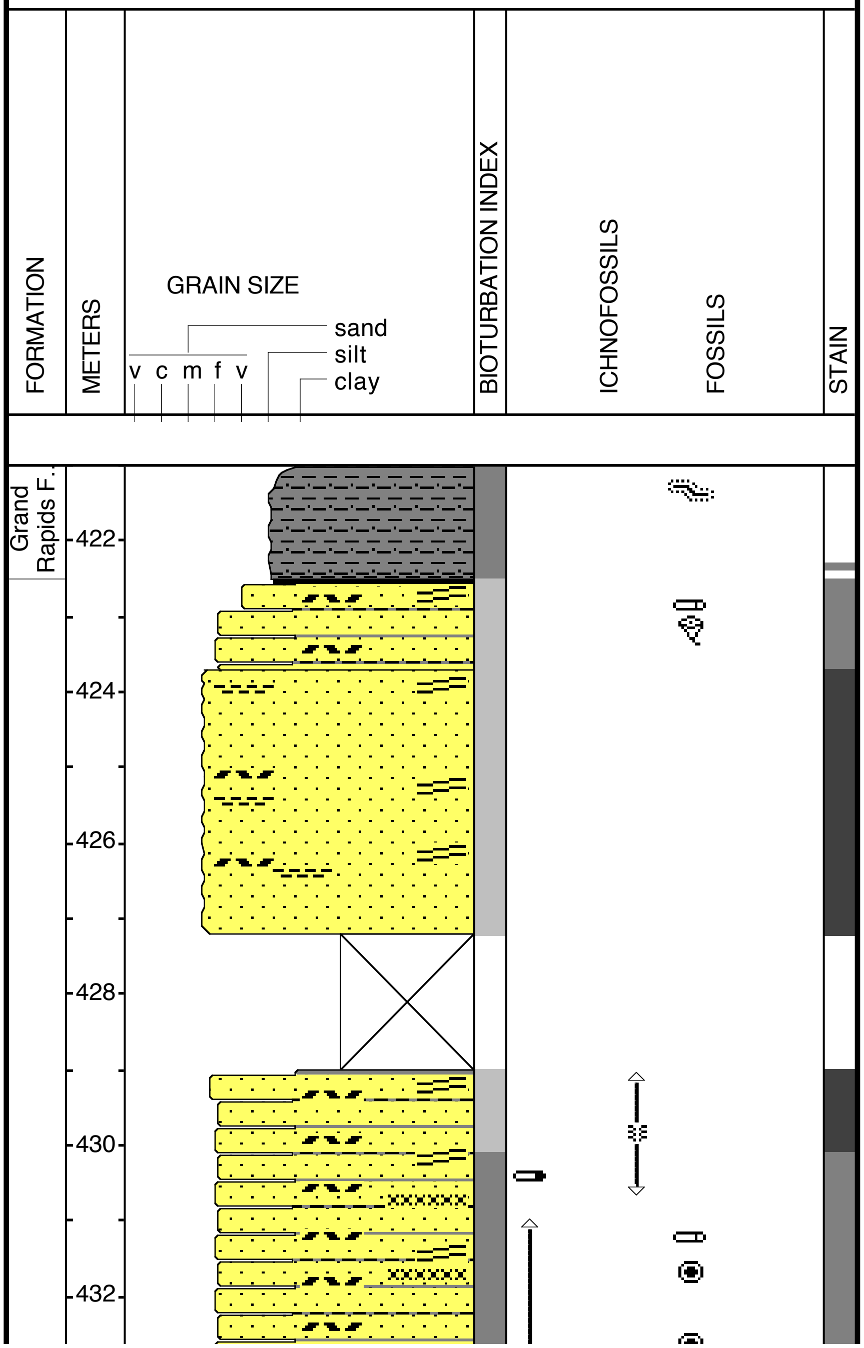
IMP 07 OV COLD LK

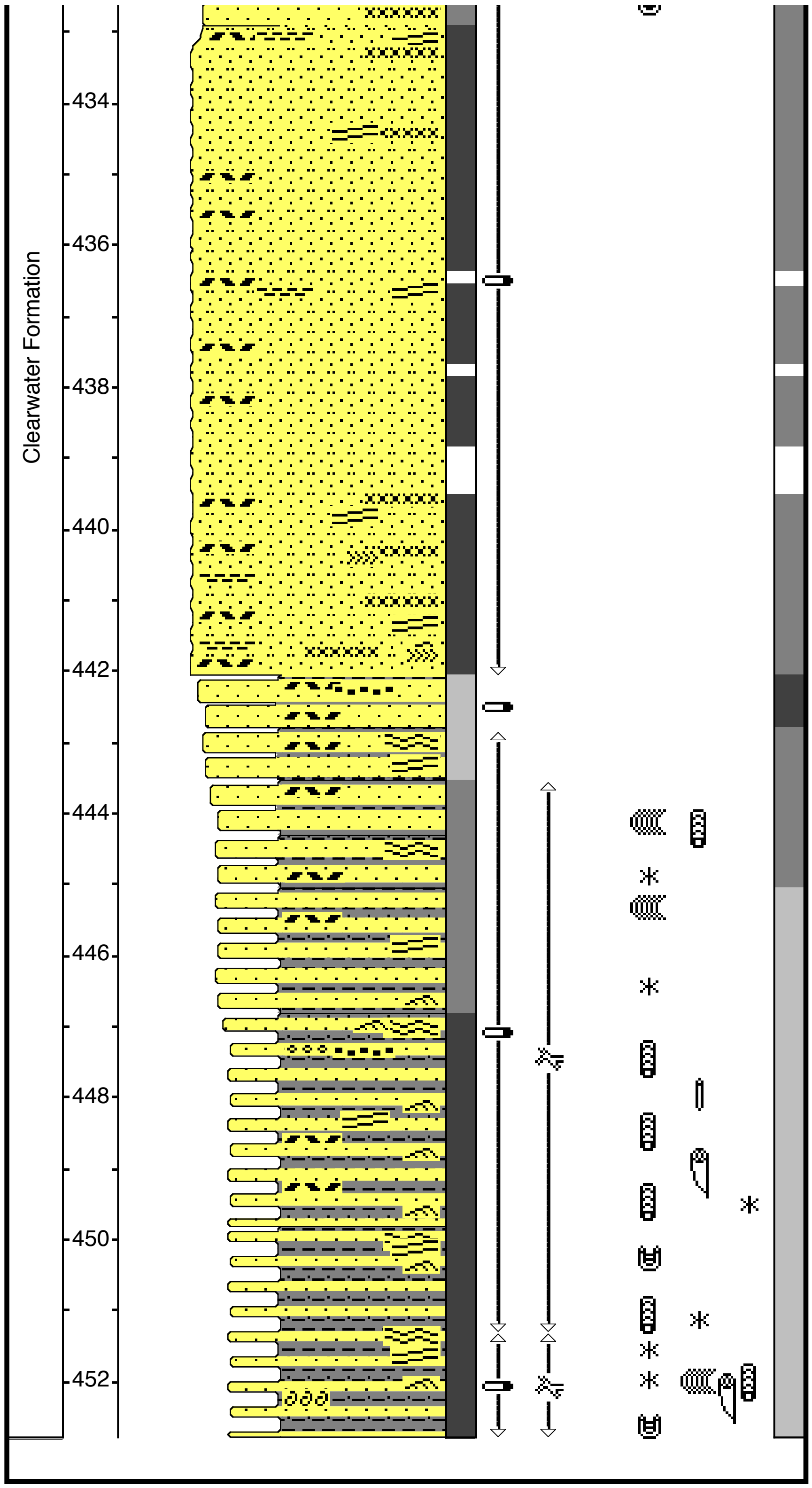
10-22-065-03w4

Date Logged: October 23rd, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, ok recovery




Clearwater Formation
434
436
438
440
442
444
446
448
450
452

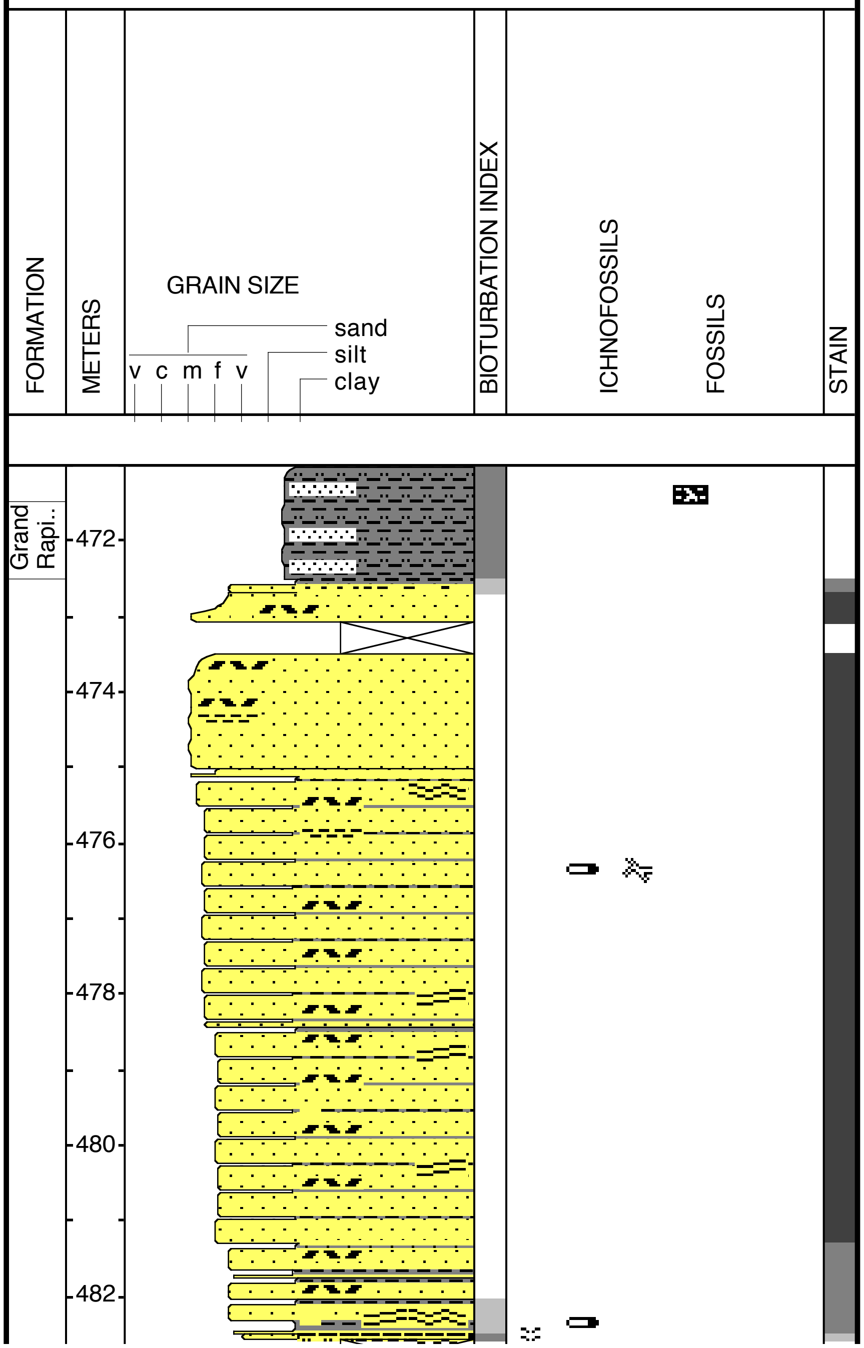
IMP 96 OV Cold LK

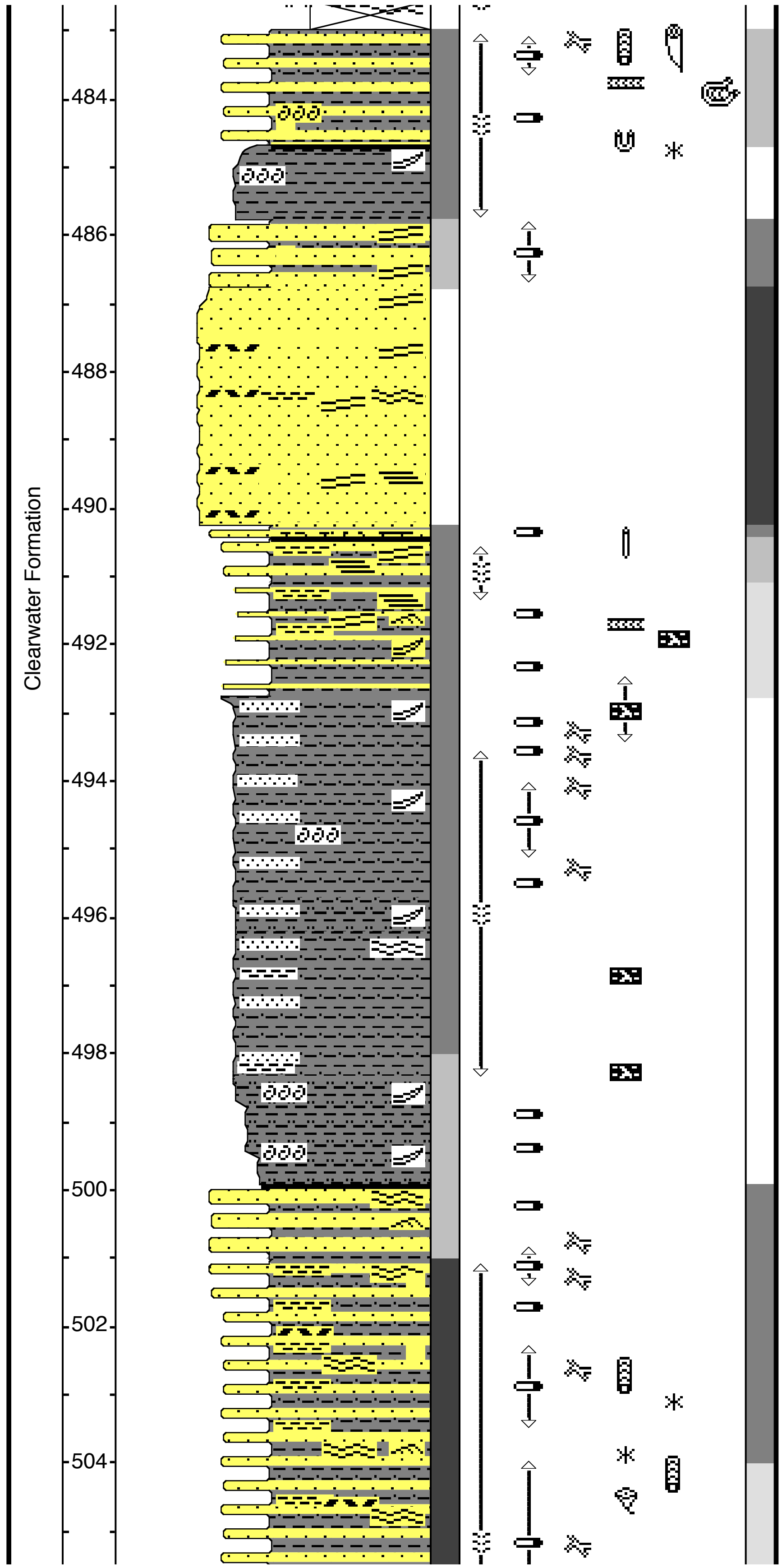
10-27-66-3w4

Date Logged: May 5th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil stained, recovery v. good




Clearwater Formation
484
486
488
490
492
494
496
498
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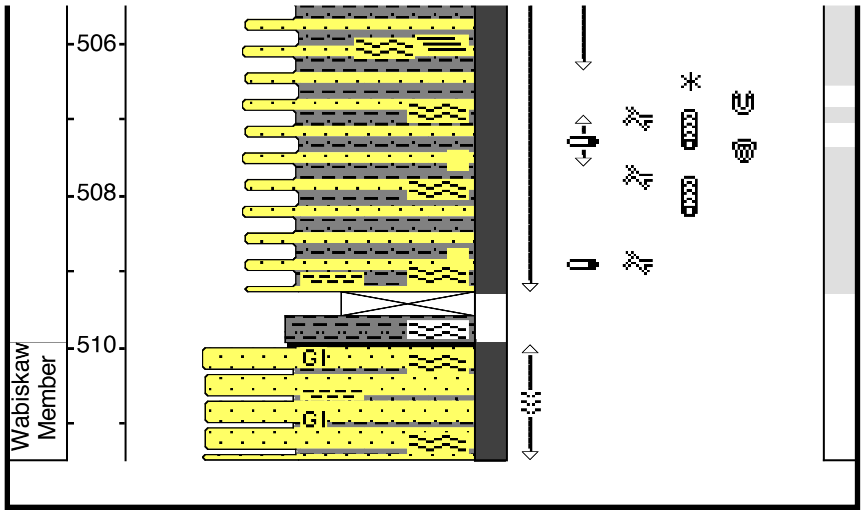
502
504


506
508
510
Wabiskaw Member
GI
GI

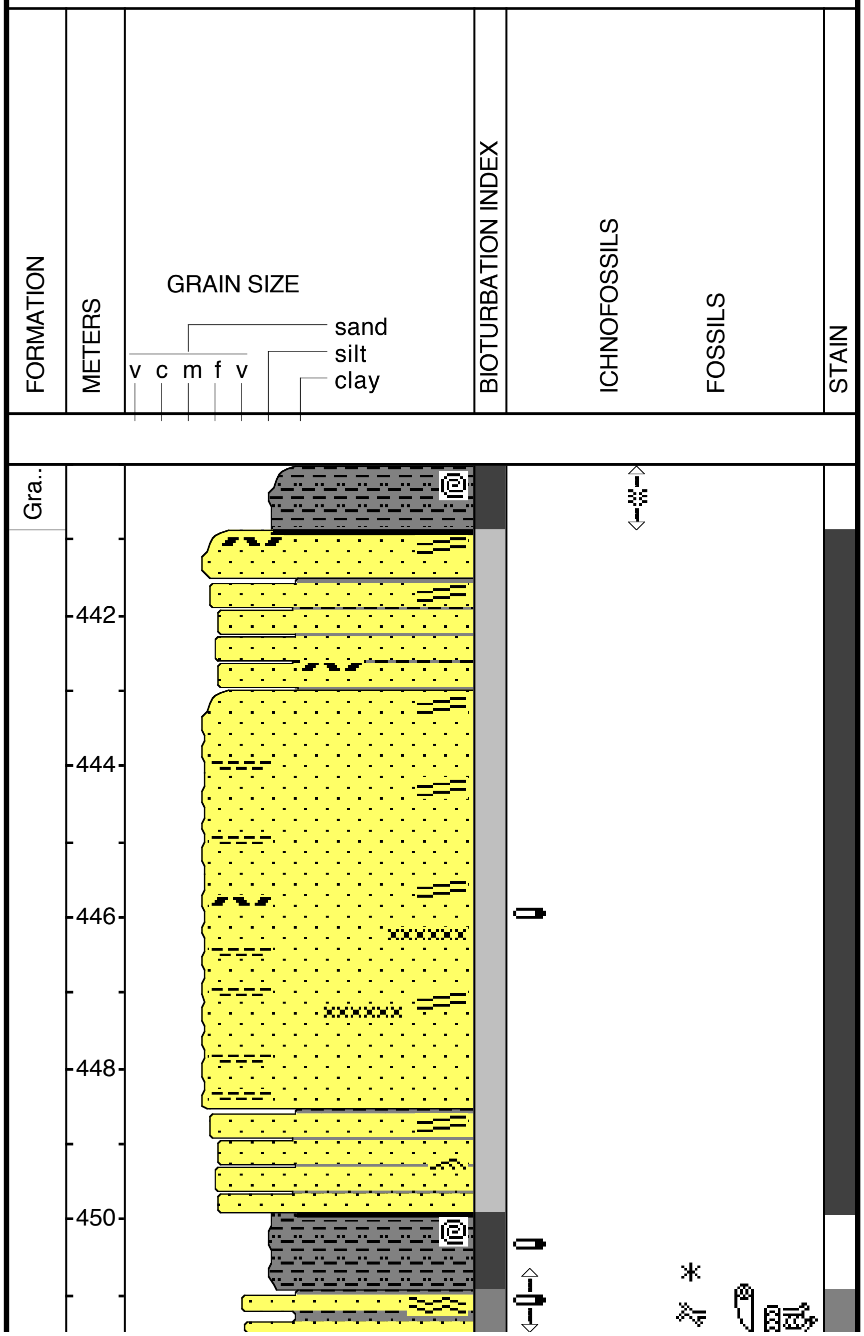
IMP 07 OV COLD LK

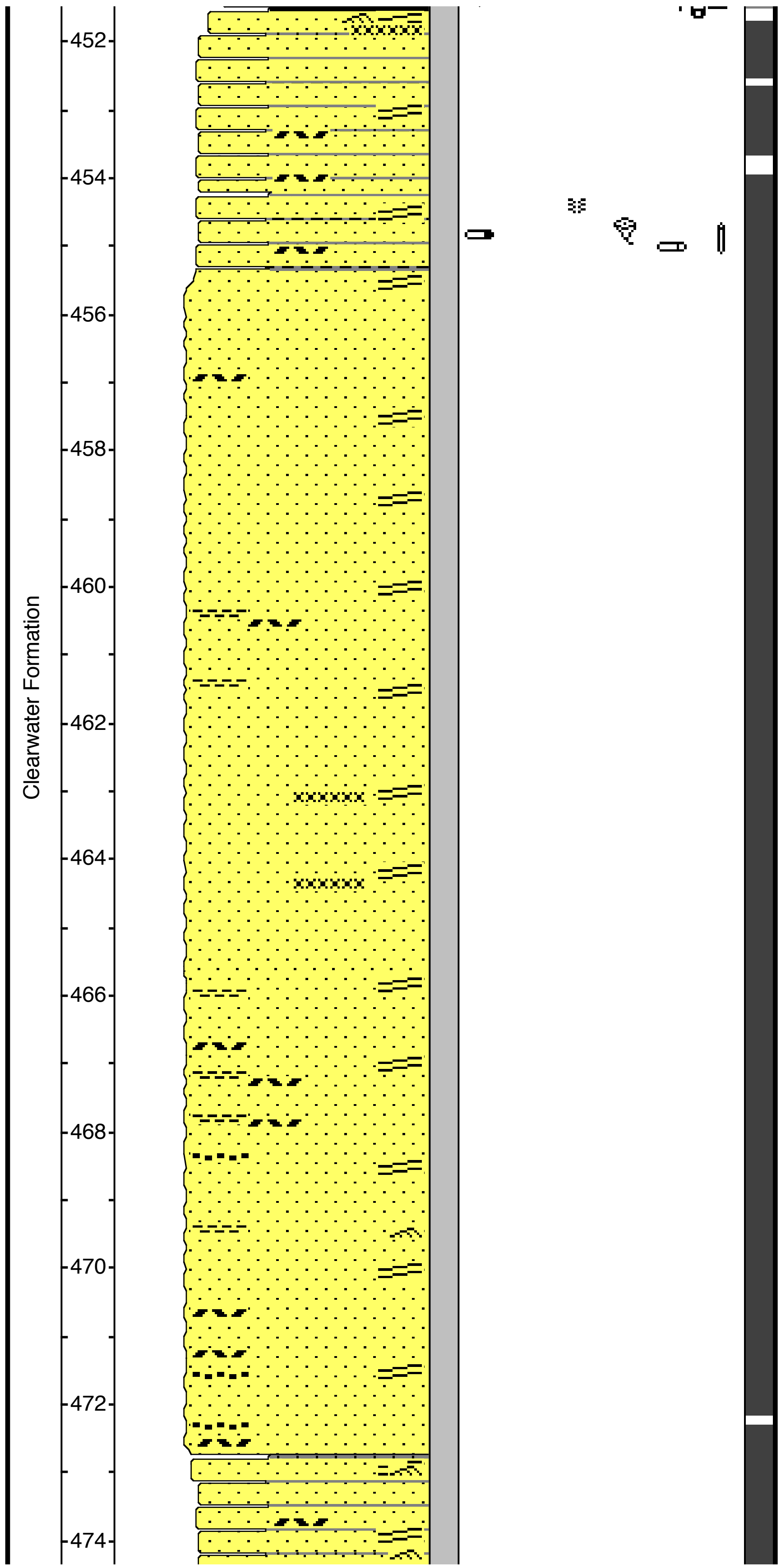
11-06-065-4w4

Date Logged: December 3rd, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery, contains McMurray and Wabiskaw and Grand Rapids above.




Clearwater Formation
452
454
456
458
460
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466
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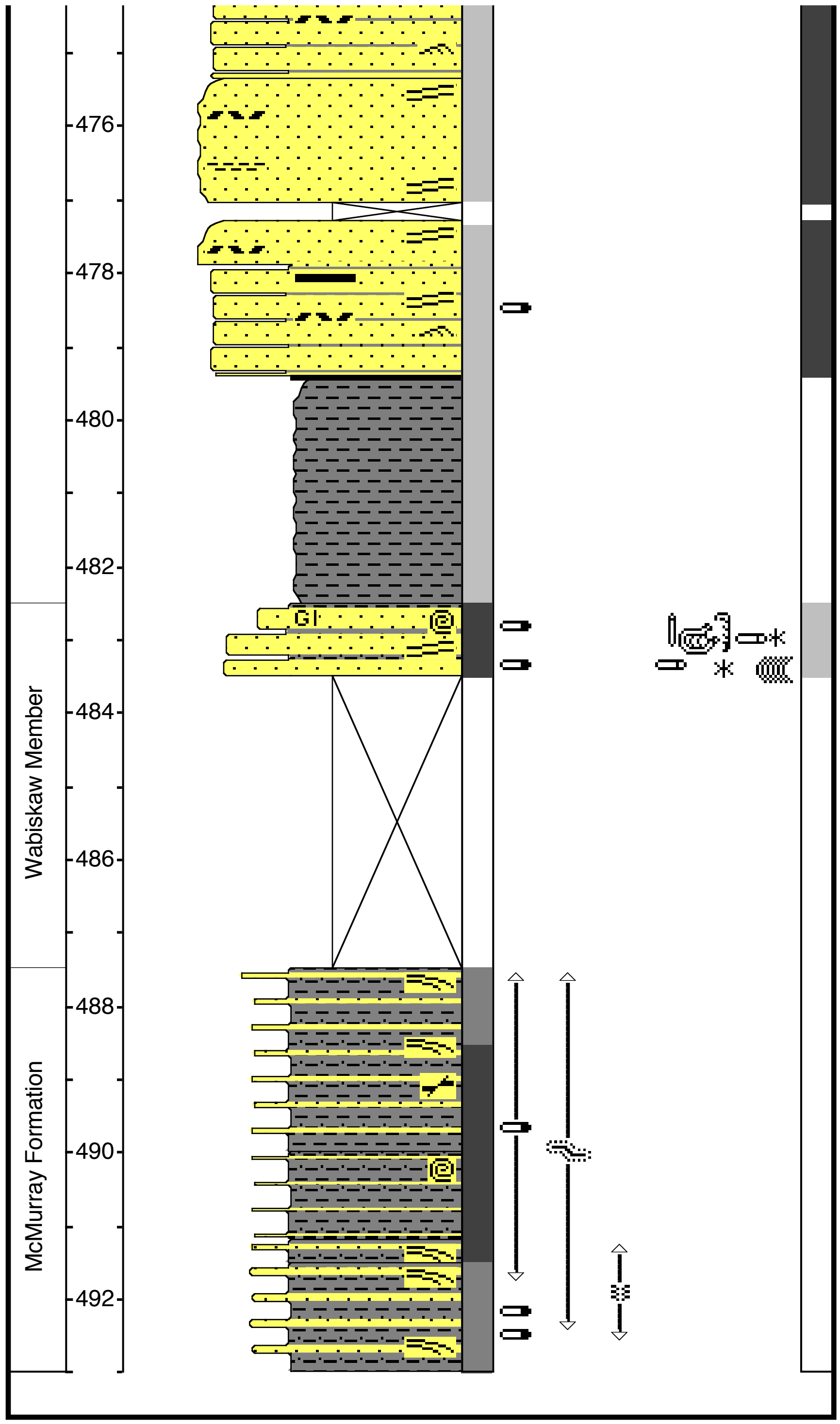
474


476
478
480
482
484
486
488
490
492
Wabiskaw Member
McMurray Formation
Gl

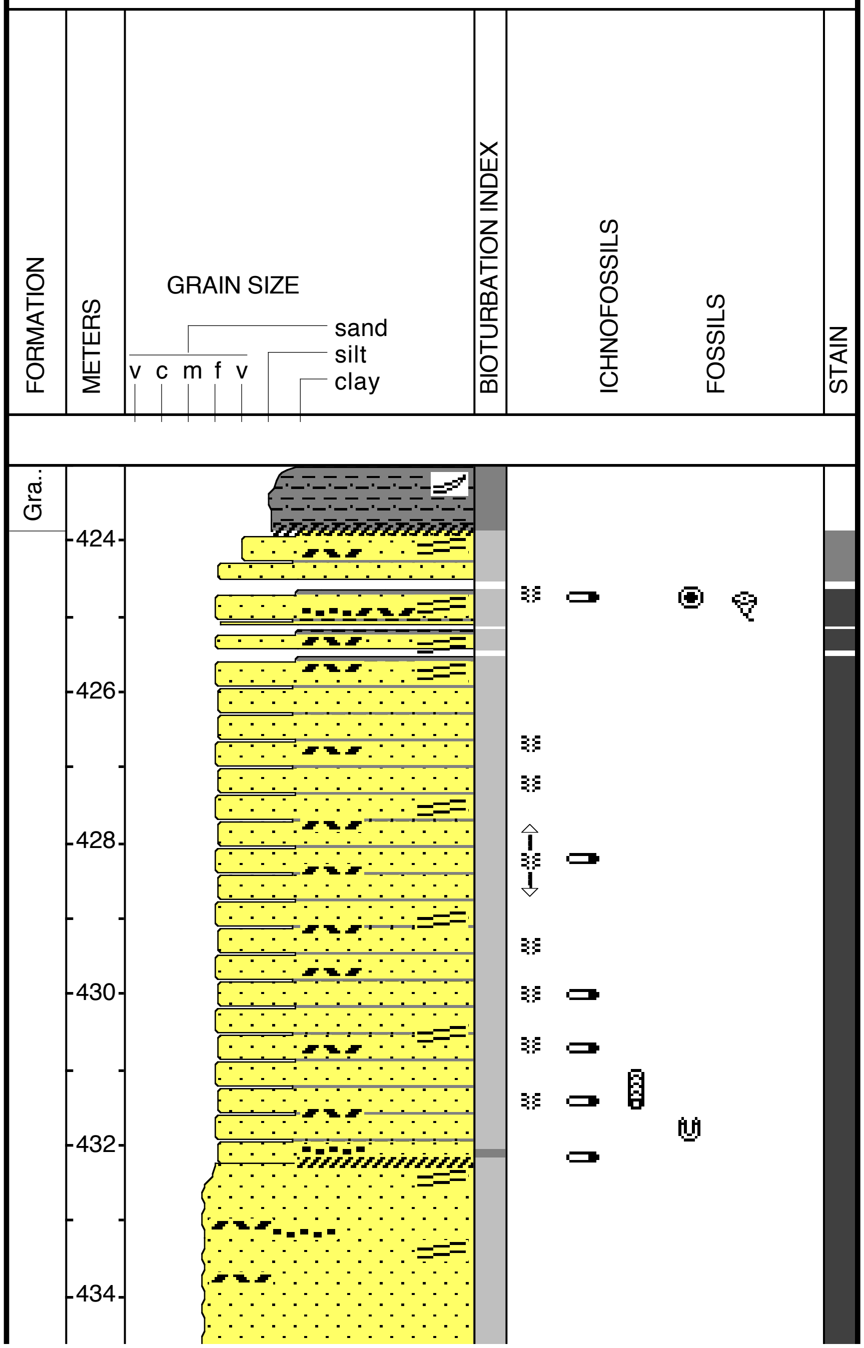
ESSO 88 COLD LK OV 11-9

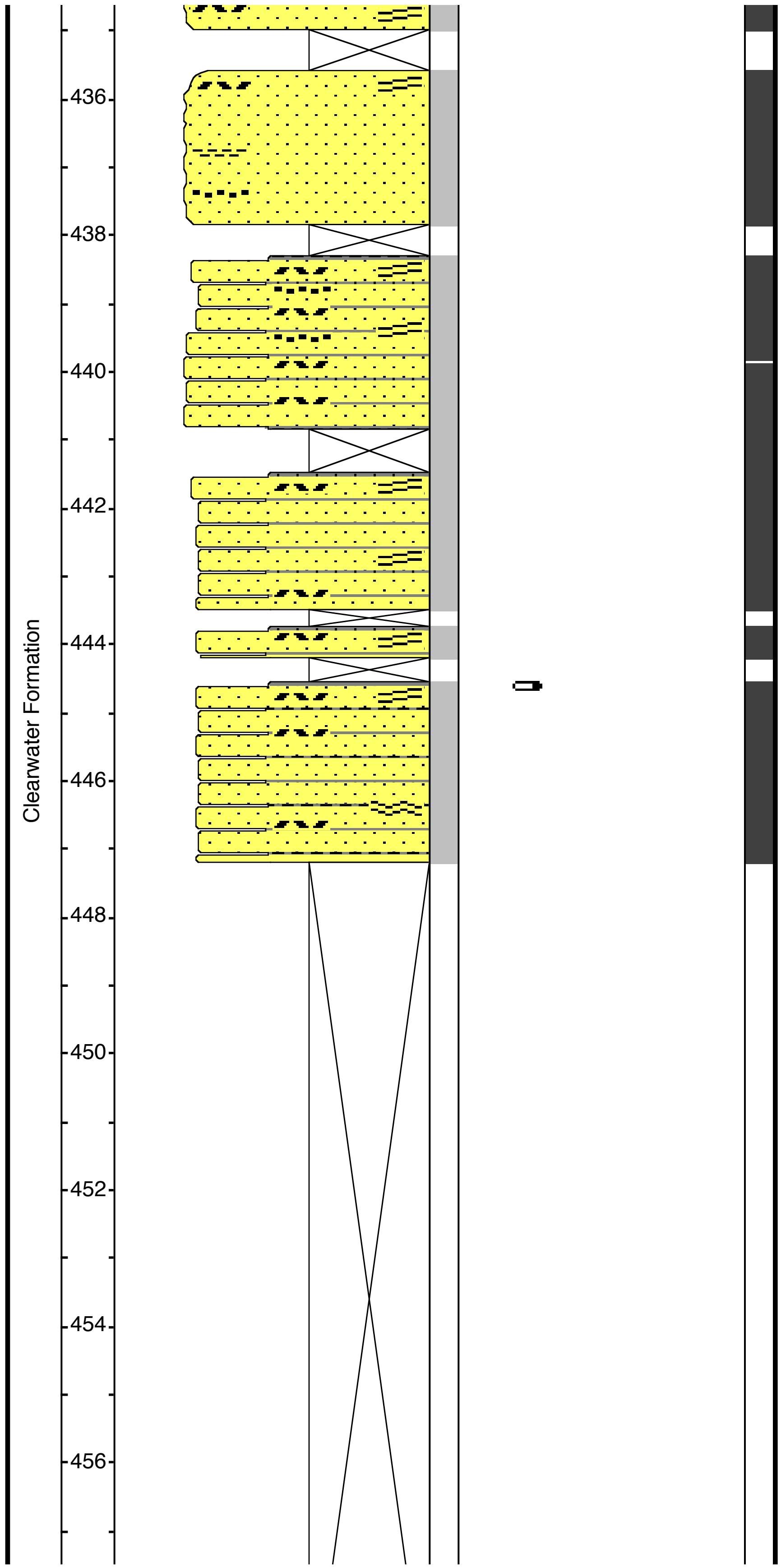
11-09-065-03W

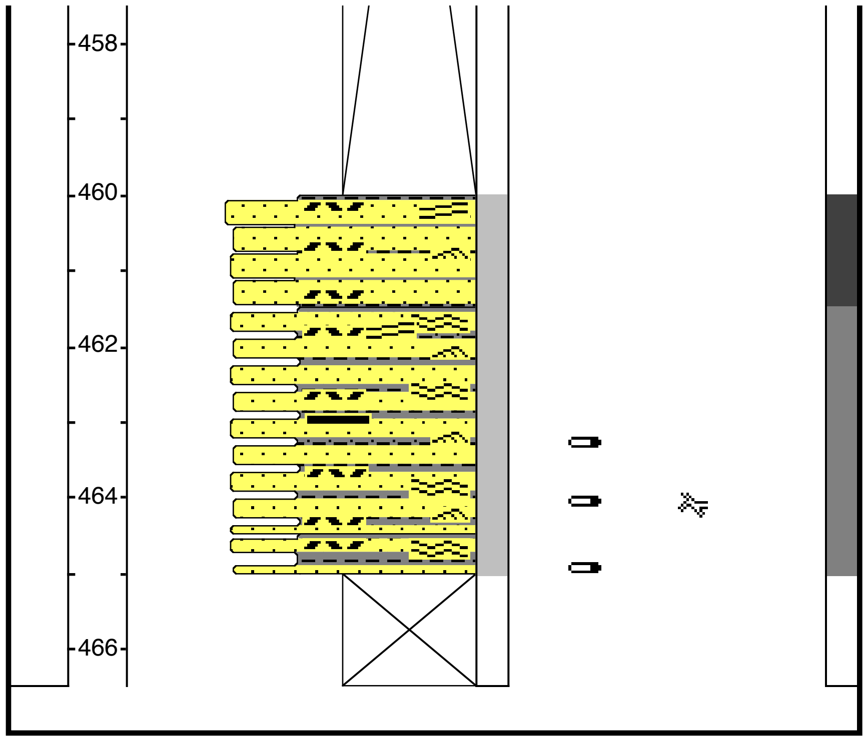
Date Logged: November 5th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, ok recovery, missing ~10m in the middle




Clearwater Formation
436
438
440
442
444
446
448
450
452
454
456


458
460
462
464
466

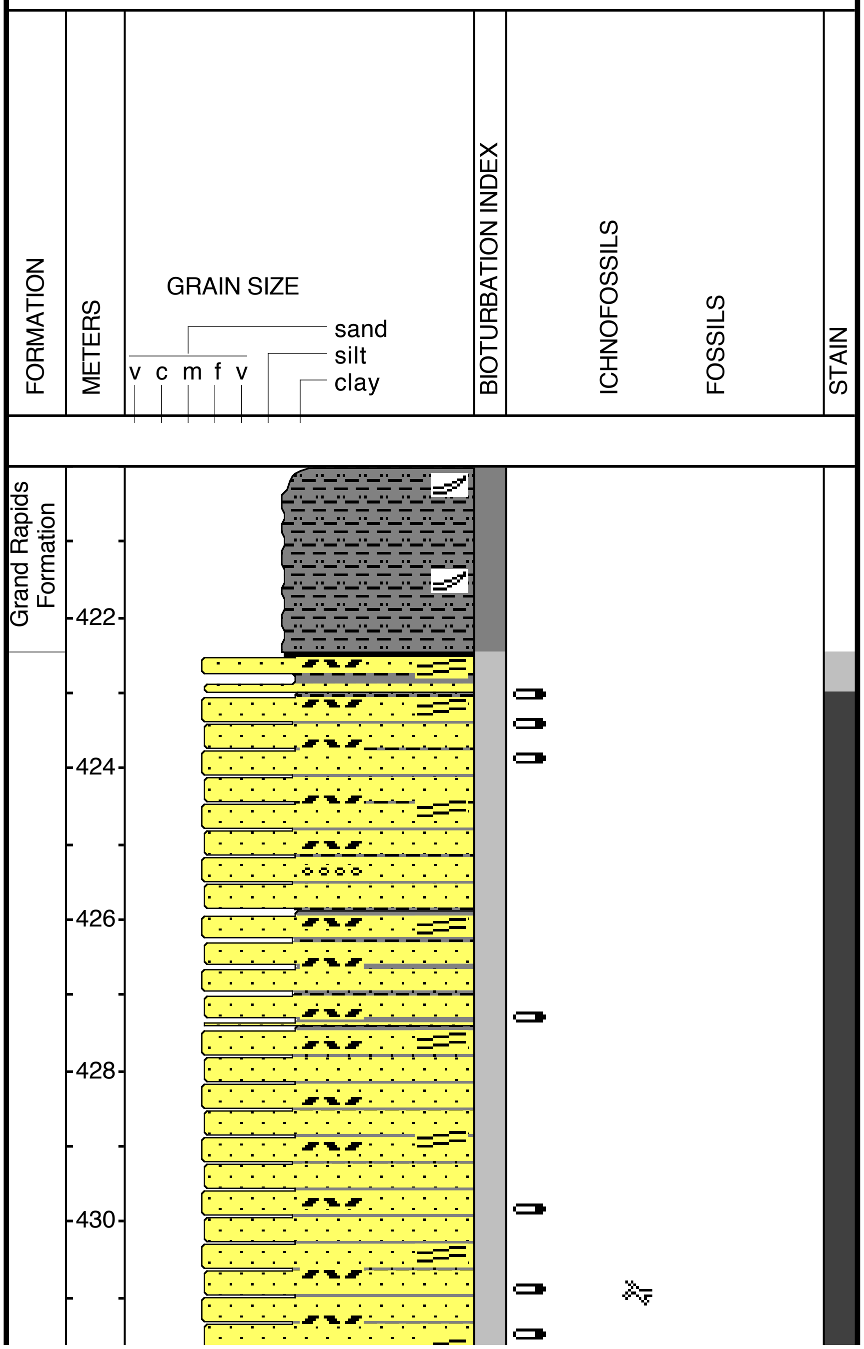
IMP 07 OV COLD LK

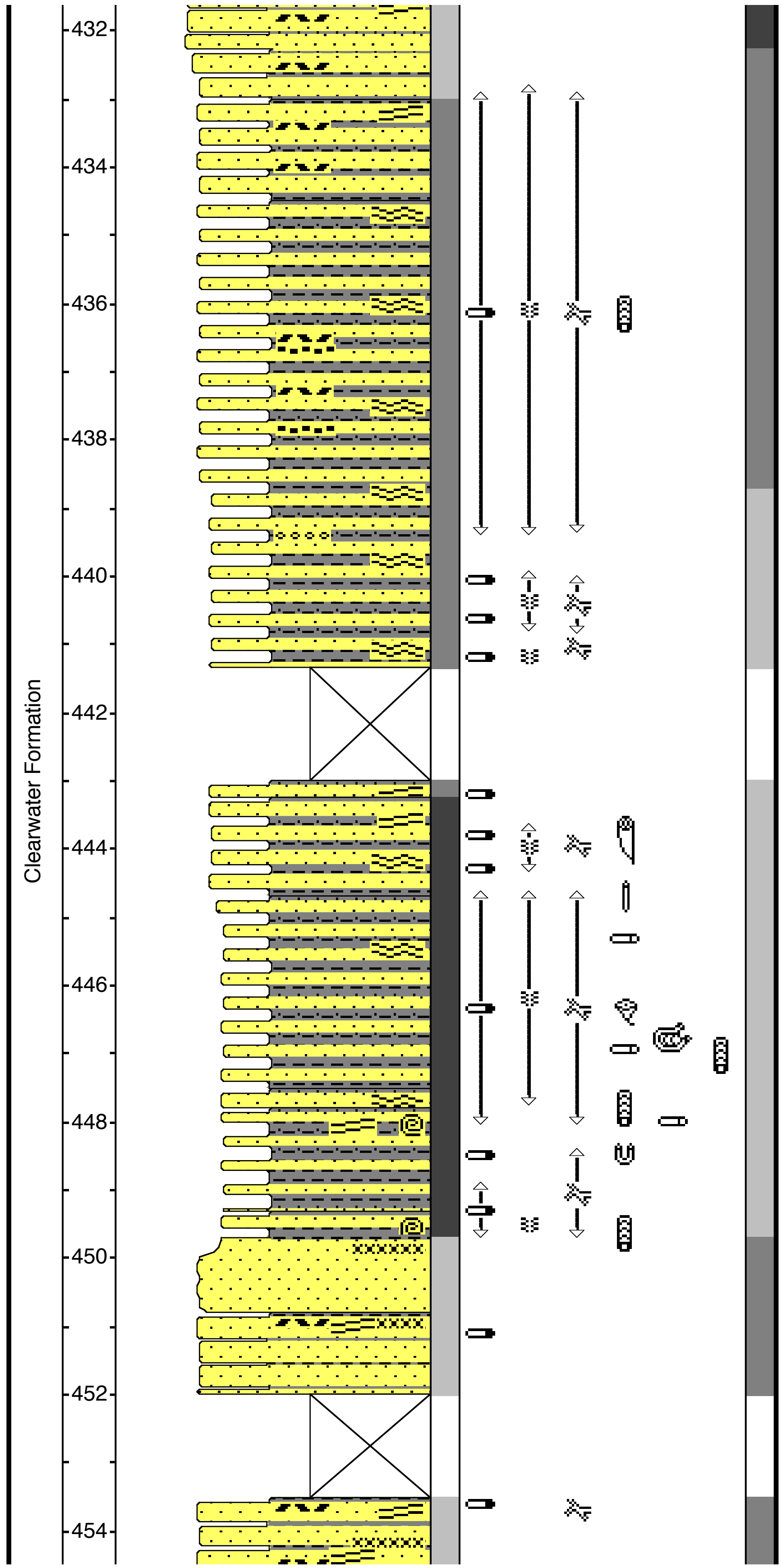
11-10-066-03w4

Date Logged: December 10th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, good recovery.




Clearwater Formation
432
434
436
438
440
442
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446
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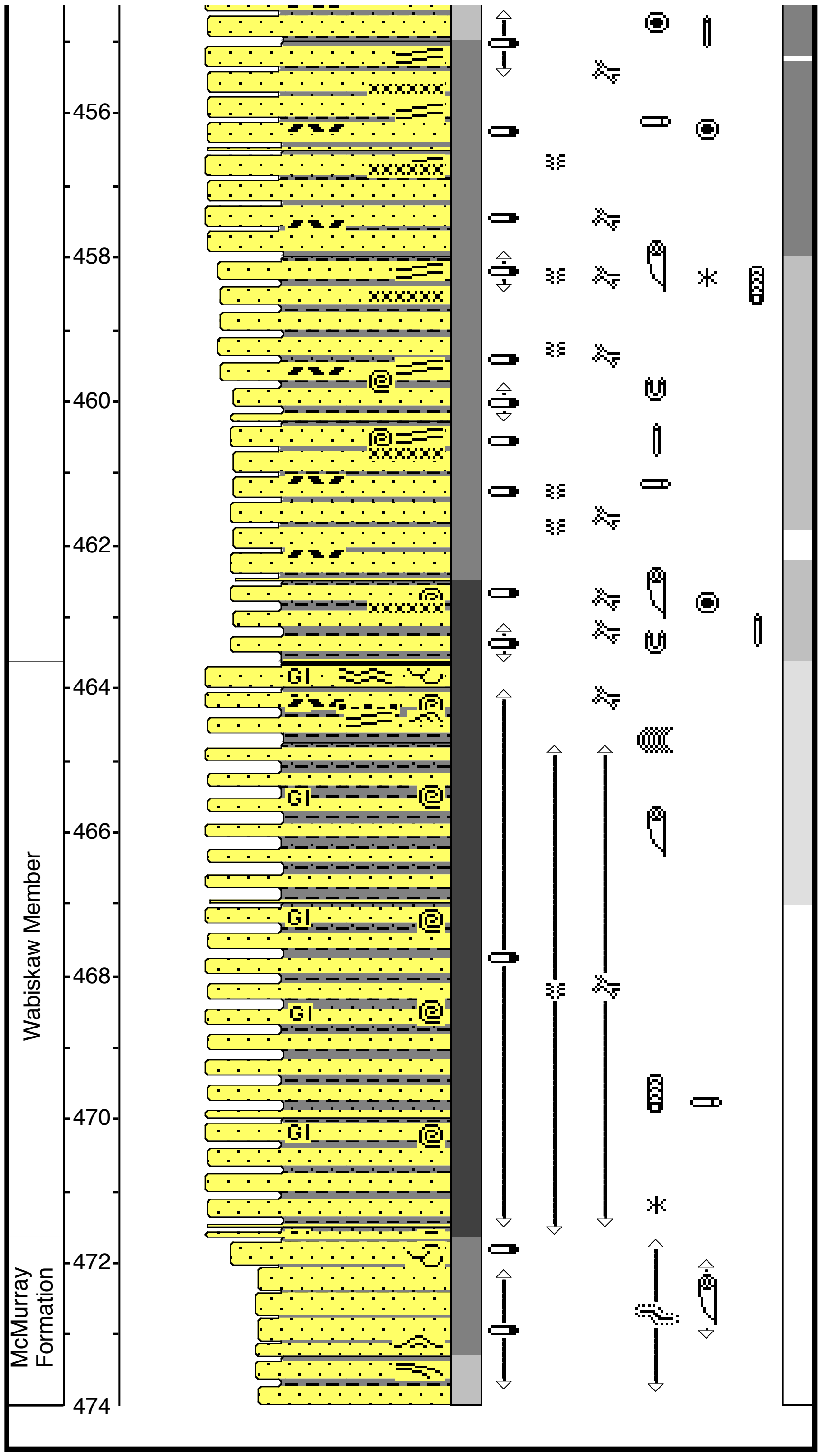
452
454


456
458
460
462
464
466
468
470
472
474
Wabiskaw Member
McMurray Formation
GI

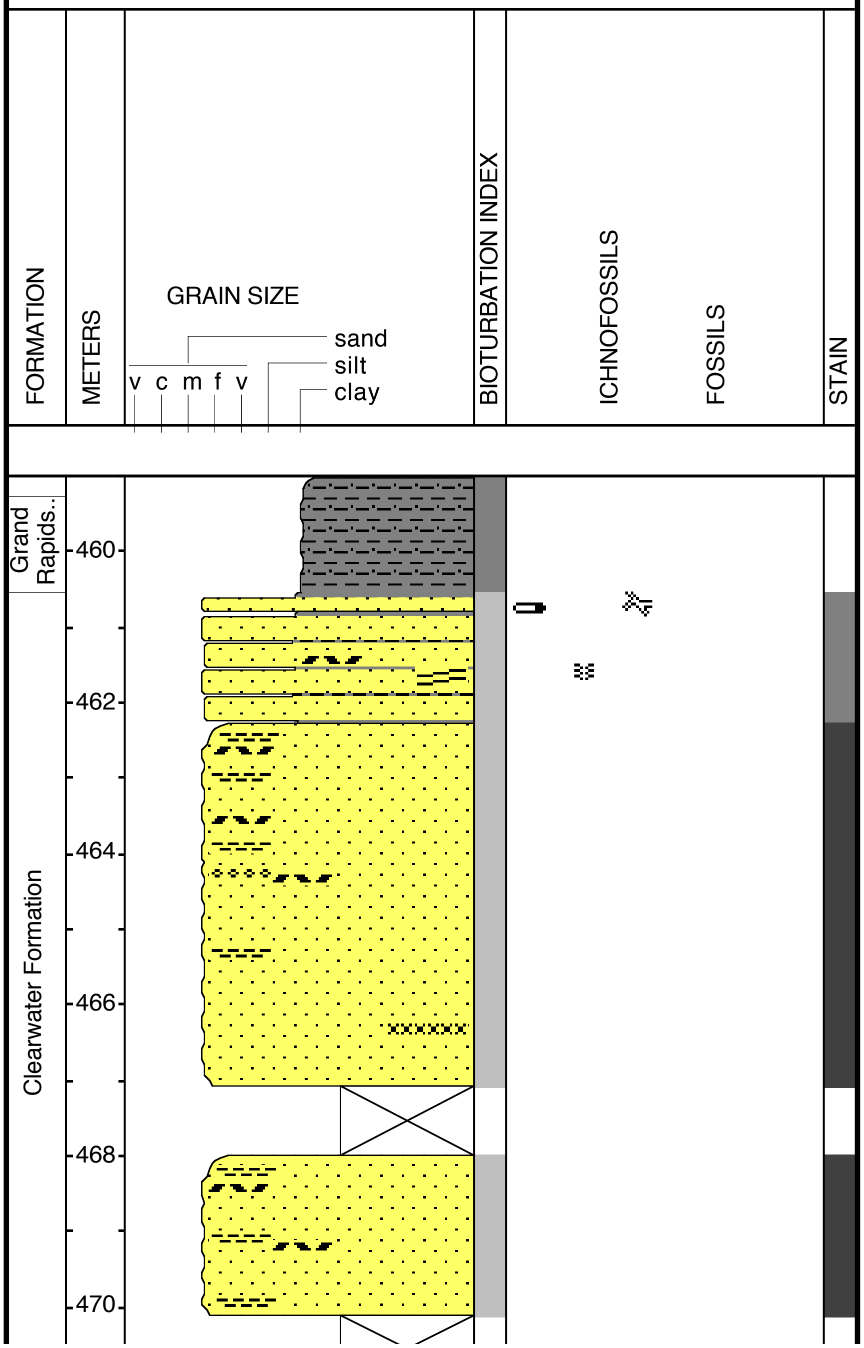
ESSO 85 COLD LK OV 11-12

11-12-066-03w4

Date Logged: October 8th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, very little oil saturation (just at the btm of the core and middle section), ok recovery.



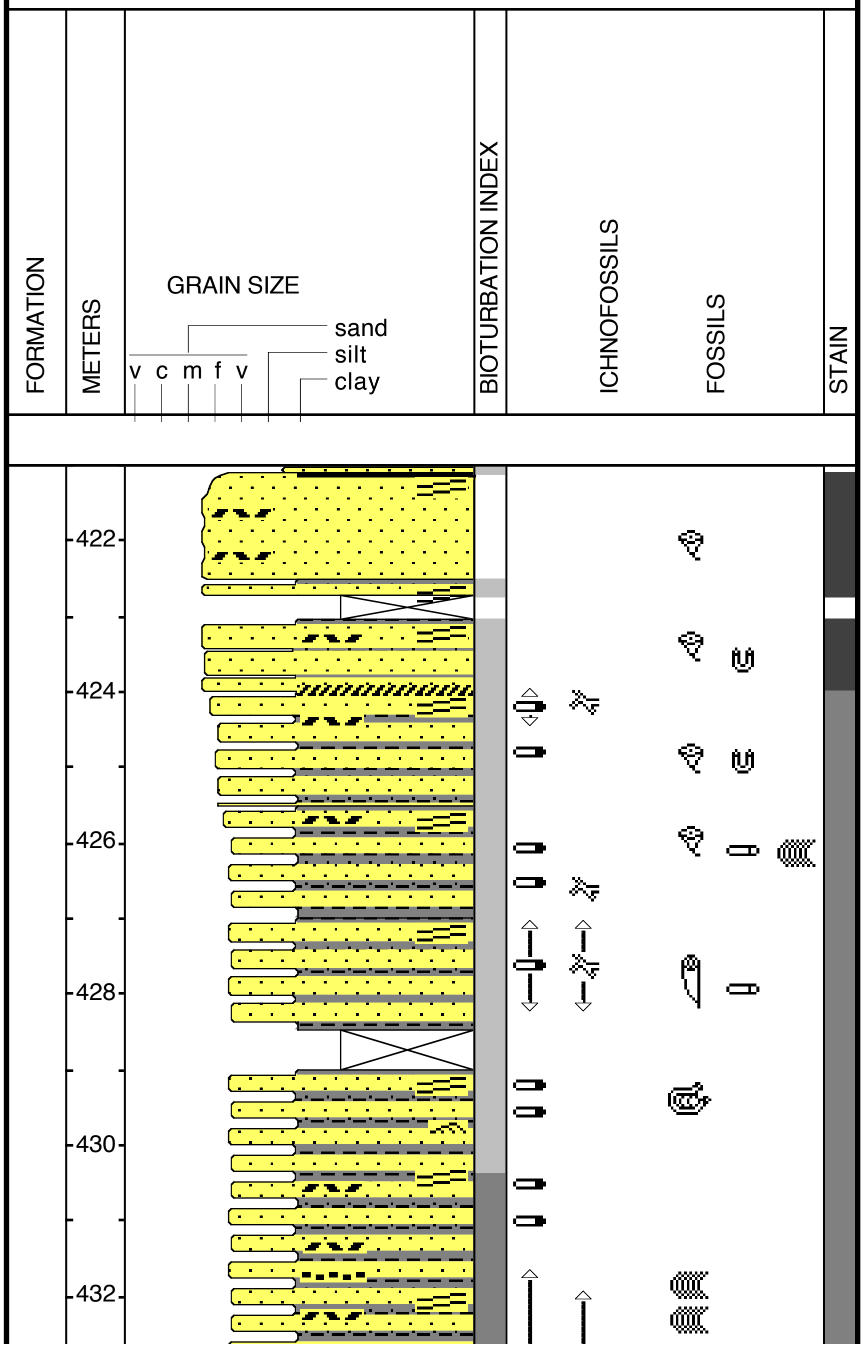
IMP 96 OV COLD LK

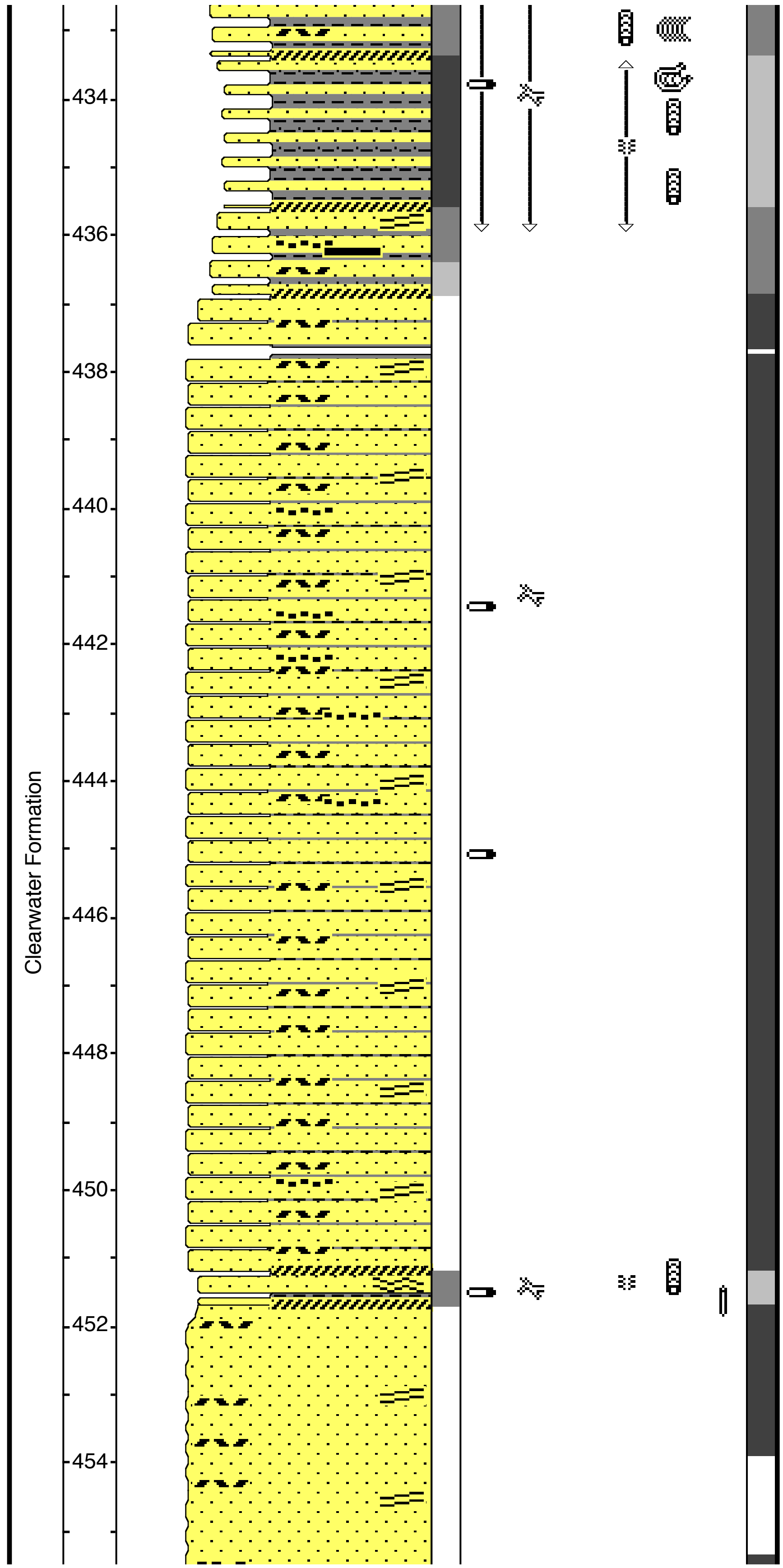
11-17-065-03w4

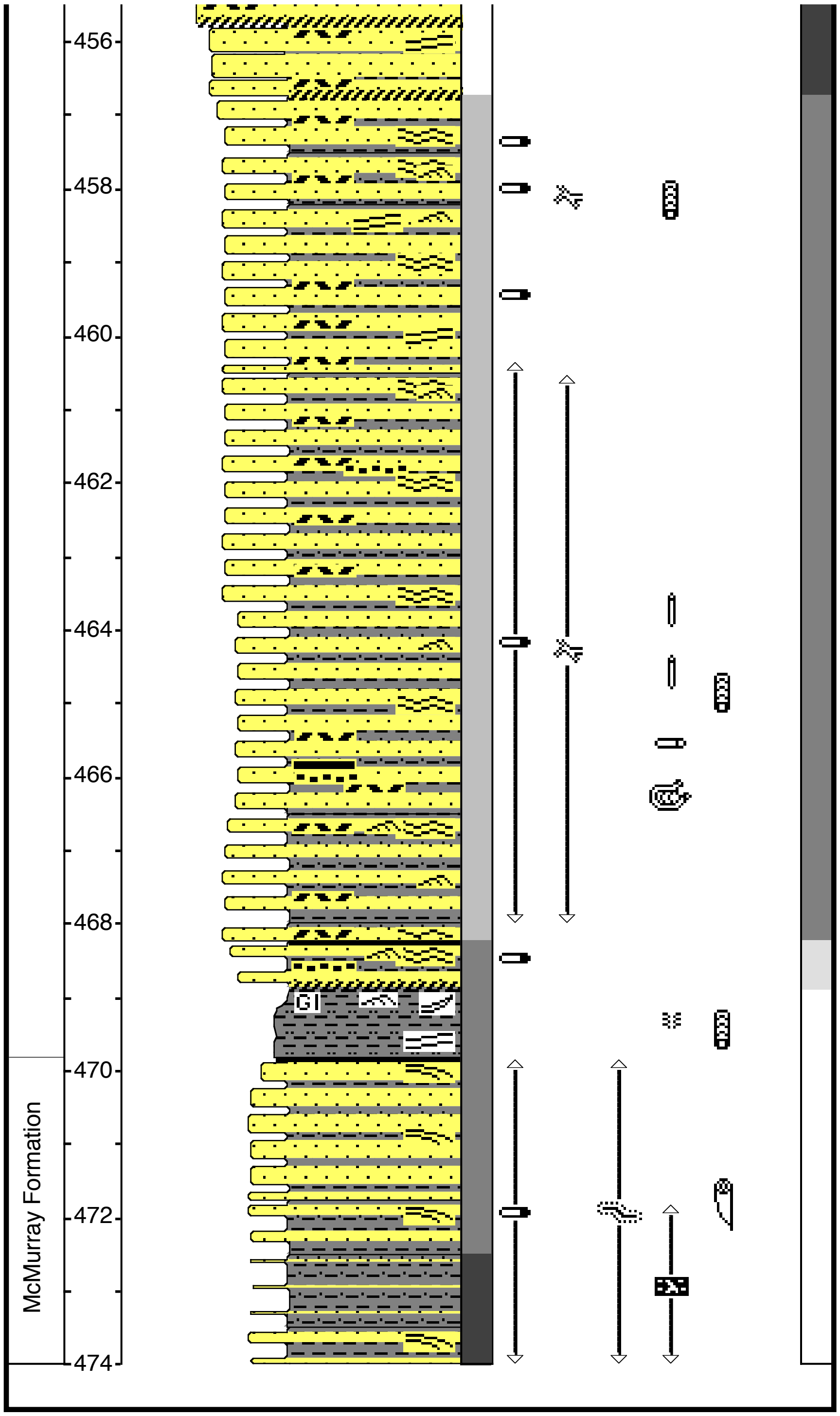
Date Logged: November 4th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery




Clearwater Formation
434
436
438
440
442
444
446
448
450
452
454


456
458
460
462
464
466
468
470
472
474
McMurray Formation
GI

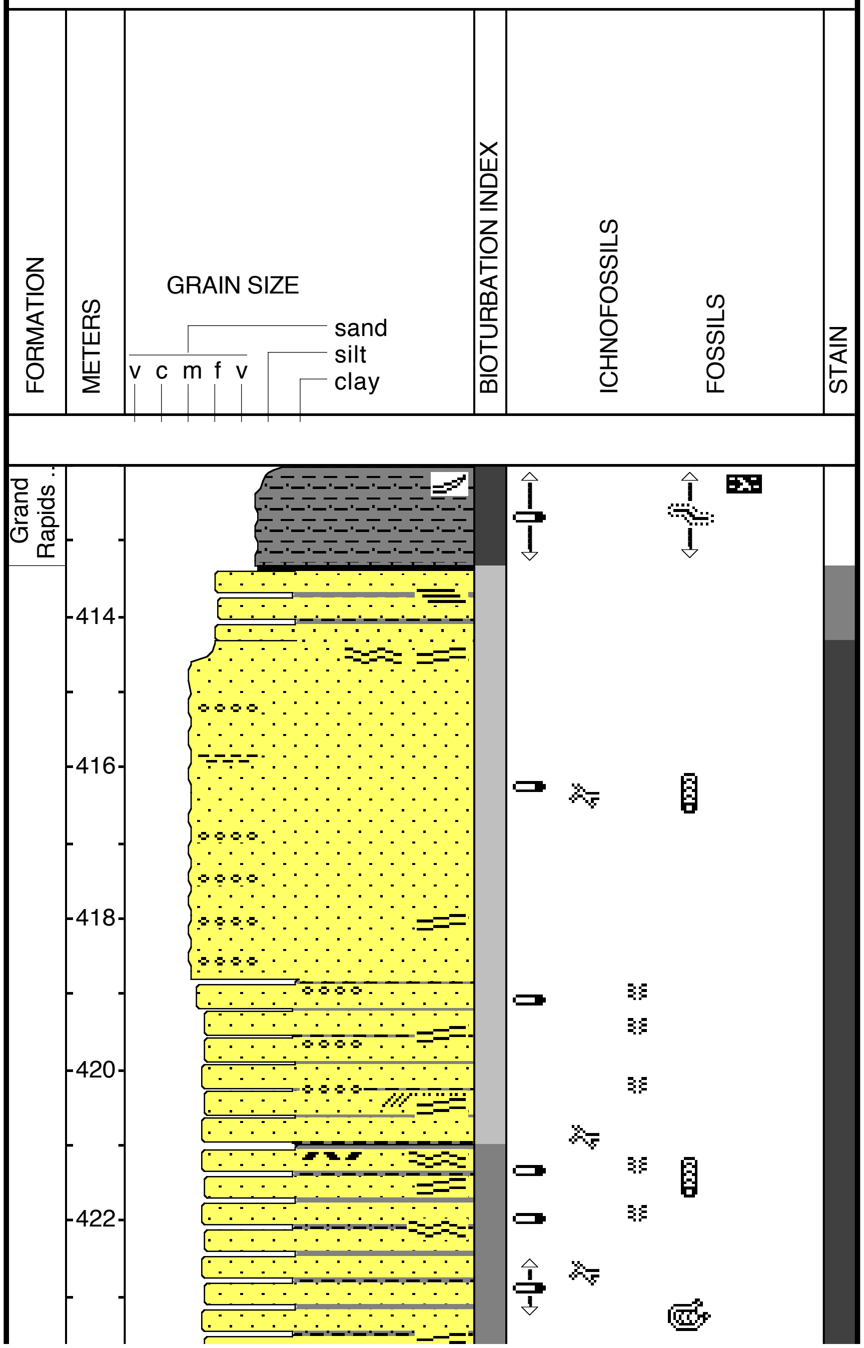
IMP 05 OV COLDLK

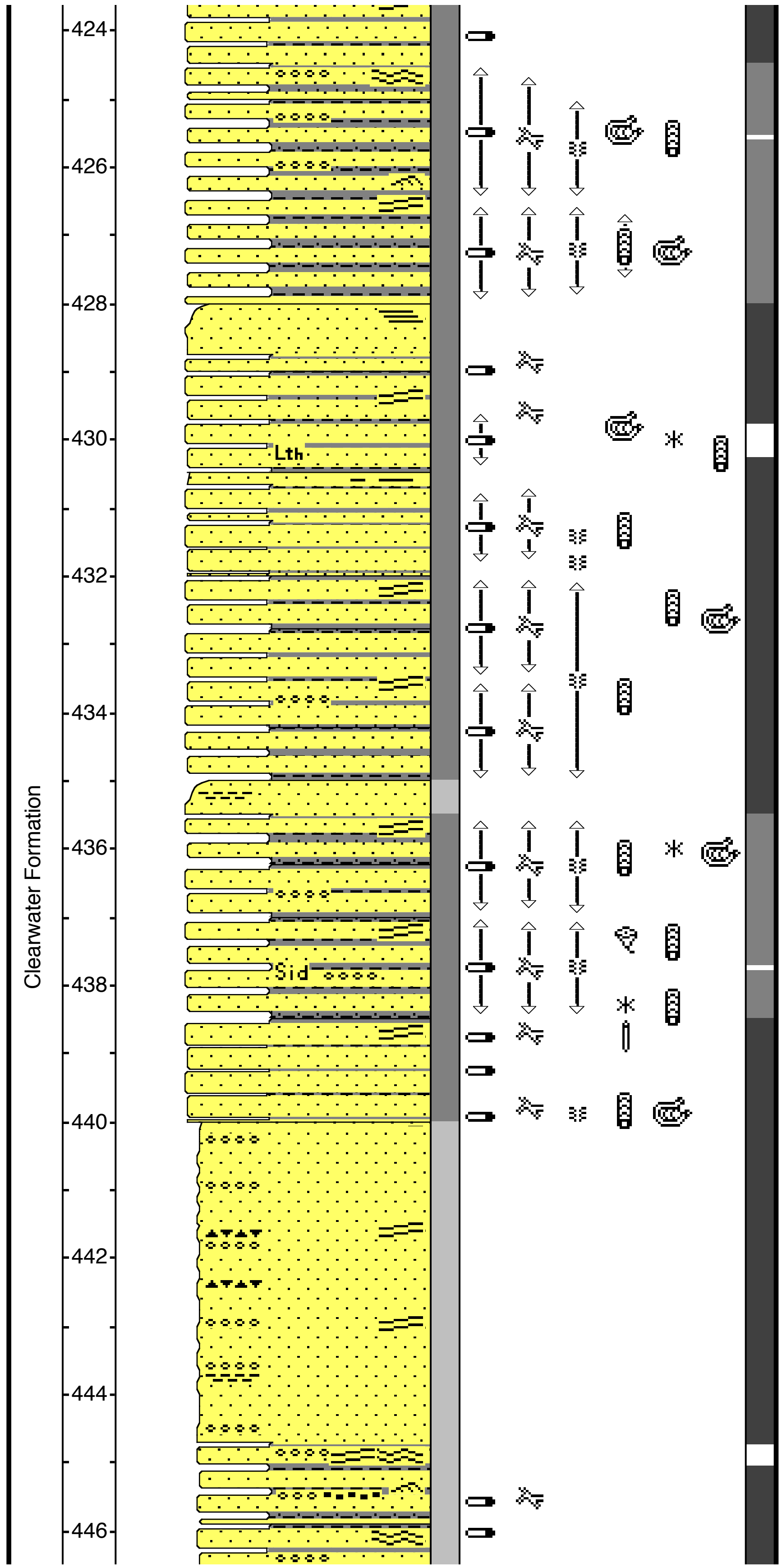
11-19-065-03w4

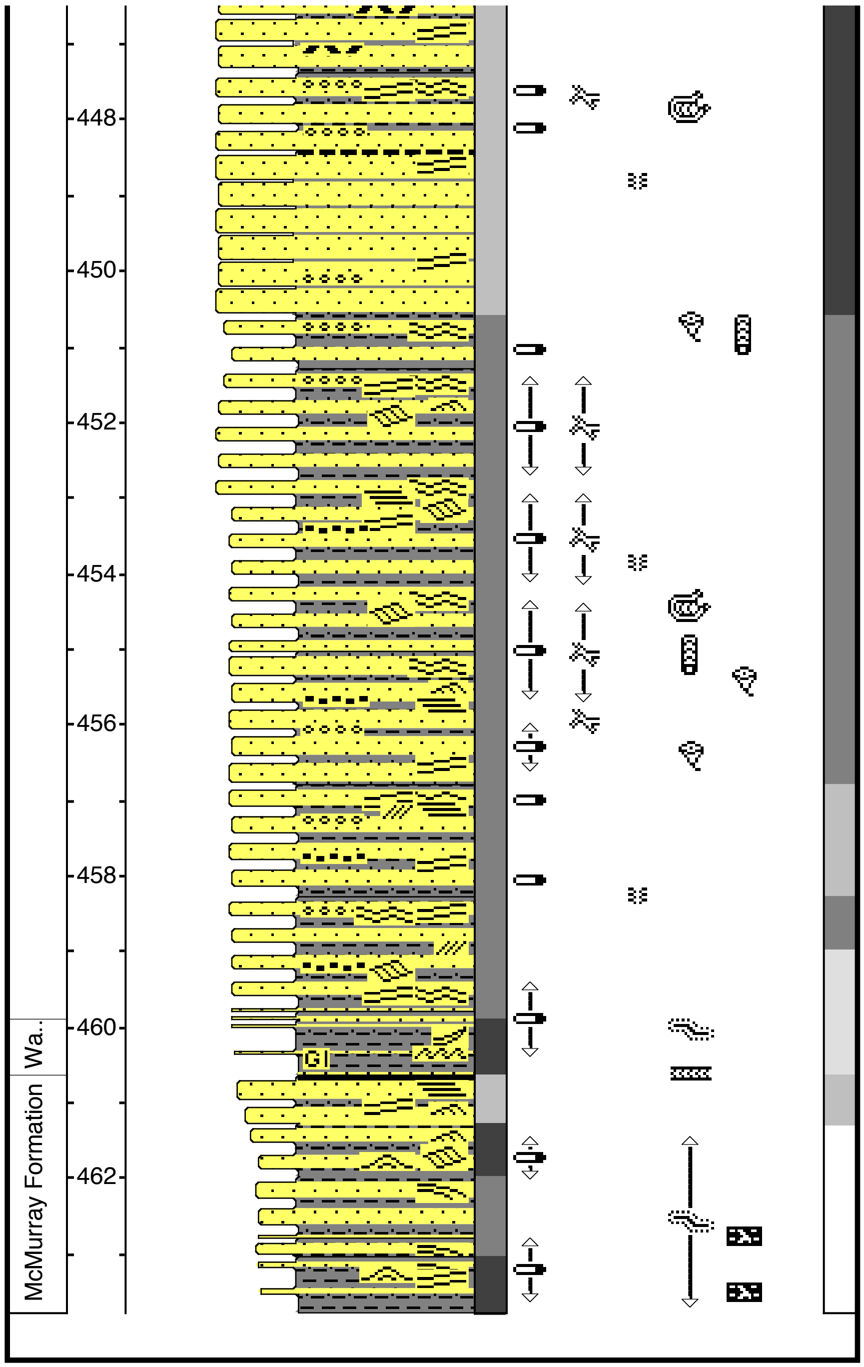
Date Logged: September 23rd, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery




Clearwater Formation
424
426
428
430
432
434
436
438
440
442
444
446
Lth
Sid


-448
-450
-452
-454
-456
-458
-460
-462
McMurray Formation
Wa..
GI

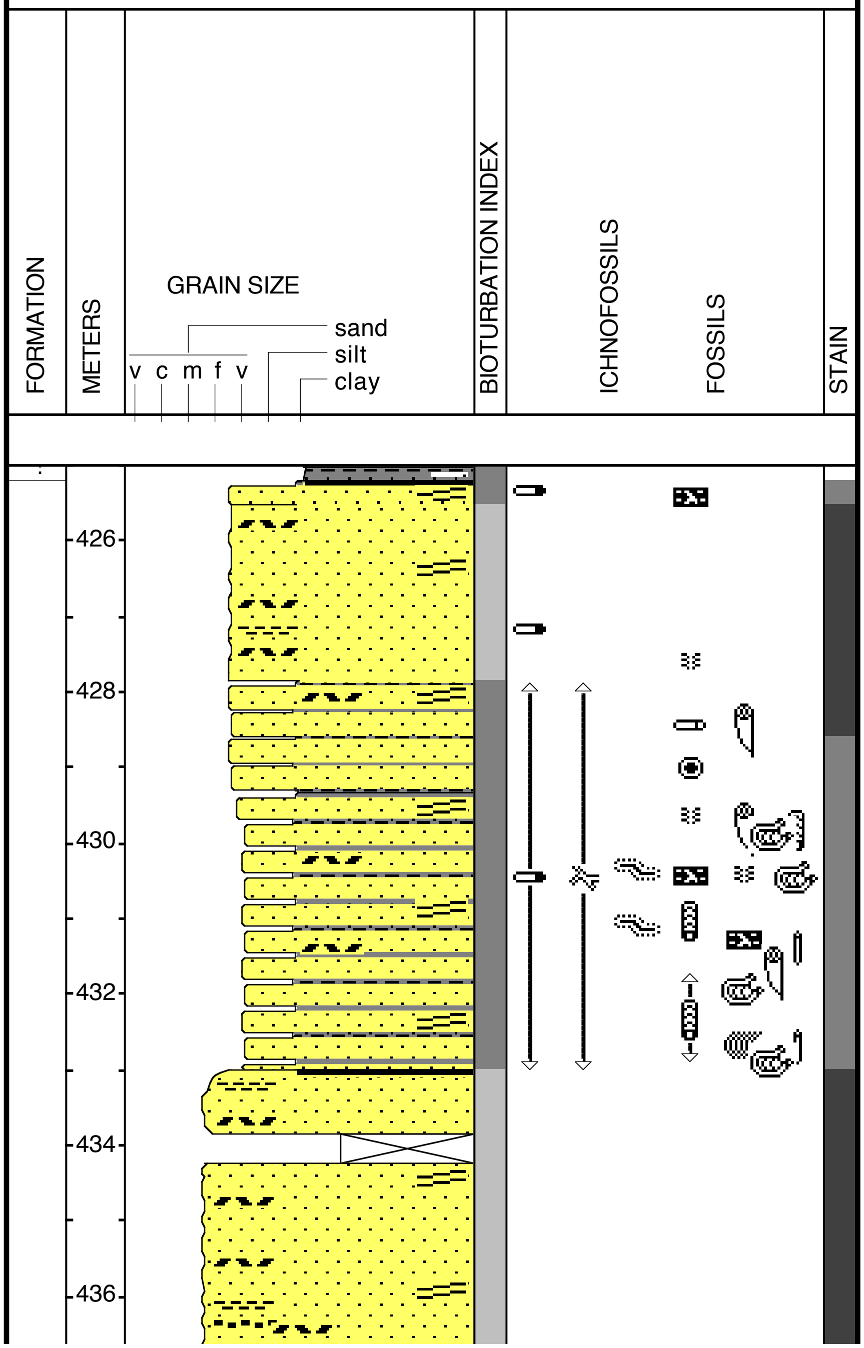
ESSO 87 C4-8 COLDLK 12-18

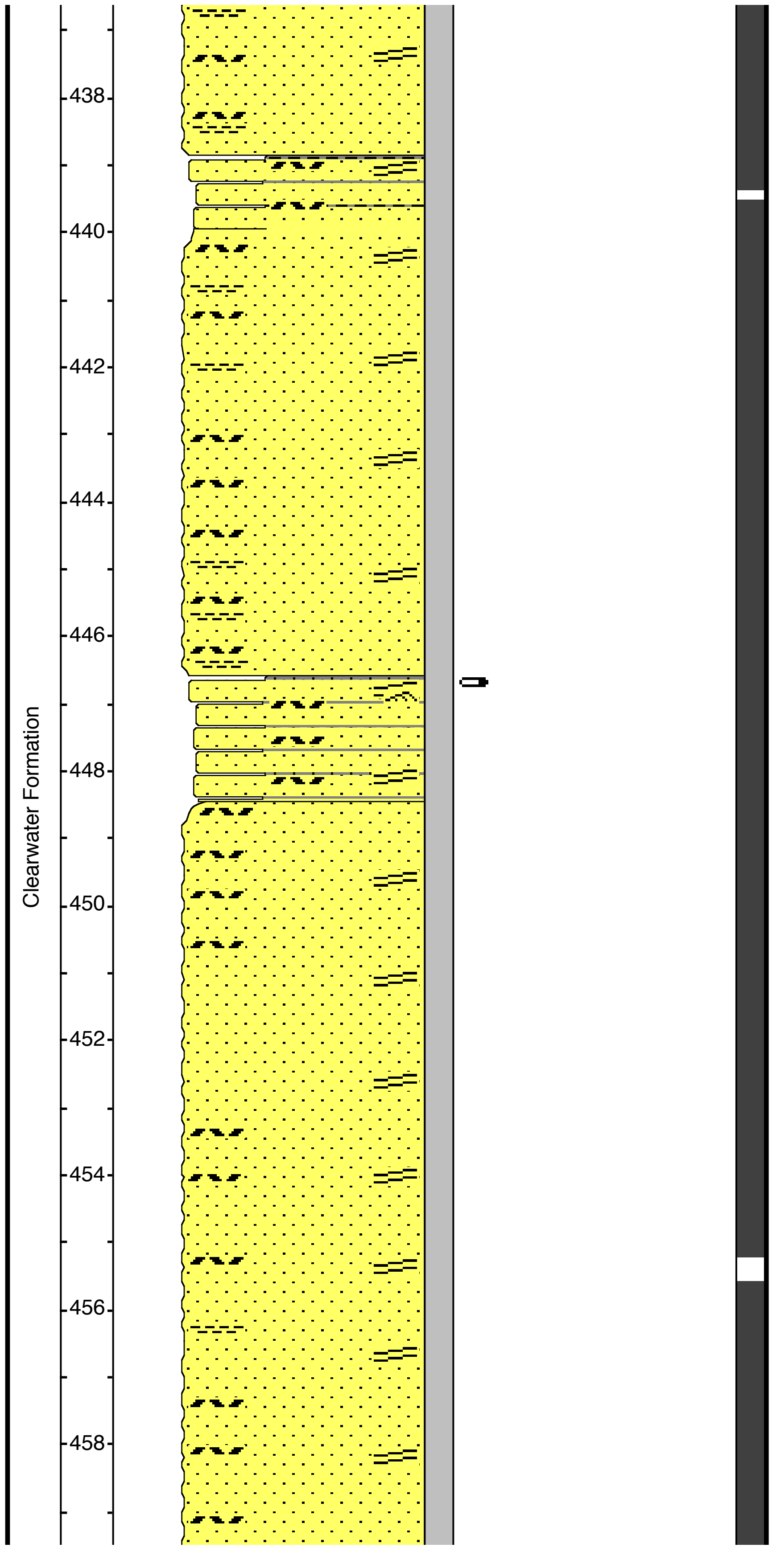
12-18-065-3w4

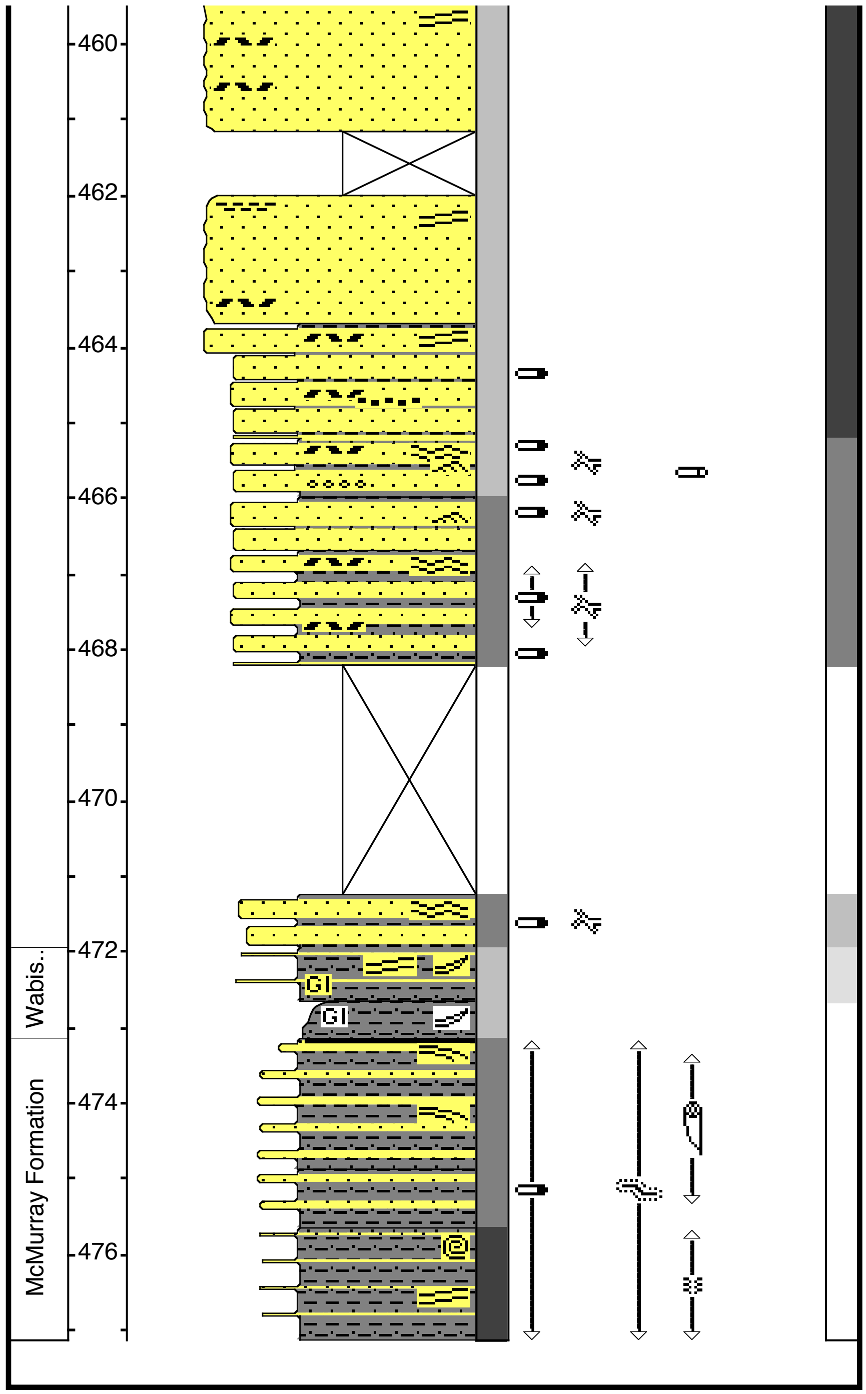
Date Logged: November 19th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, good recovery




Clearwater Formation
438
440
442
444
446
448
450
452
454
456
458


460
462
464
466
468
470
472
474
476
McMurray Formation
Wabis..
Gl
Gl

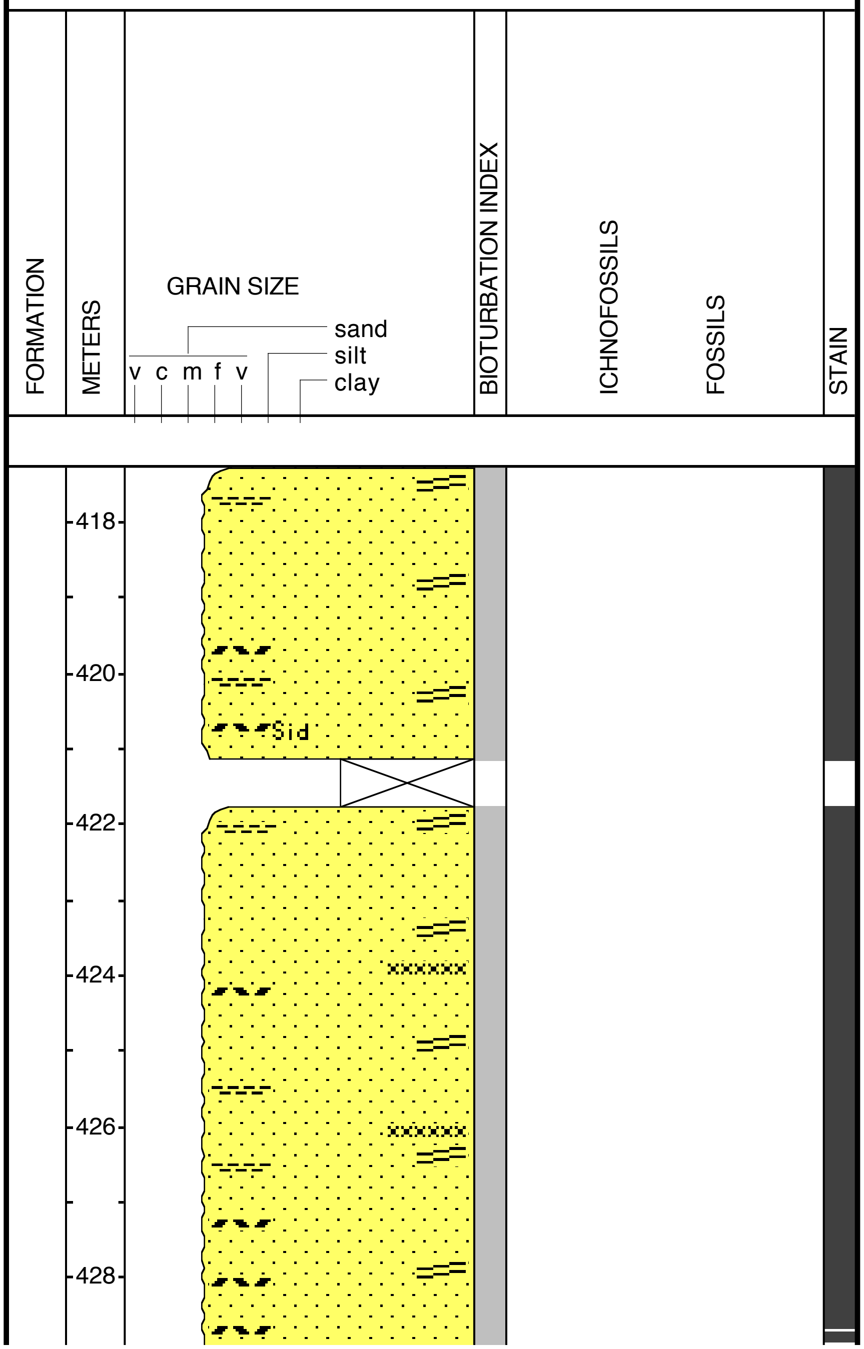
IMP 2-78 COLD LK OV

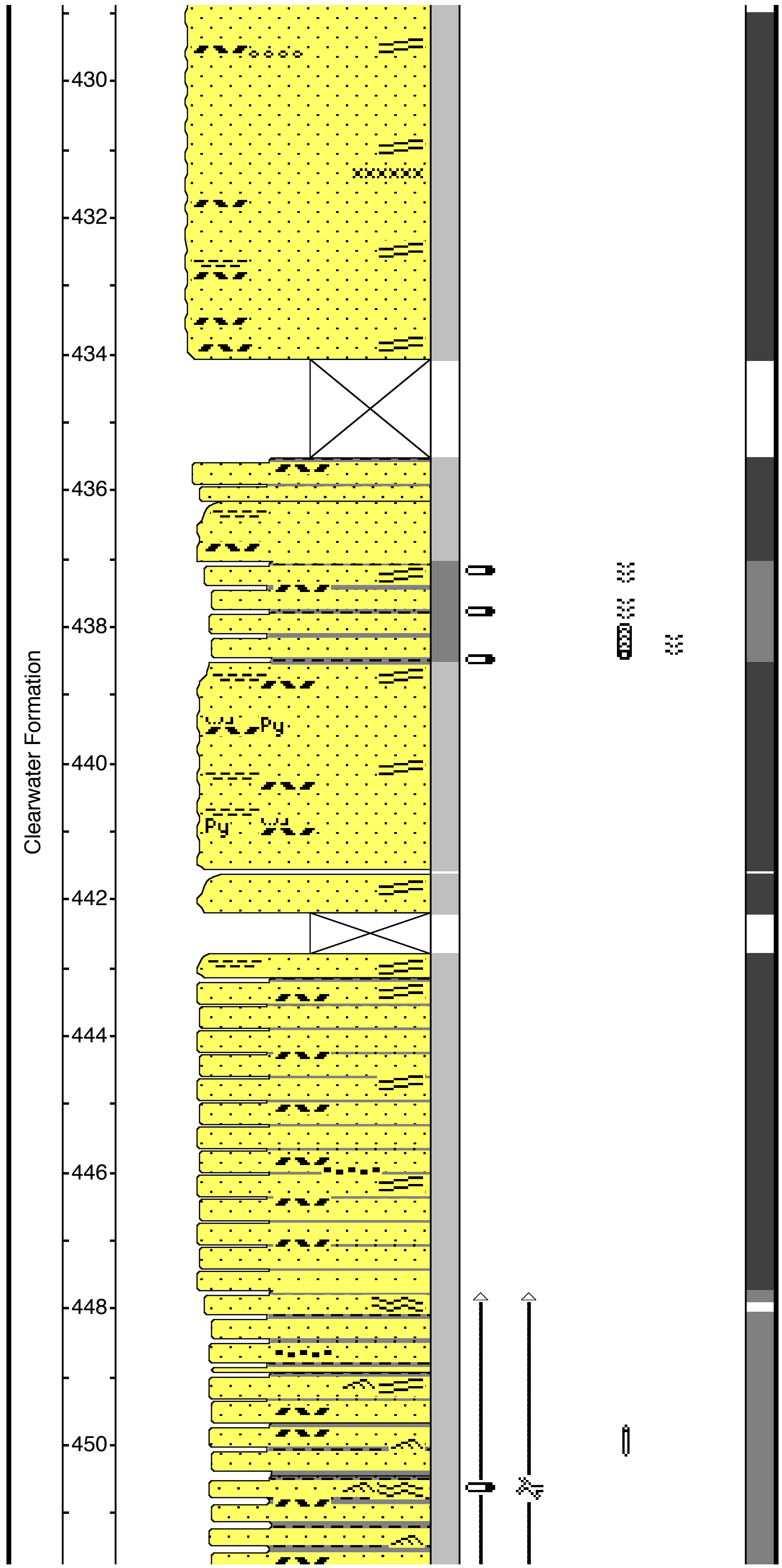
12-25-065-04w4

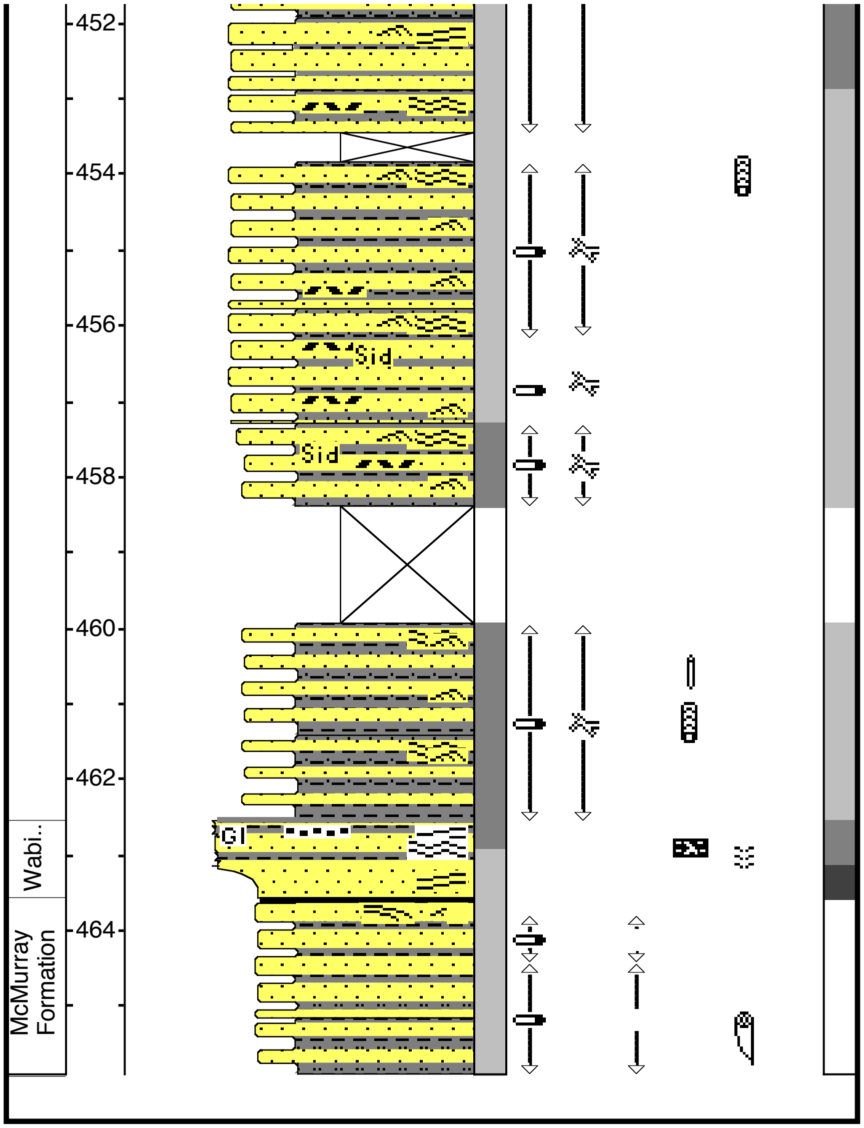
Date Logged: November 19th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery.




Clearwater Formation
430
432
434
436
438
440
442
444
446
448
450
Py
Py



452
454
456
458
460
462
464
Sid
Sid
Gl
Wabi..
McMurray Formation

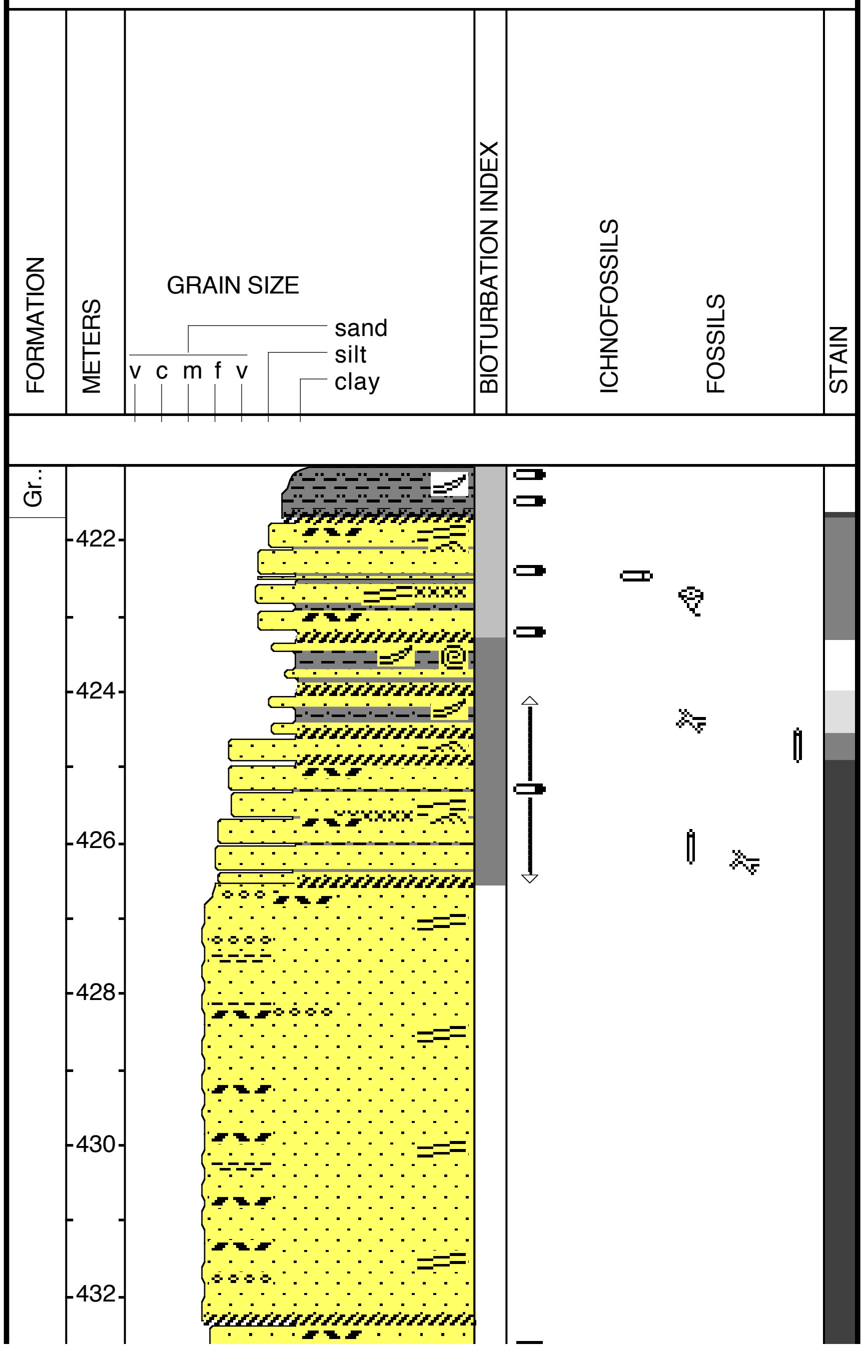
IMPERIAL 99/00 OV COLD LAKE

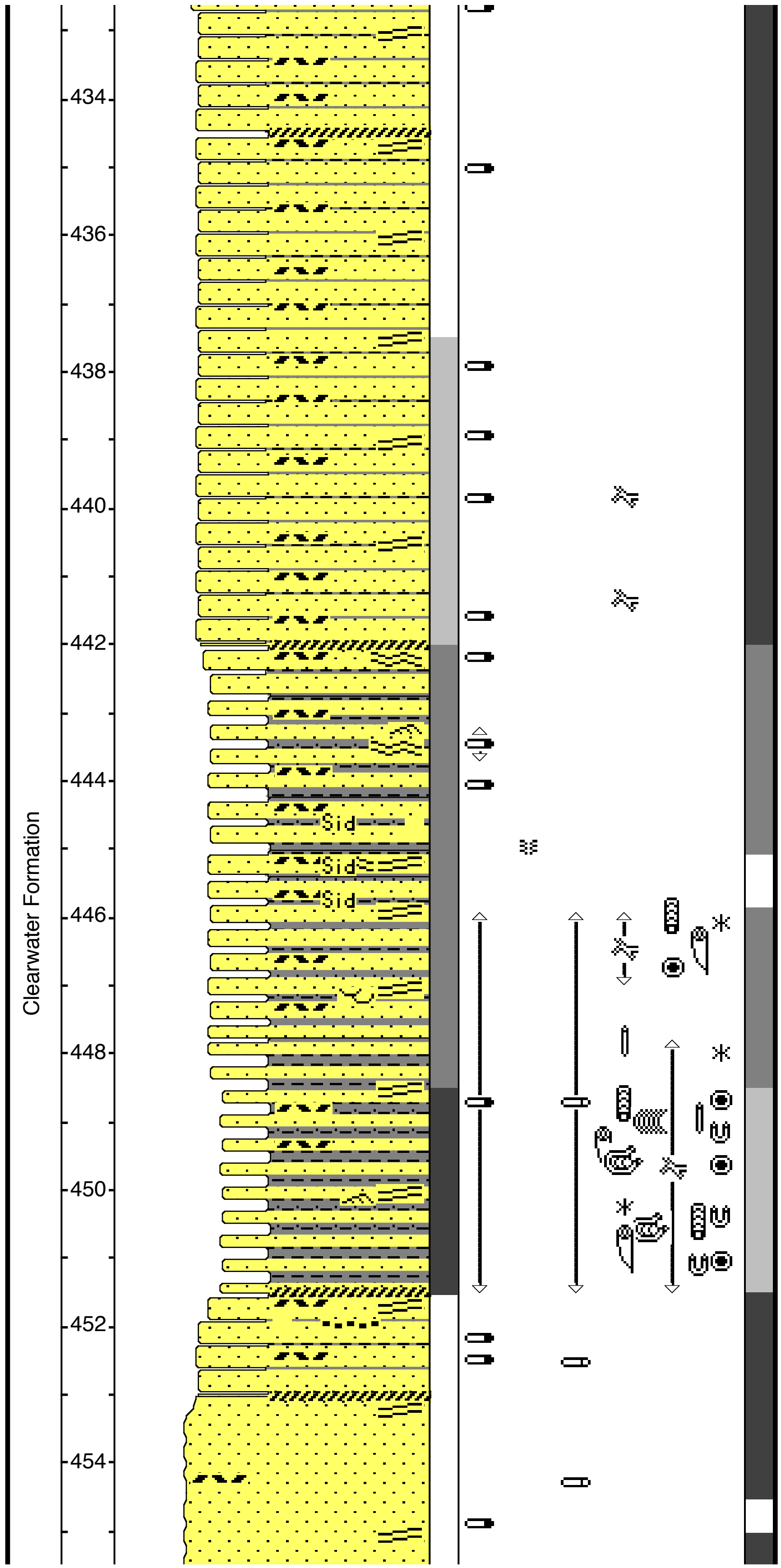
12-29-065-2w4

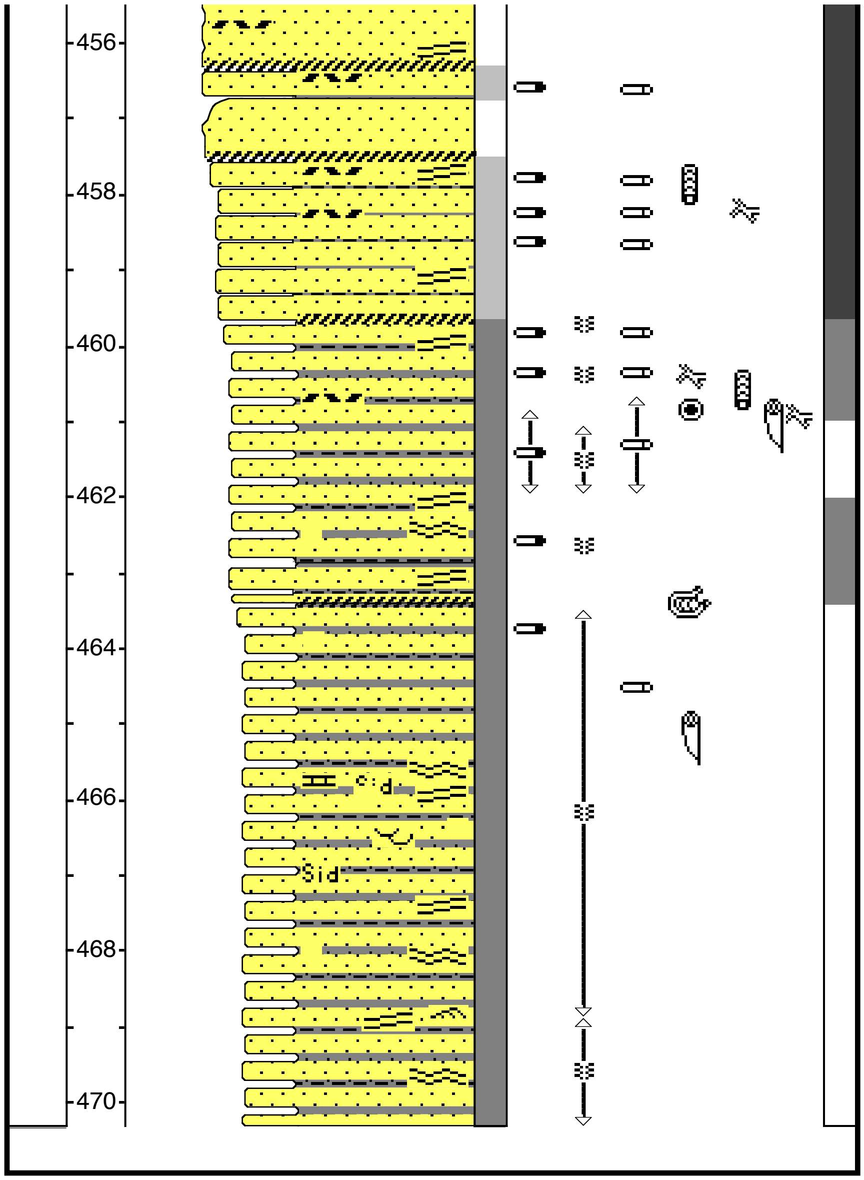
Date Logged: October 28th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery




Clearwater Formation
434
436
438
440
442
444
446
448
450
452
454
Sid
Sid
Sid


456
458
460
462
464
466
468
470
Sid

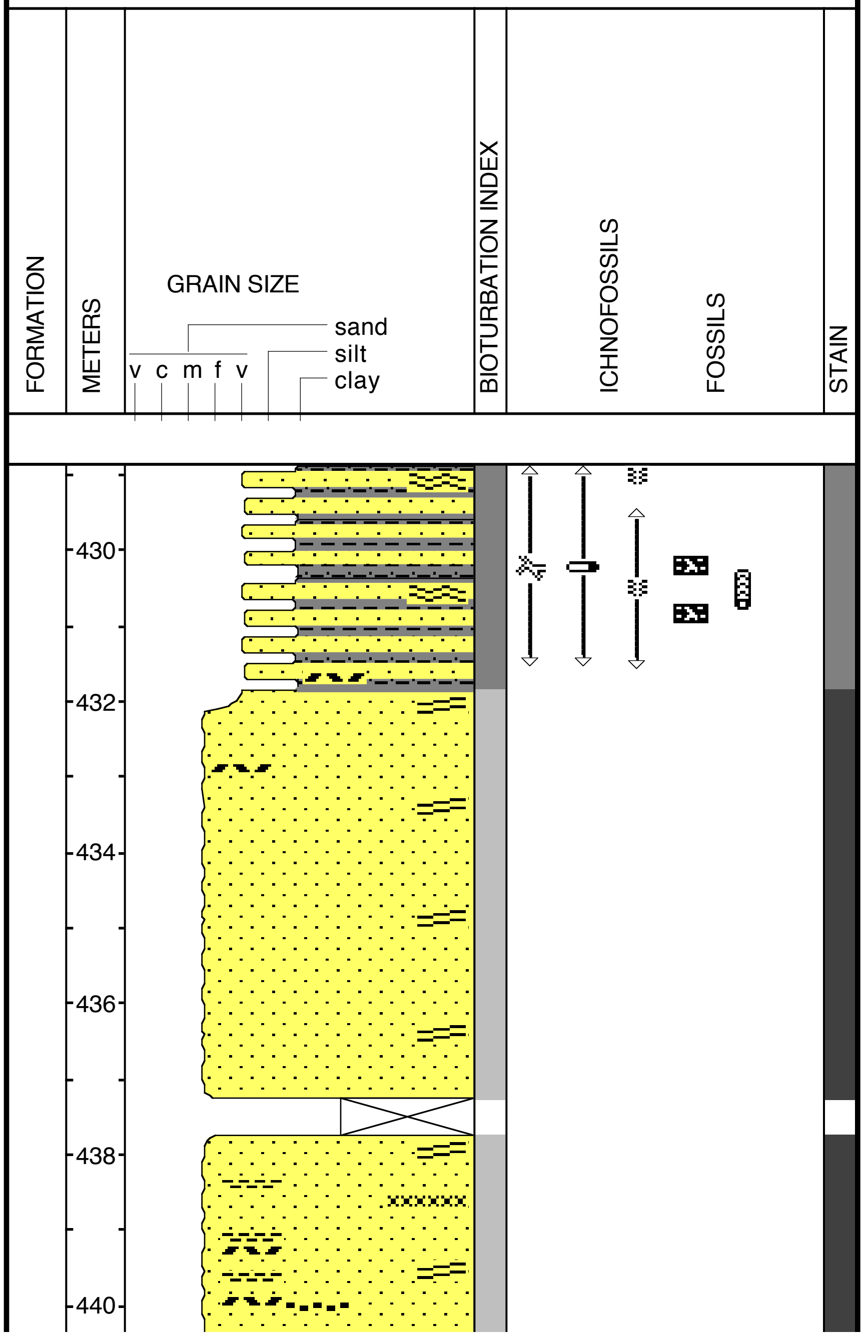
IMP 2-78 COLD LK OV

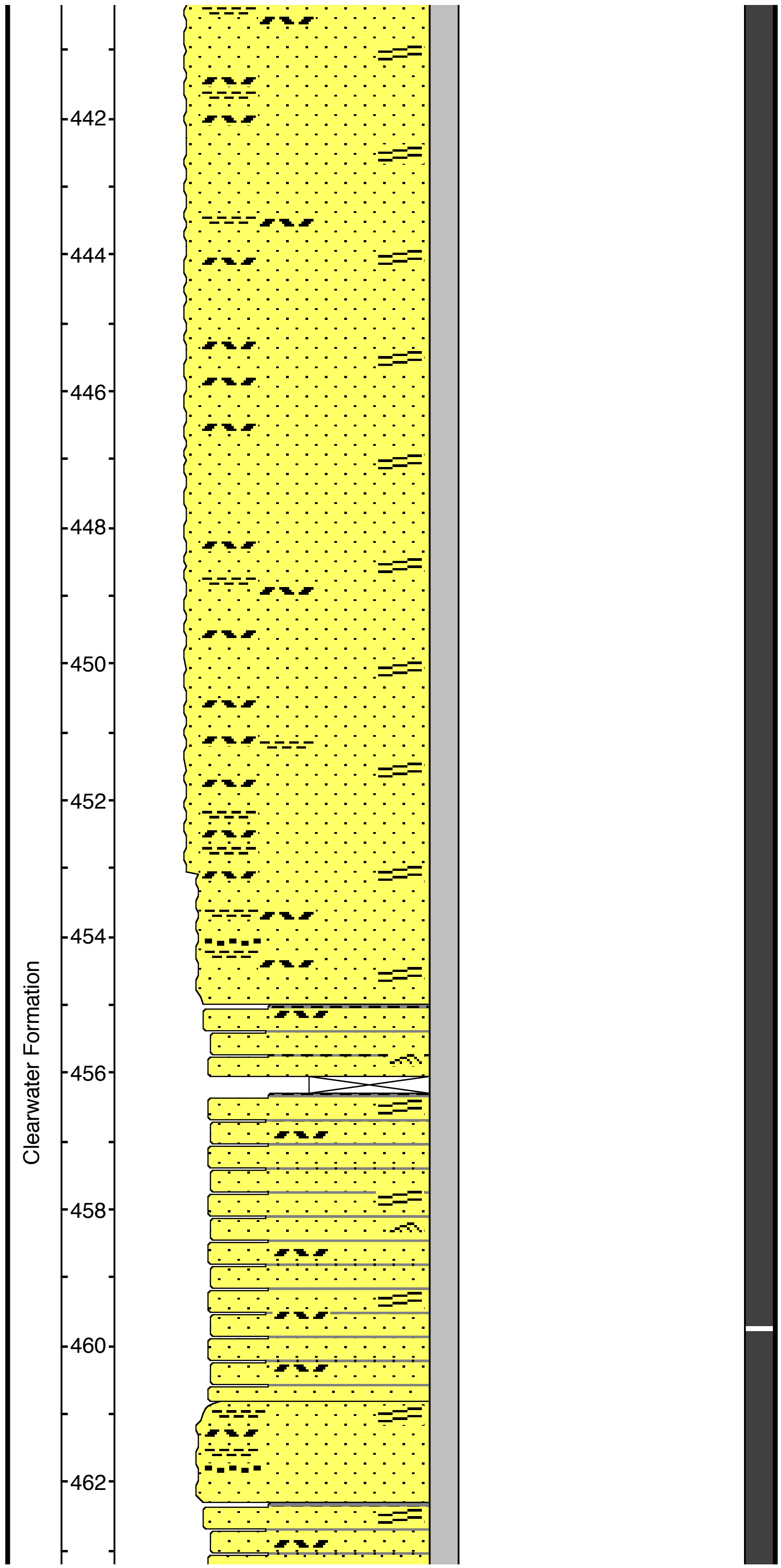
13-13-065-04w4

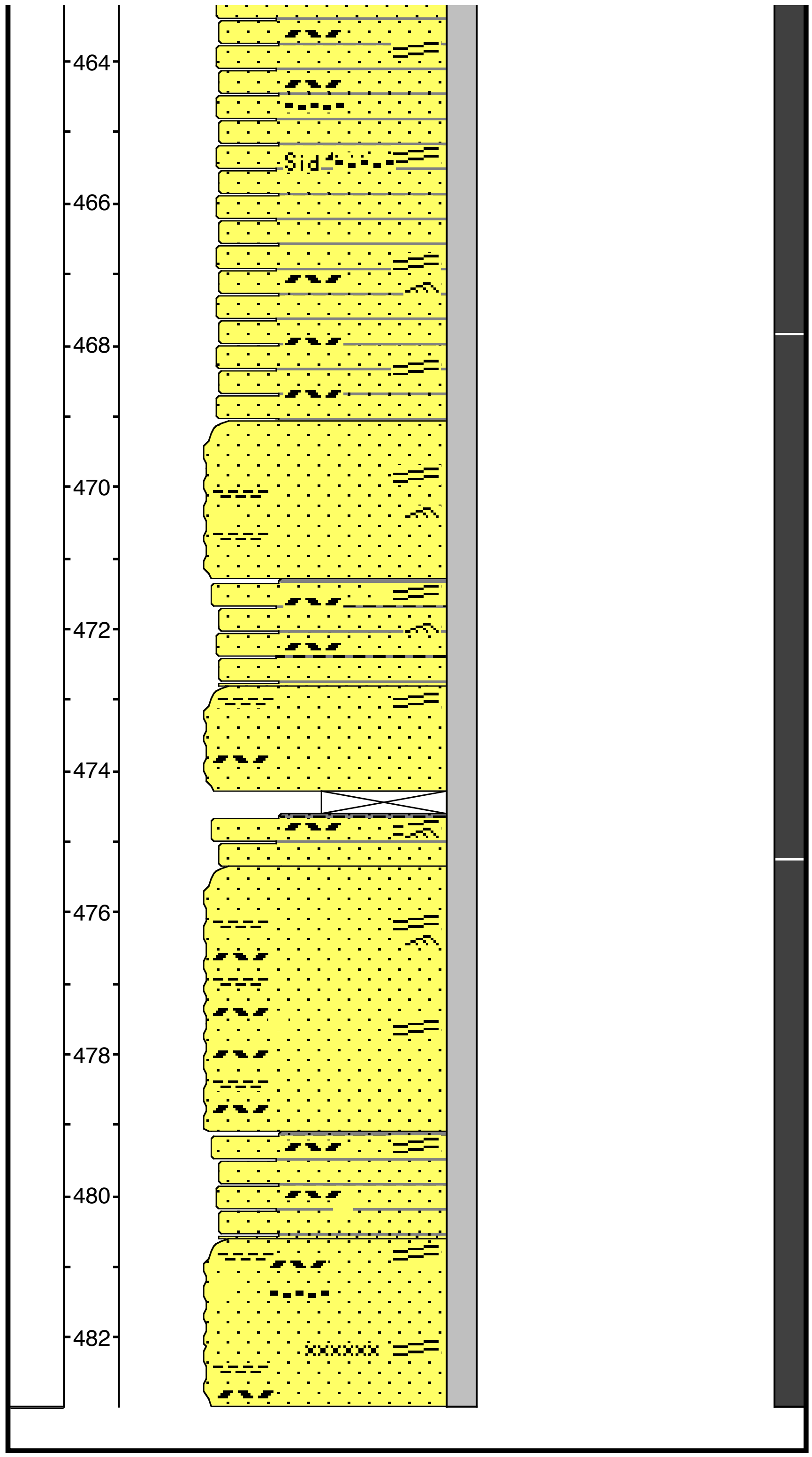
Date Logged: November 25th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery, core does not include both the McMurray or the Grand Rapids above




Clearwater Formation
442
444
446
448
450
452
454
456
458
460
462


464
466
468
470
472
474
476
478
480
482
Sid

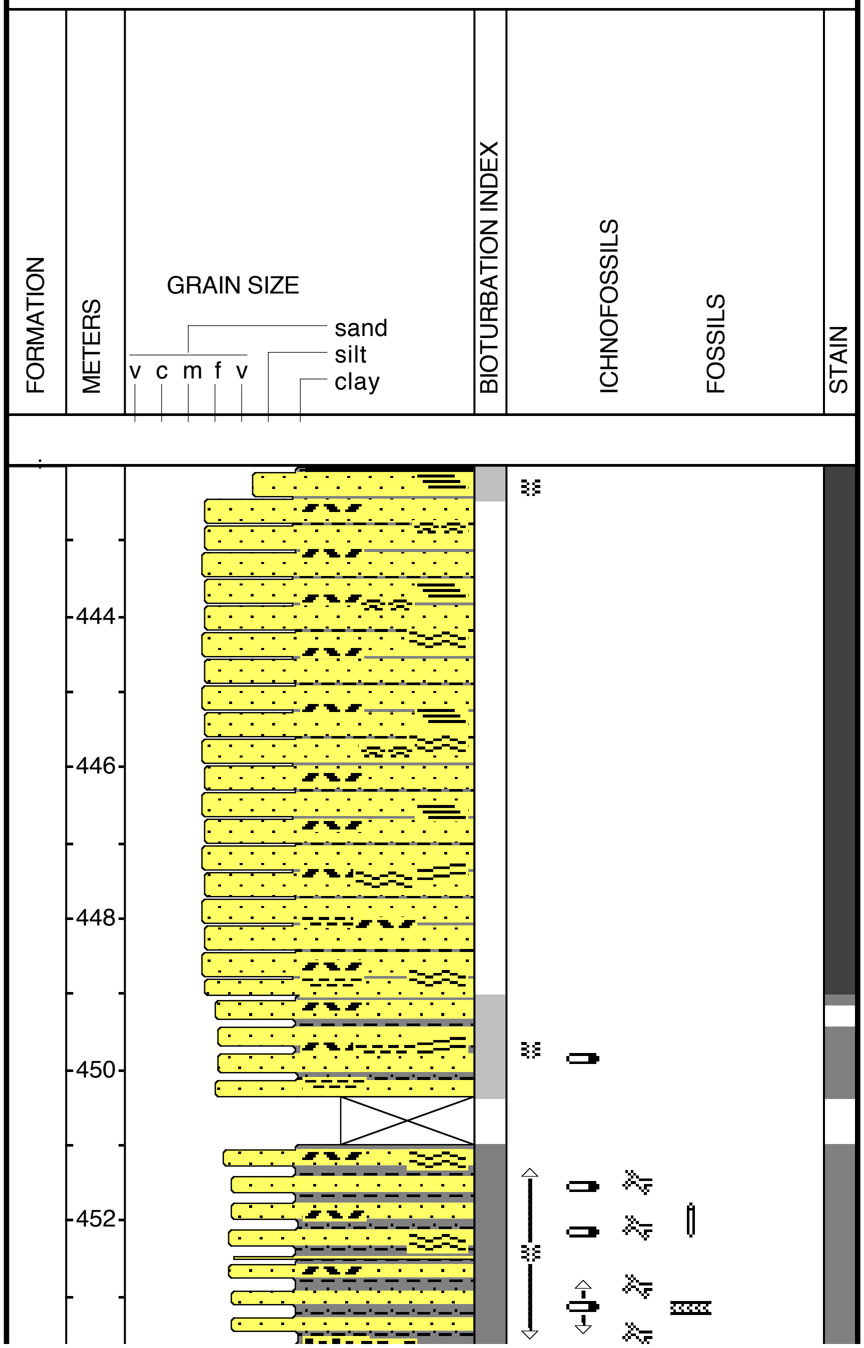
IMP 96 OV COLD LK

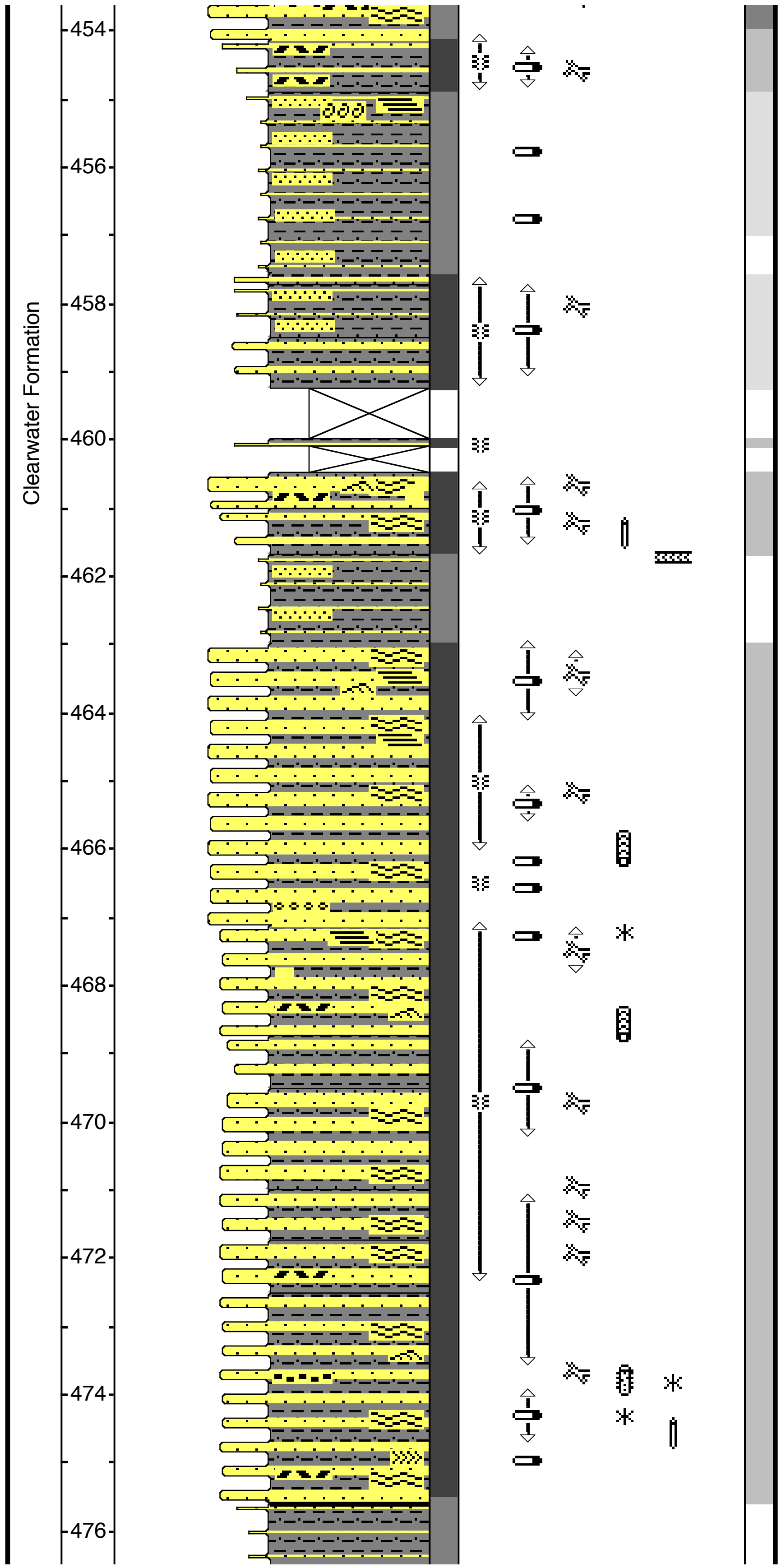
13 -13-066-03 w4

Date Logged: February 18th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed, oil stained core, recovery good




Clearwater Formation
454
456
458
460
462
464
466
468
470
472
474
476

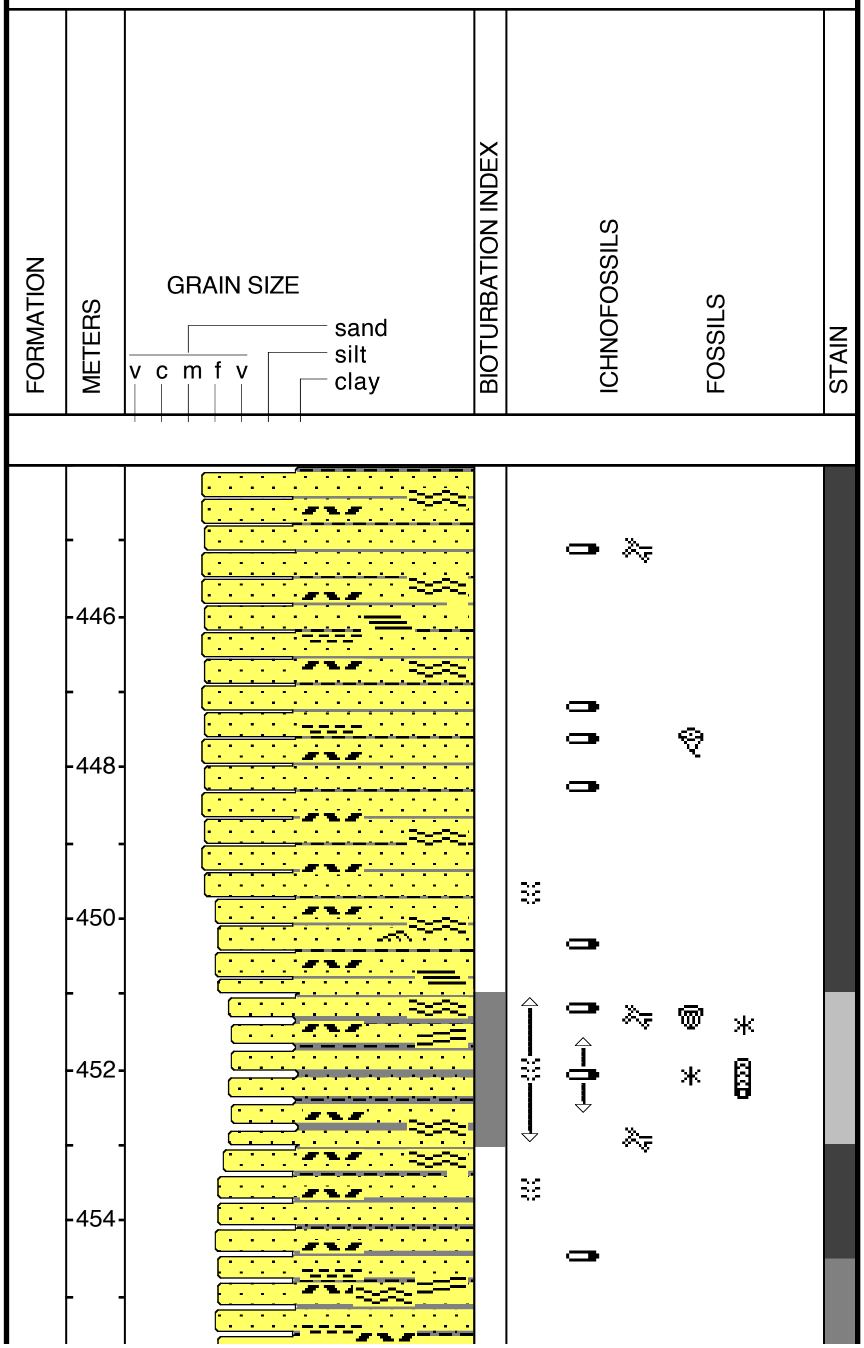
ESSO 83 MARIE OV

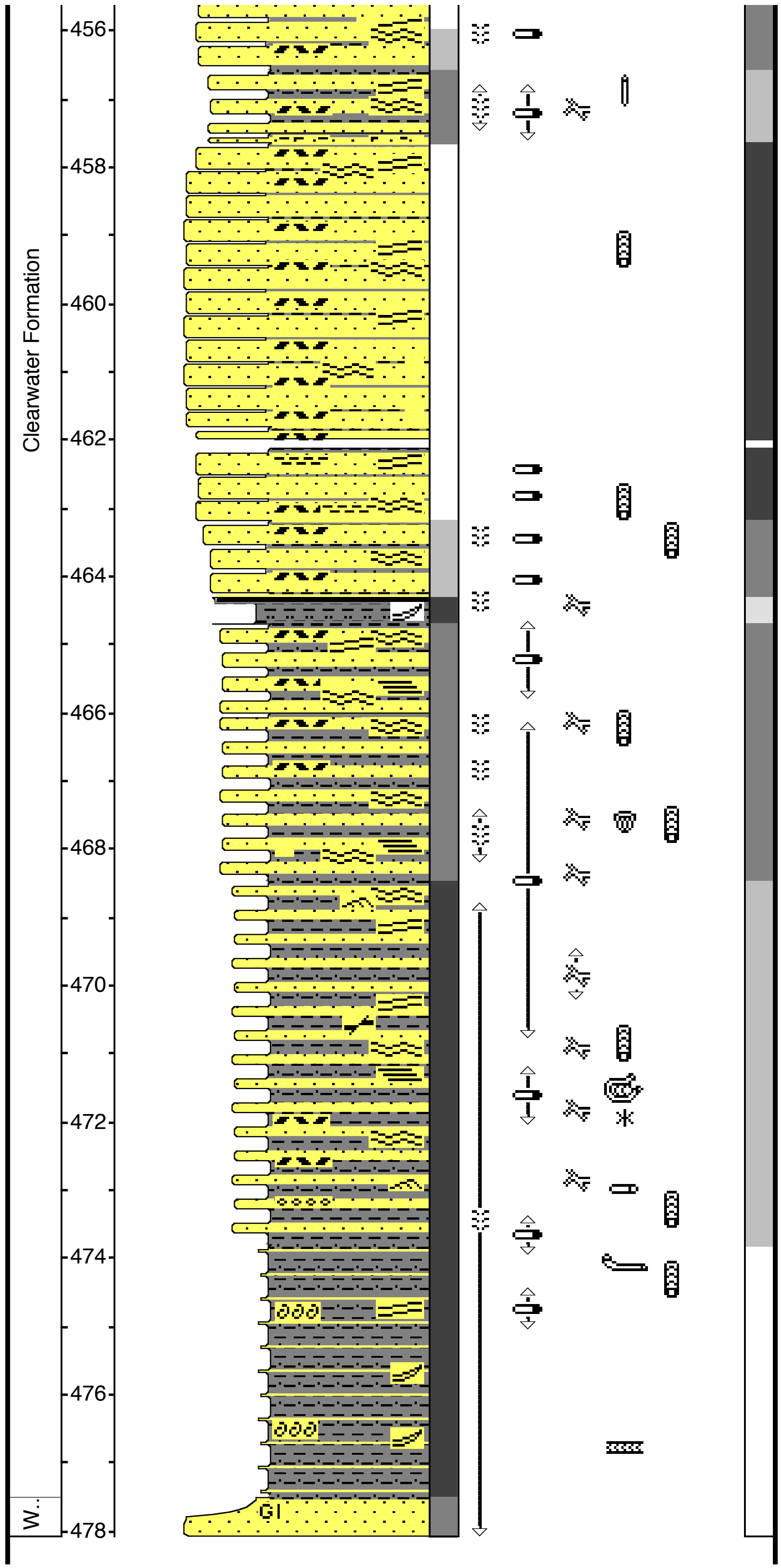
13-19-66-2w4

Date Logged: May 12, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, very good recovery




Clearwater Formation
W..
-456-
-458-
-460-
-462-
-464-
-466-
-468-
-470-
-472-
-474-
-476-
-478-
Gl

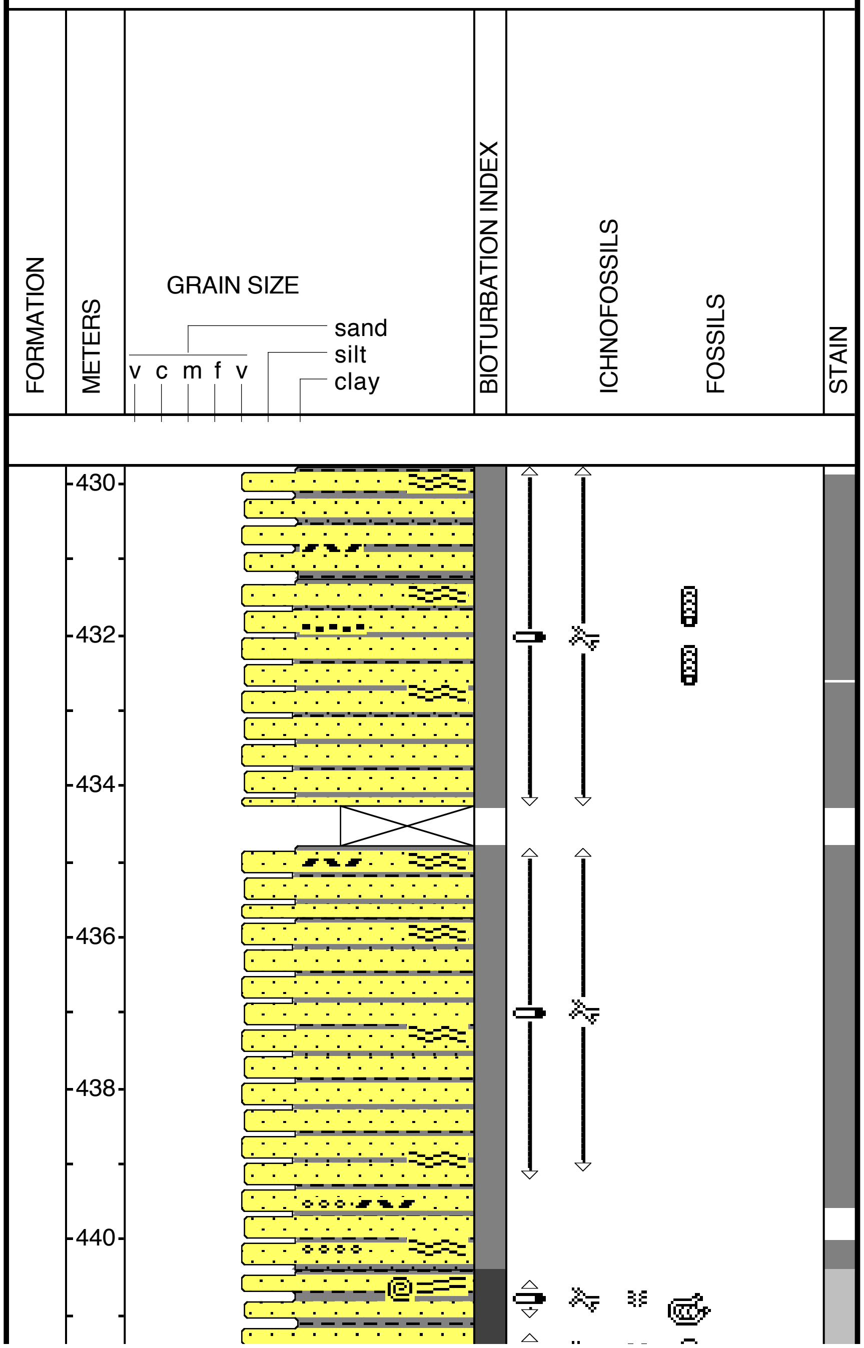
IMP 1-78 COLD LK OV

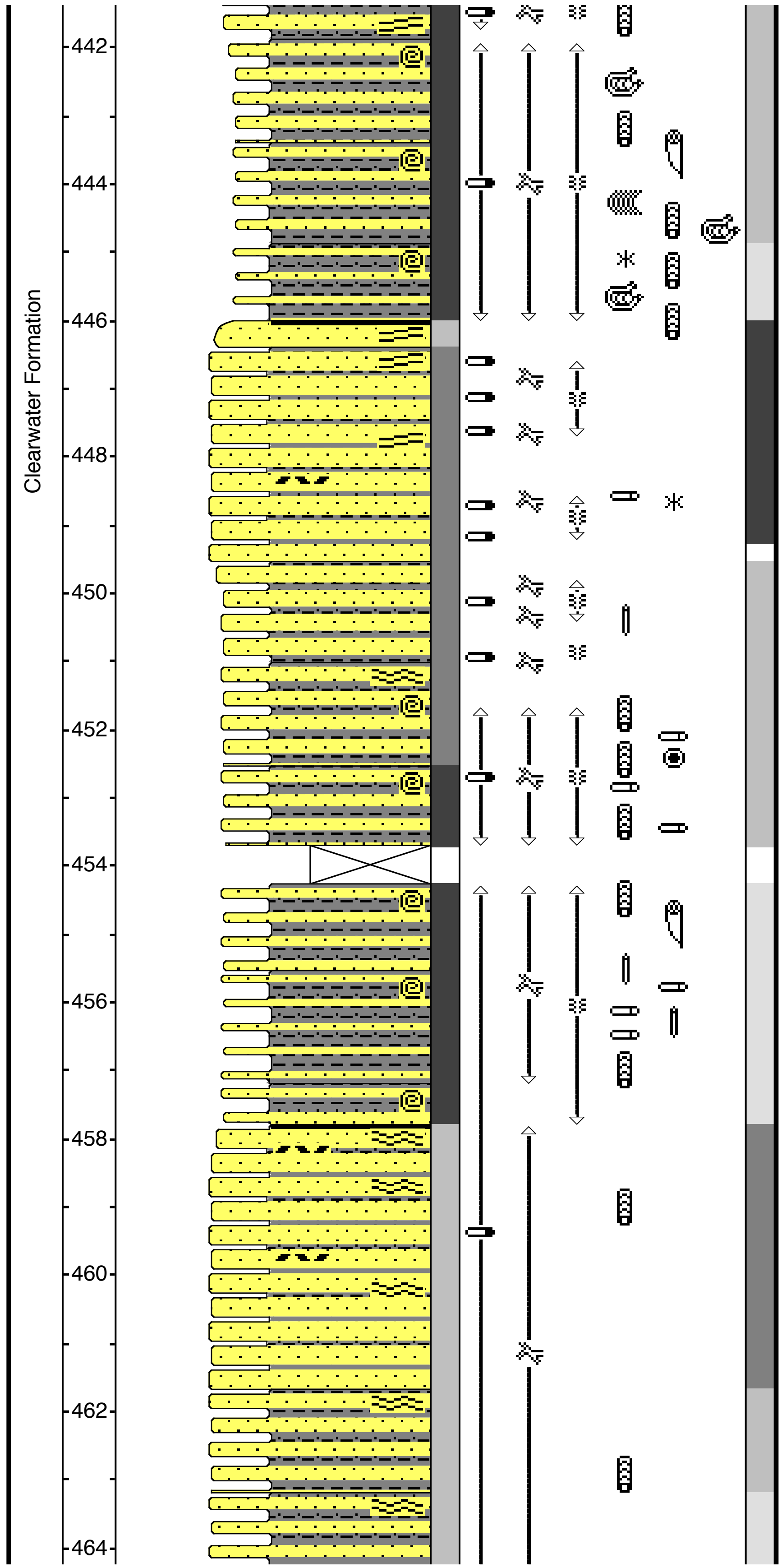
13-35-065-03w4

Date Logged: December 3rd, 2009

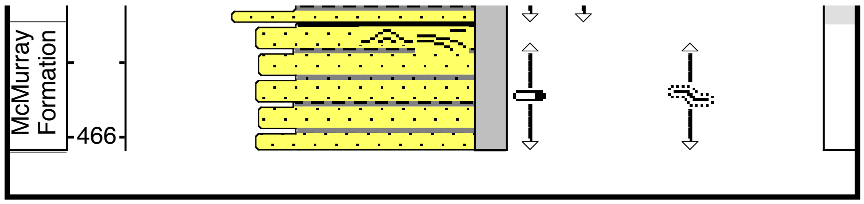
Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery, no McMurray/ Wabiskaw or Grand Rapids





Clearwater Formation
-442
-444
-446
-448
-450
-452
-454
-456
-458
-460
-462
-464


McMurray Formation
466

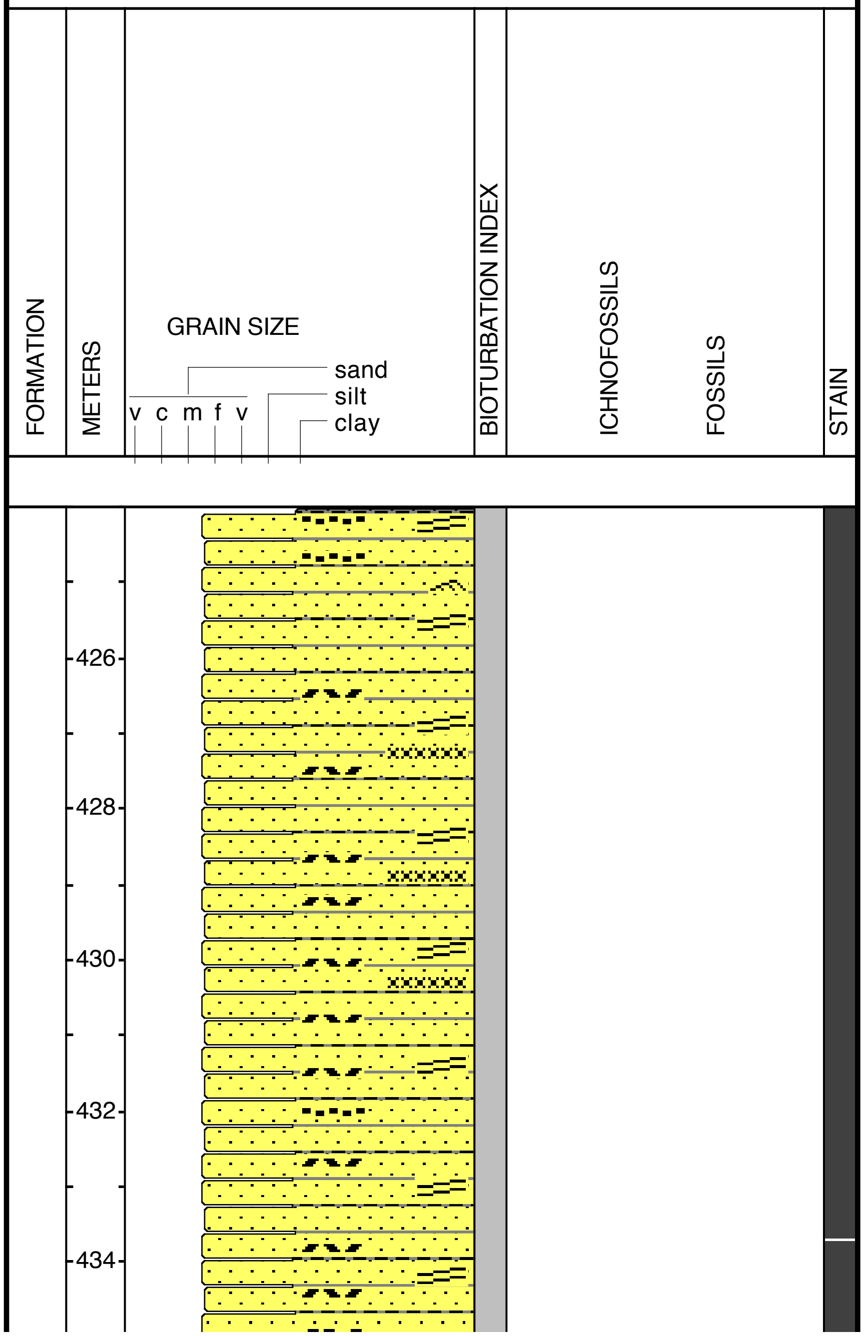
IMP 96 OV COLD LK

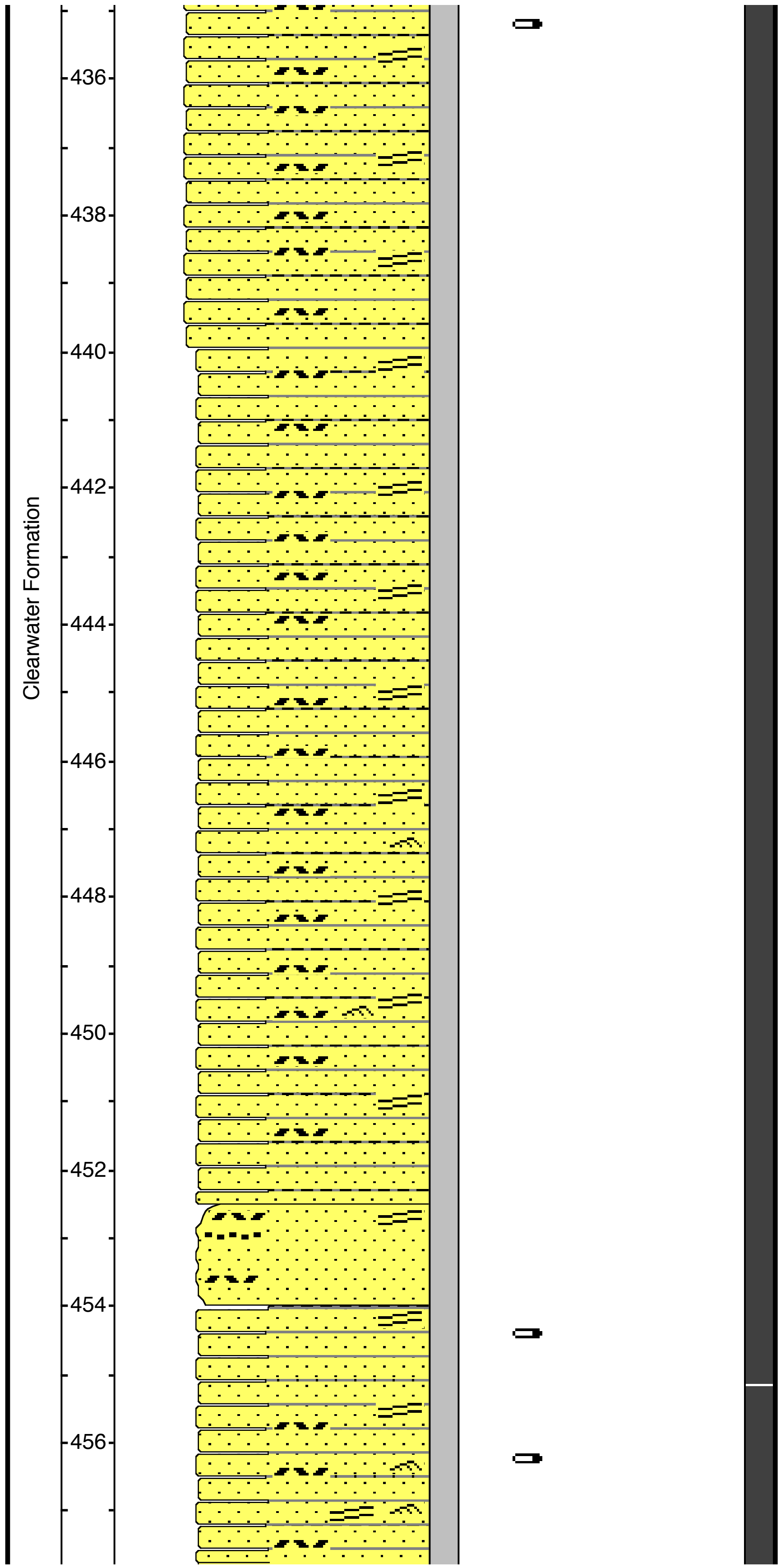
14-09-065-04w4

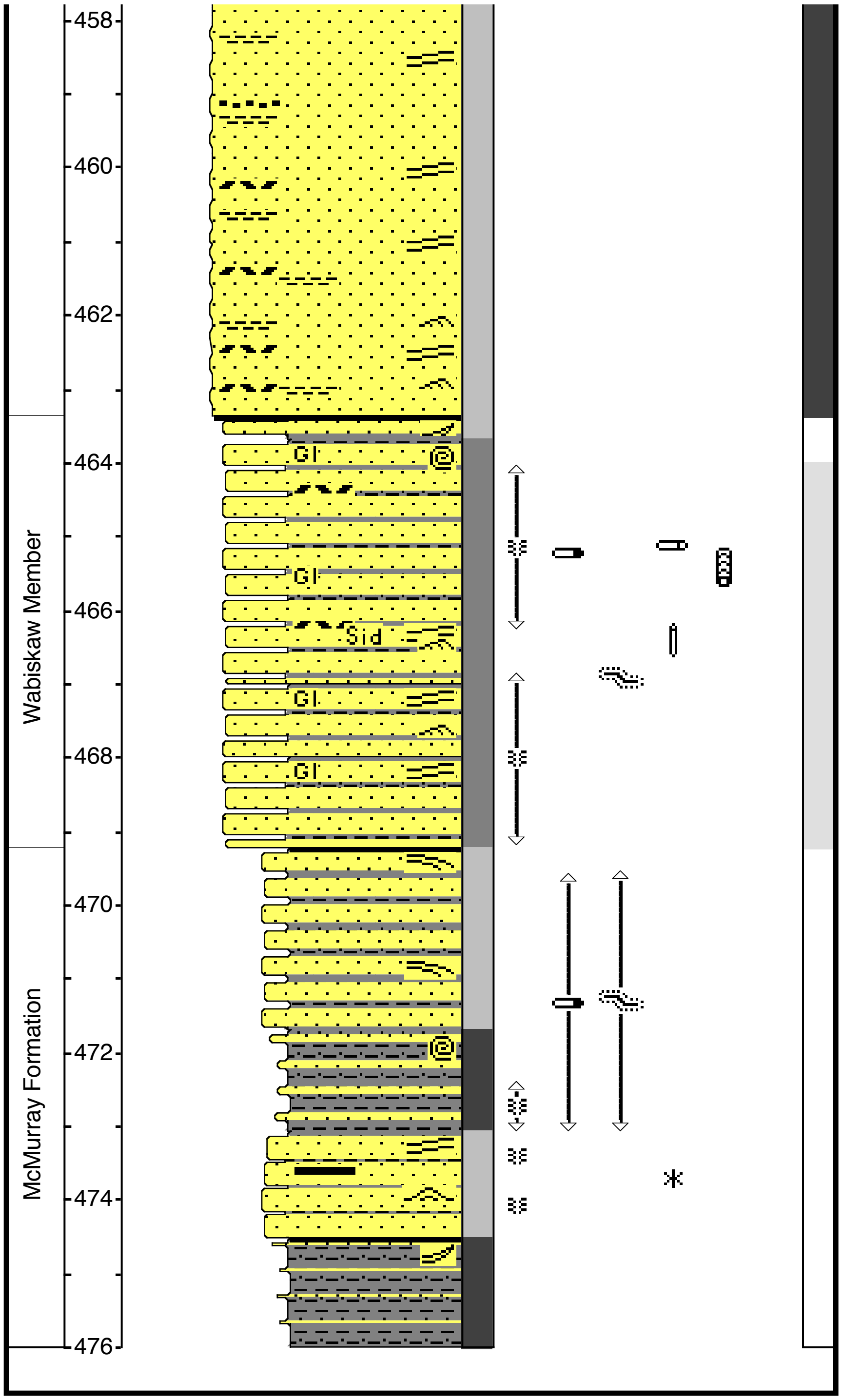
Date Logged: November 26th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, good recovery, contains McMurray and Wabiskaw at the btm but no Grand Rapids at the top.




Clearwater Formation
436
438
440
442
444
446
448
450
452
454
456


458
460
462
464
466
468
470
472
474
476
Wabiskaw Member
McMurray Formation
Gl
Gl
Sid
Gl
Gl

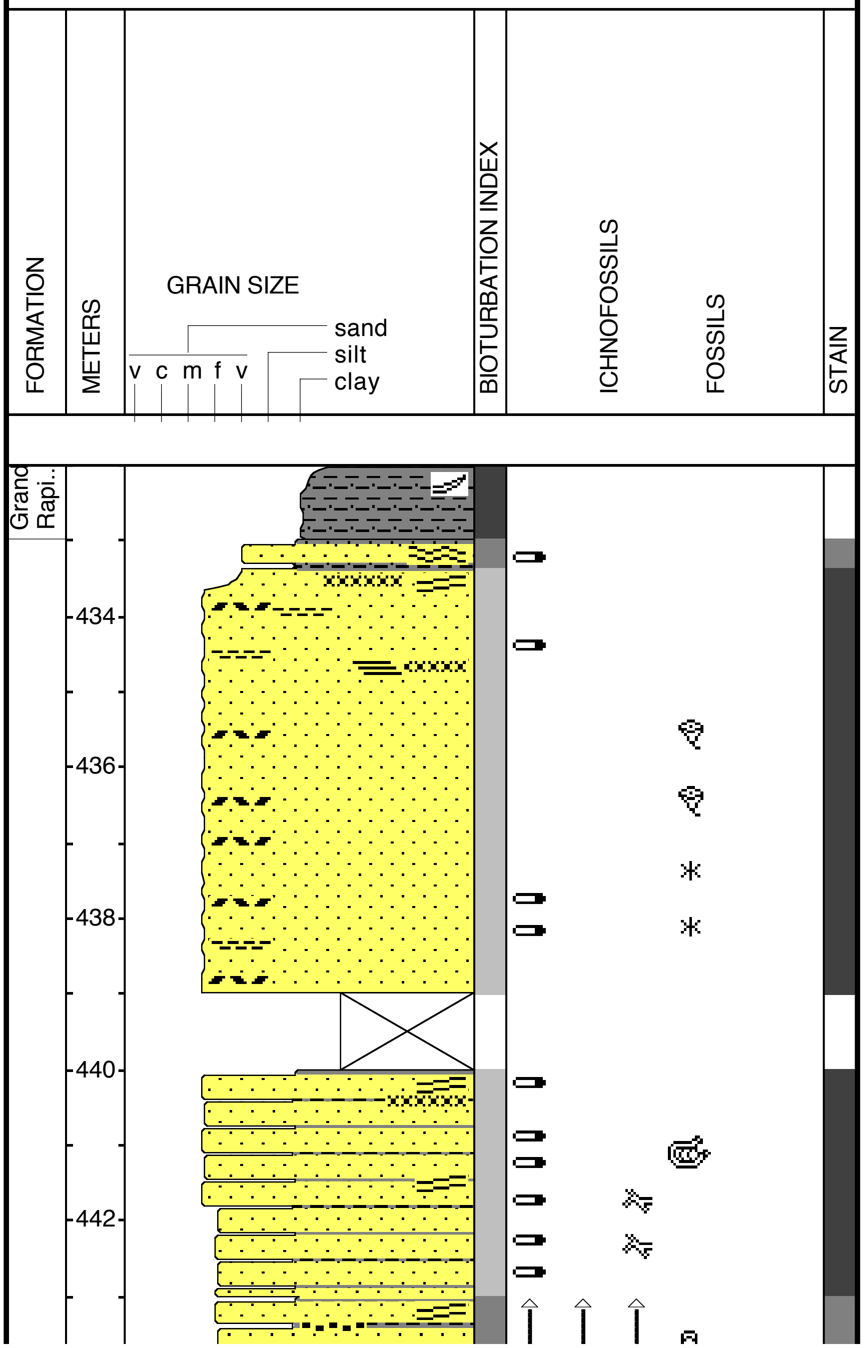
IMP 97 OV COLD LK

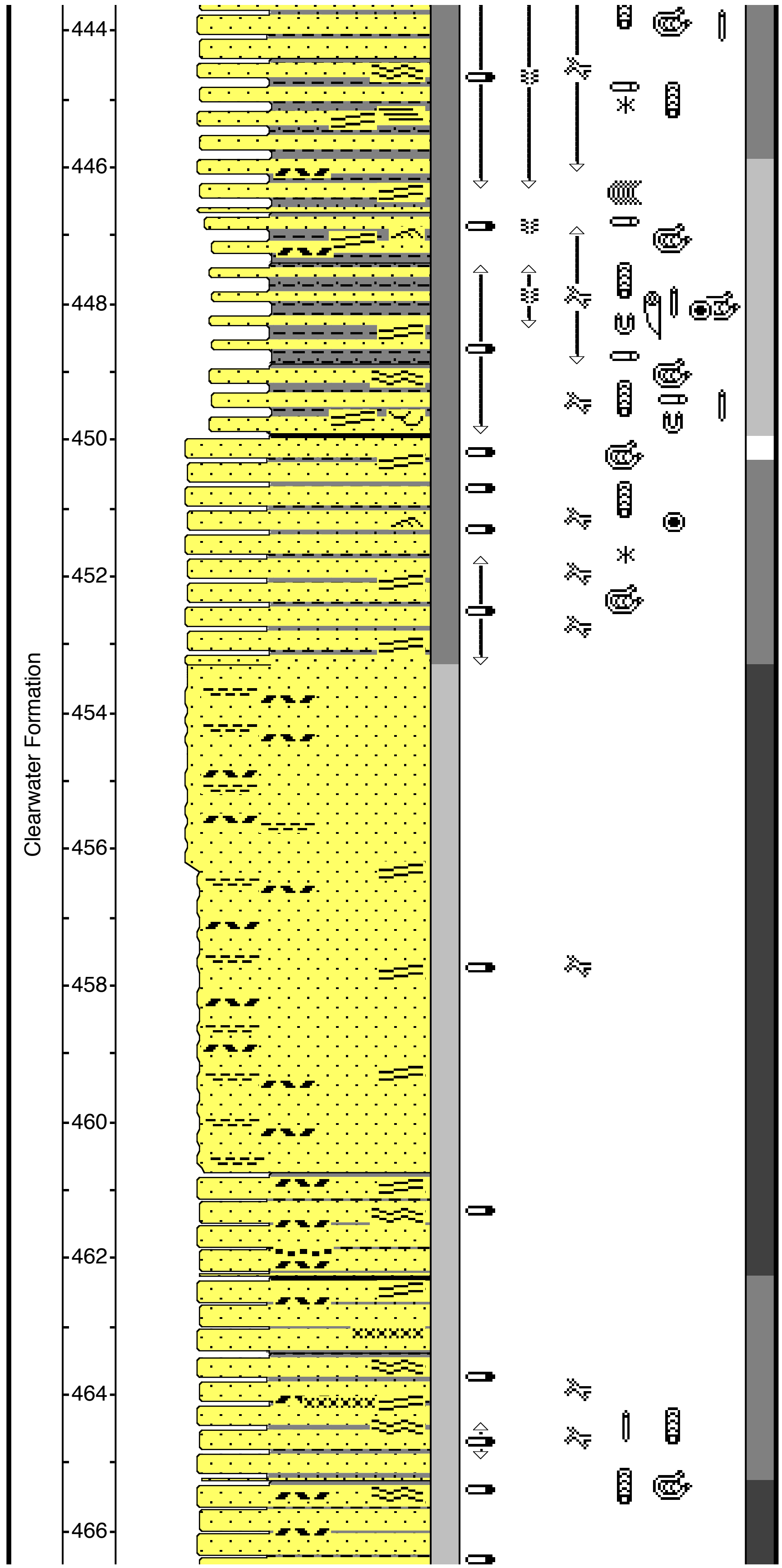
14-10-065-03w4

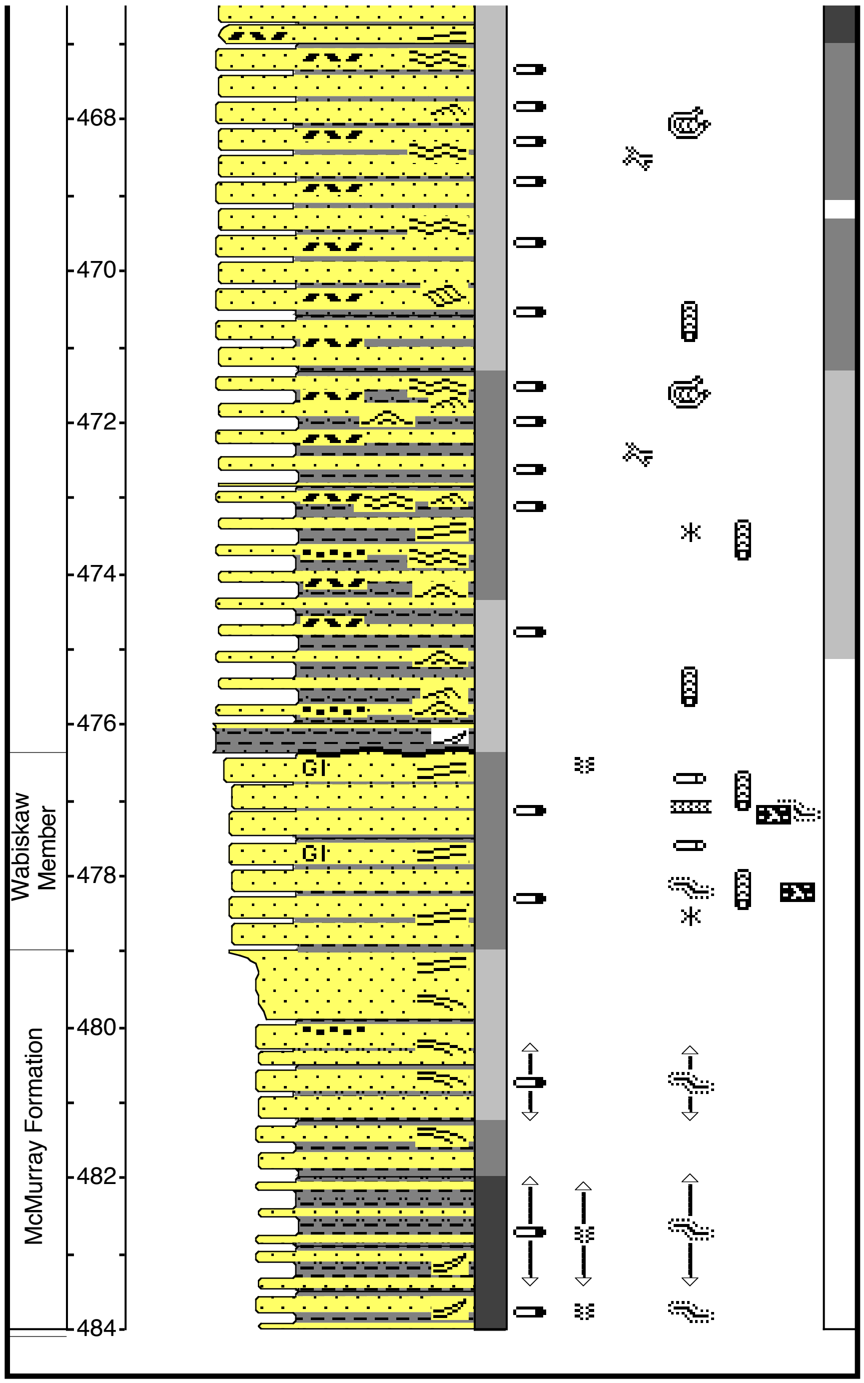
Date Logged: October 16th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, good recovery




Clearwater Formation
444
446
448
450
452
454
456
458
460
462
464
466



468
470
472
474
476
478
480
482
484
Wabiskaw Member
McMurray Formation
GI
GI

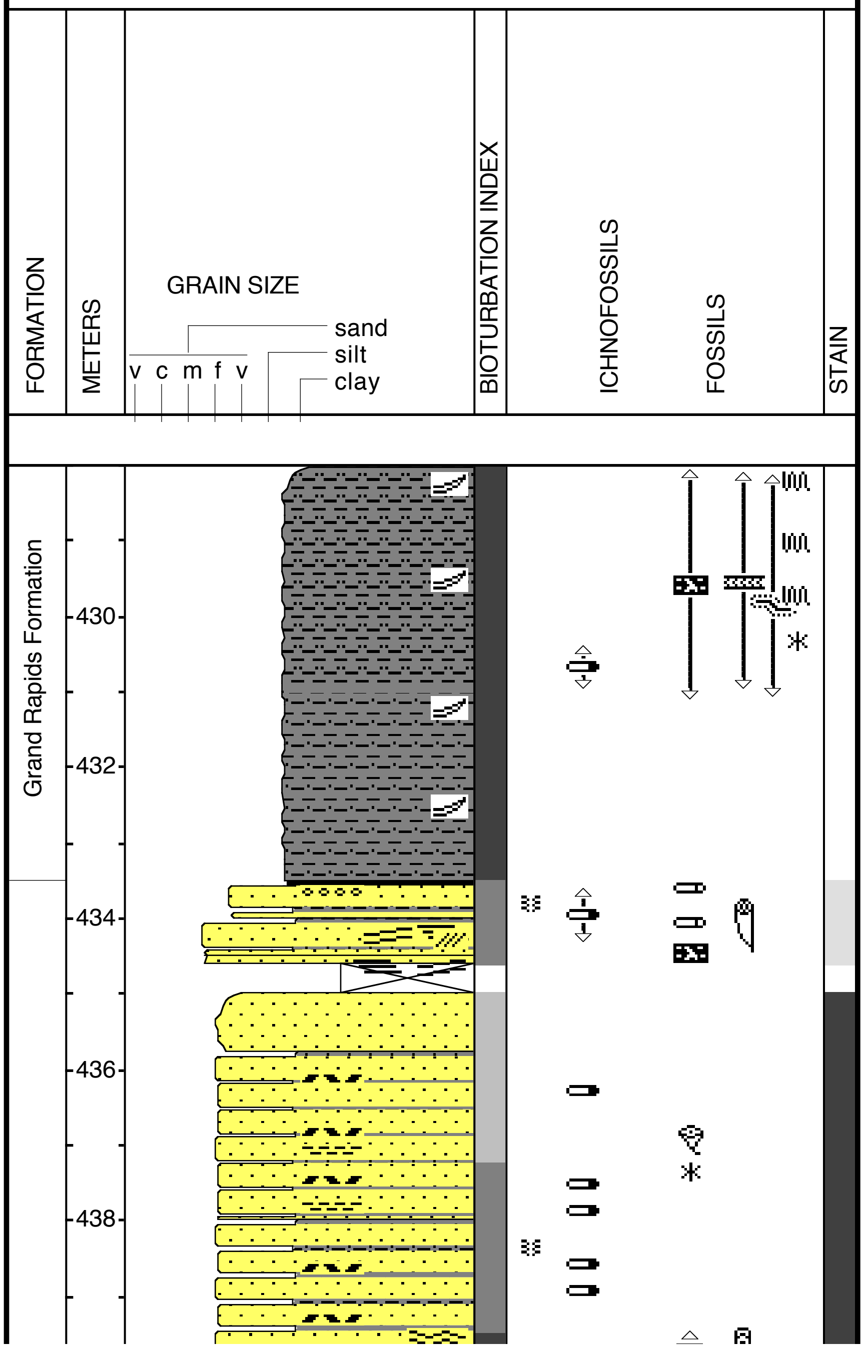
IMPERIAL 99/00 OV COLD LAKE

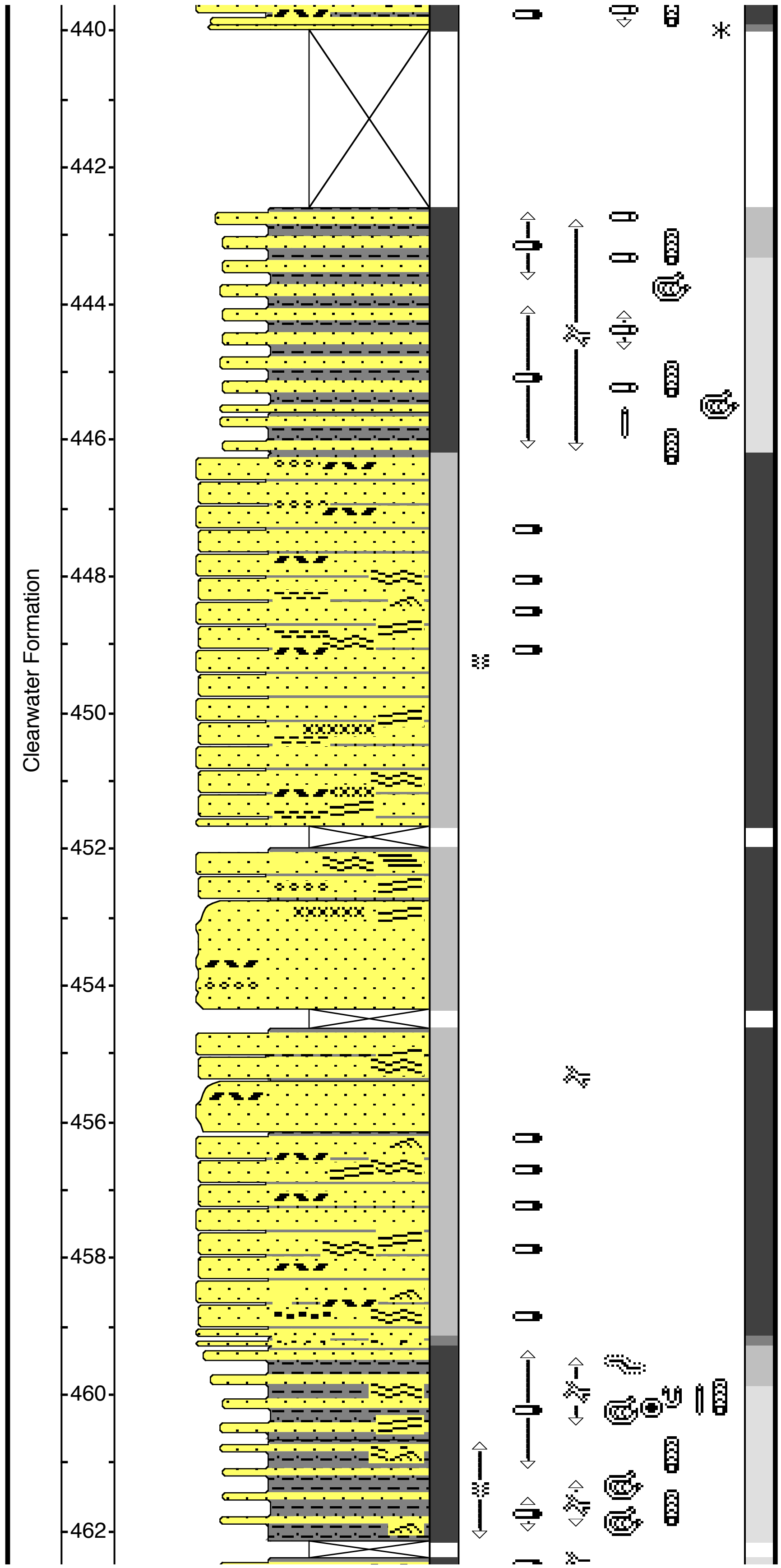
14 -25-65 -03 w4

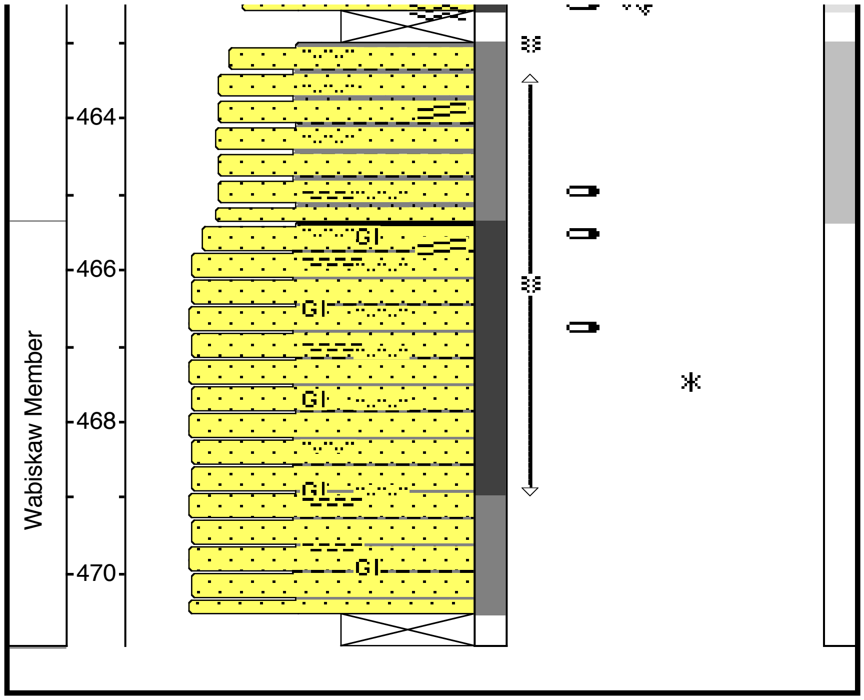
Date Logged: July 17th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, recovery good




Clearwater Formation
440
442
444
446
448
450
452
454
456
458
460
462



Wabiskaw Member
464
466
468
470
Gl
Gl
Gl
Gl
Gl

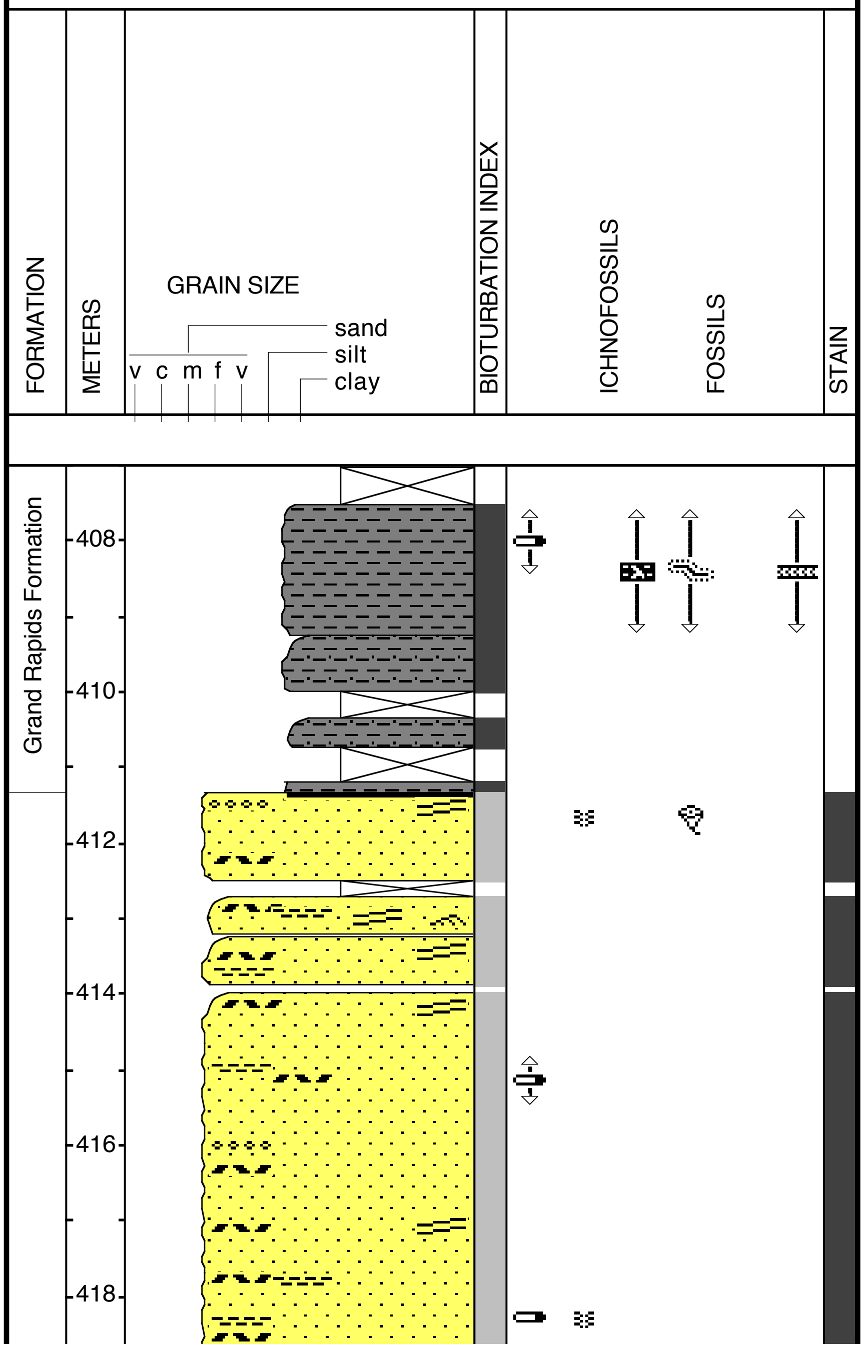
IMP 07 OV WOLF LK

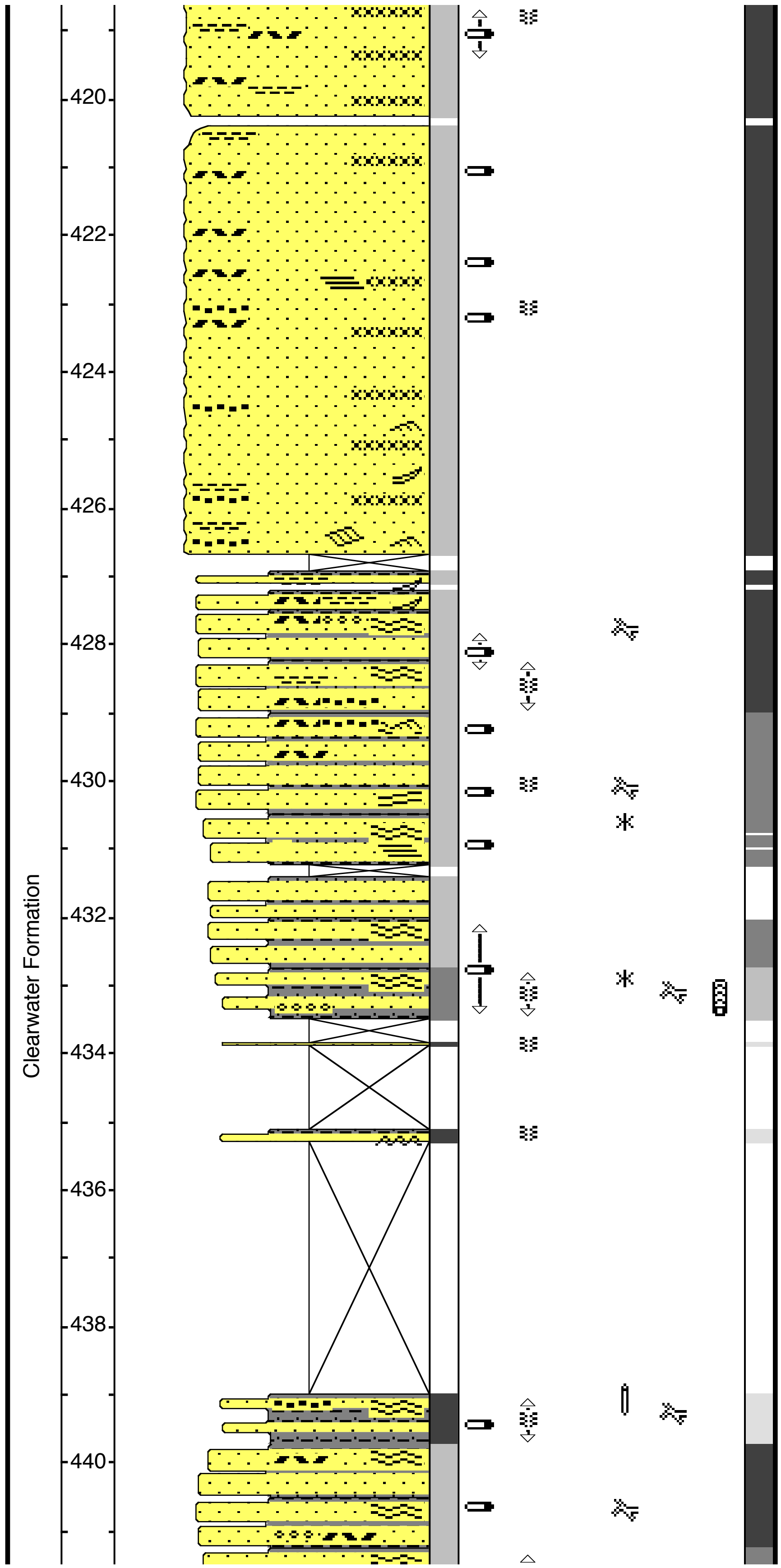
14-27-65-3w4

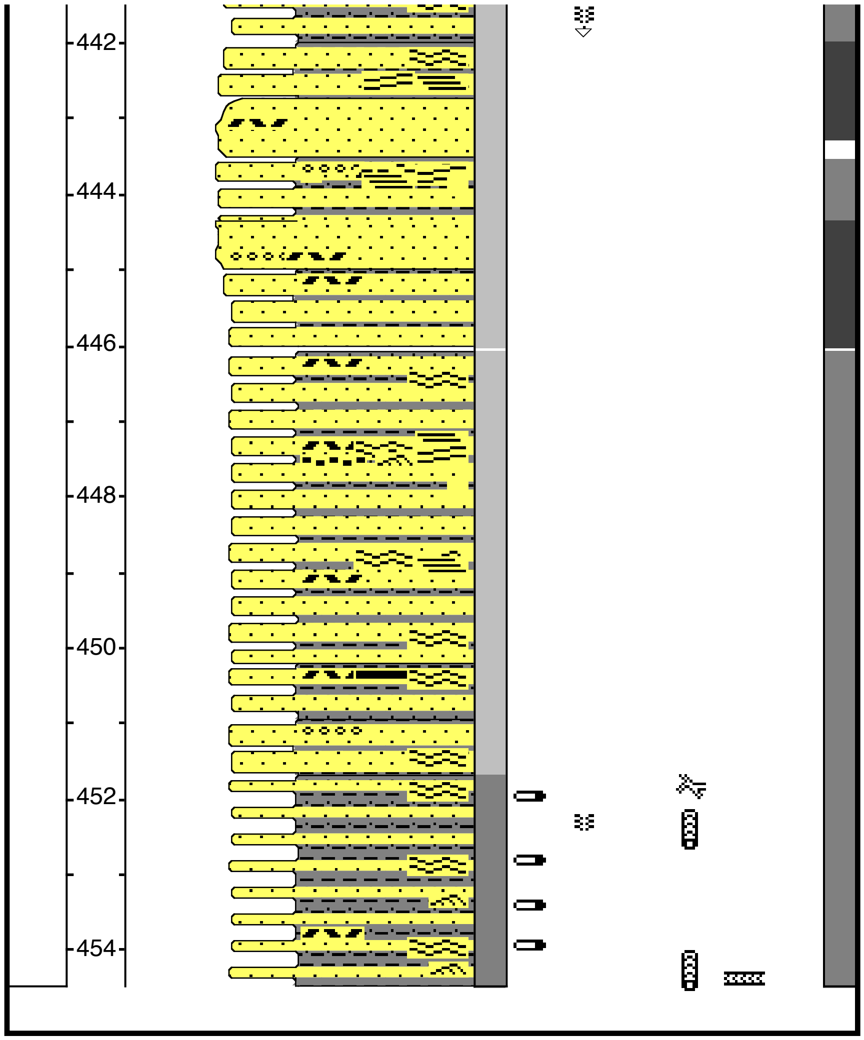
Date Logged: June 19th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, good recovery, oil saturated




Clearwater Formation
420
422
424
426
428
430
432
434
436
438
440


442
444
446
448
450
452
454

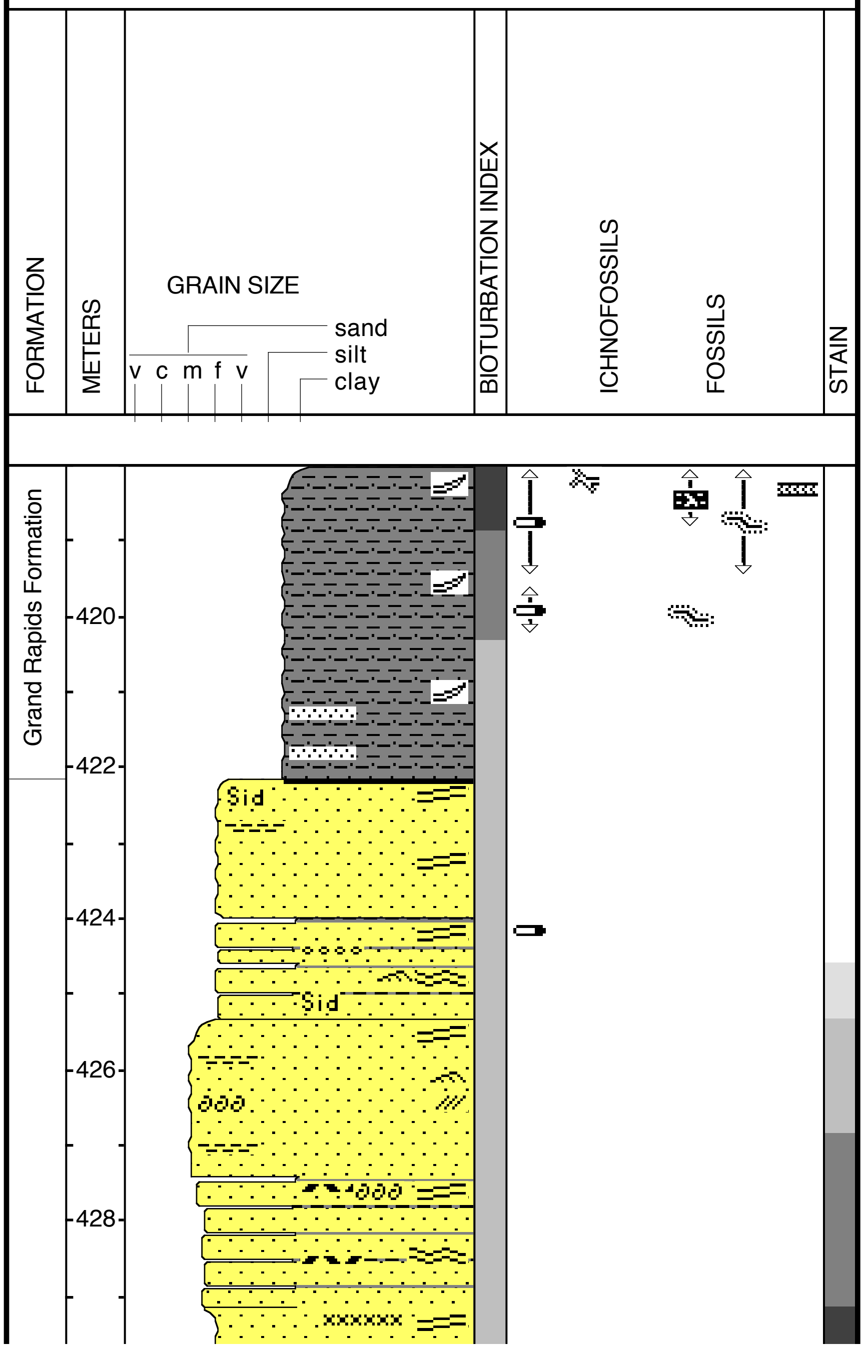
IMPERIAL 99/00 OV COLD LAKE

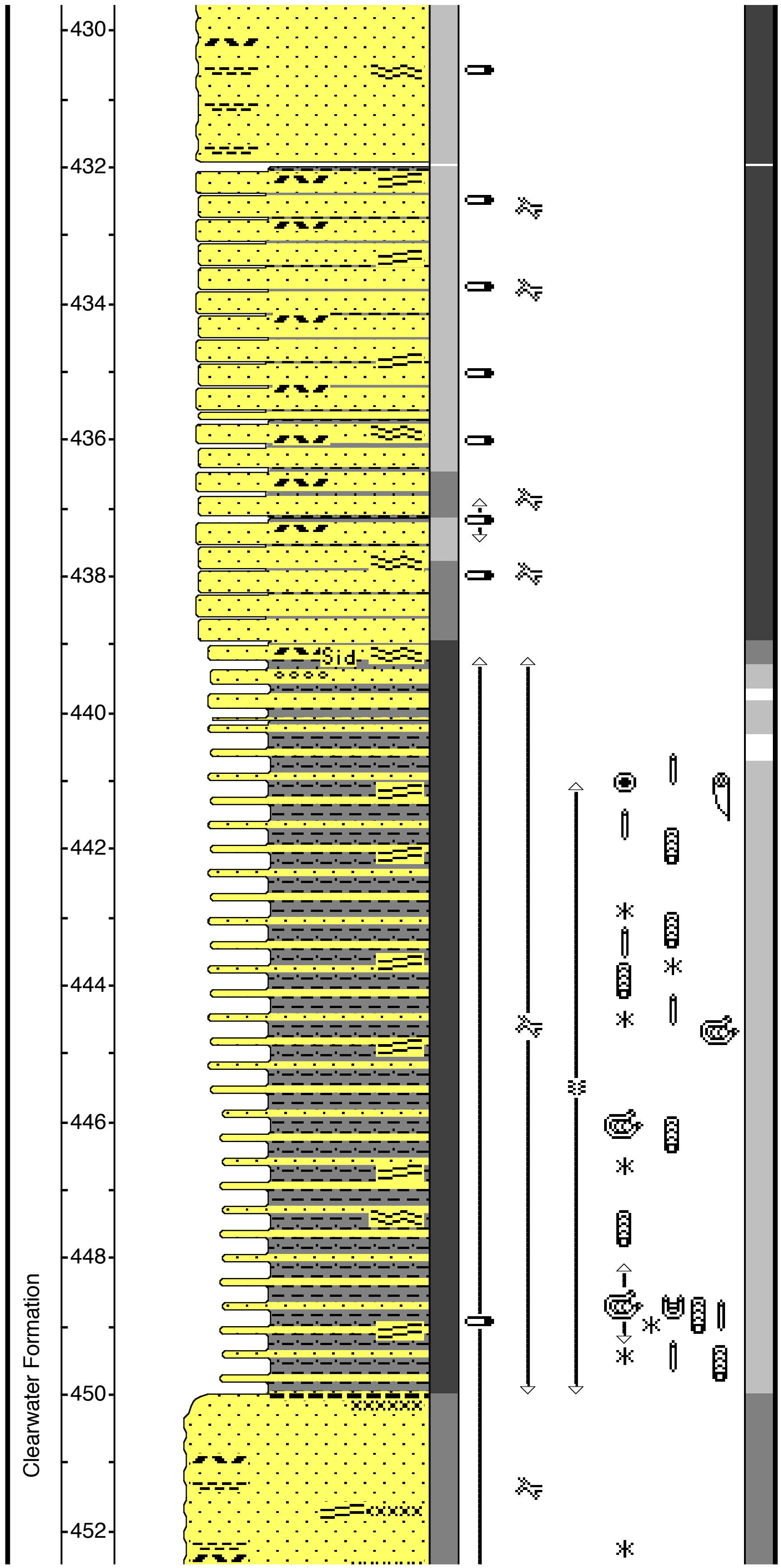
14-32-065-02w4

Date Logged: October 22nd, 2009

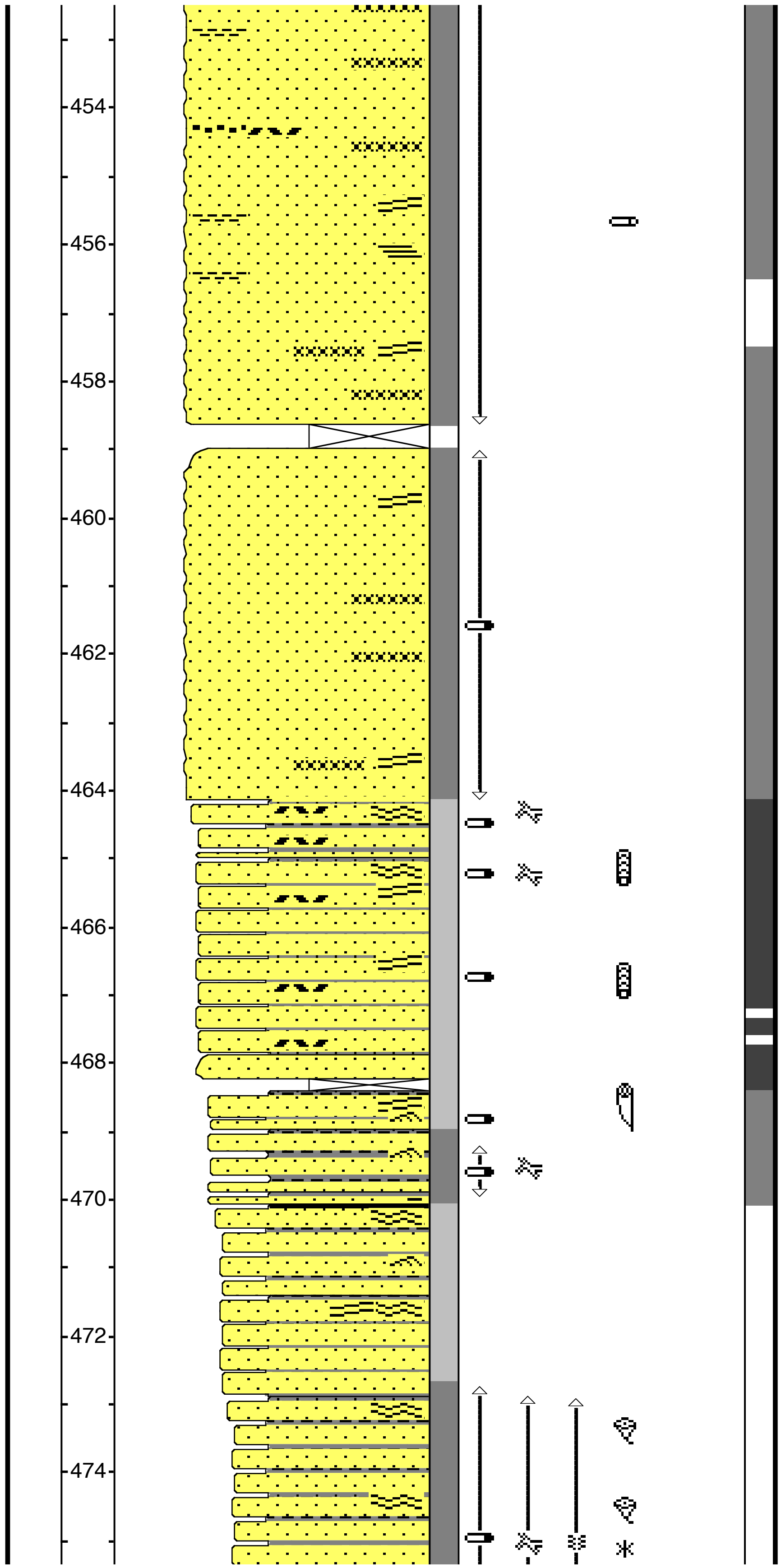
Logged by: Carolyn Currie

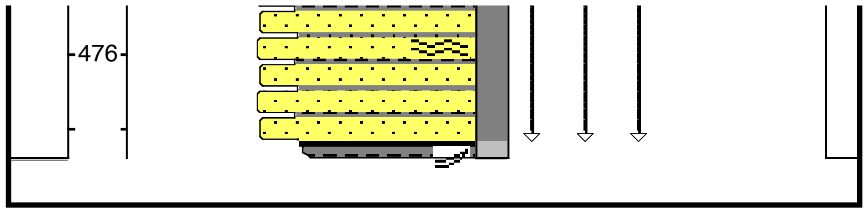
Remarks: 3.5" slabbed core, oil stained, v. good recovery.





Clearwater Formation
430
432
434
436
438
440
442
444
446
448
450
452
Sid


454
456
458
460
462
464
466
468
470
472
474


476

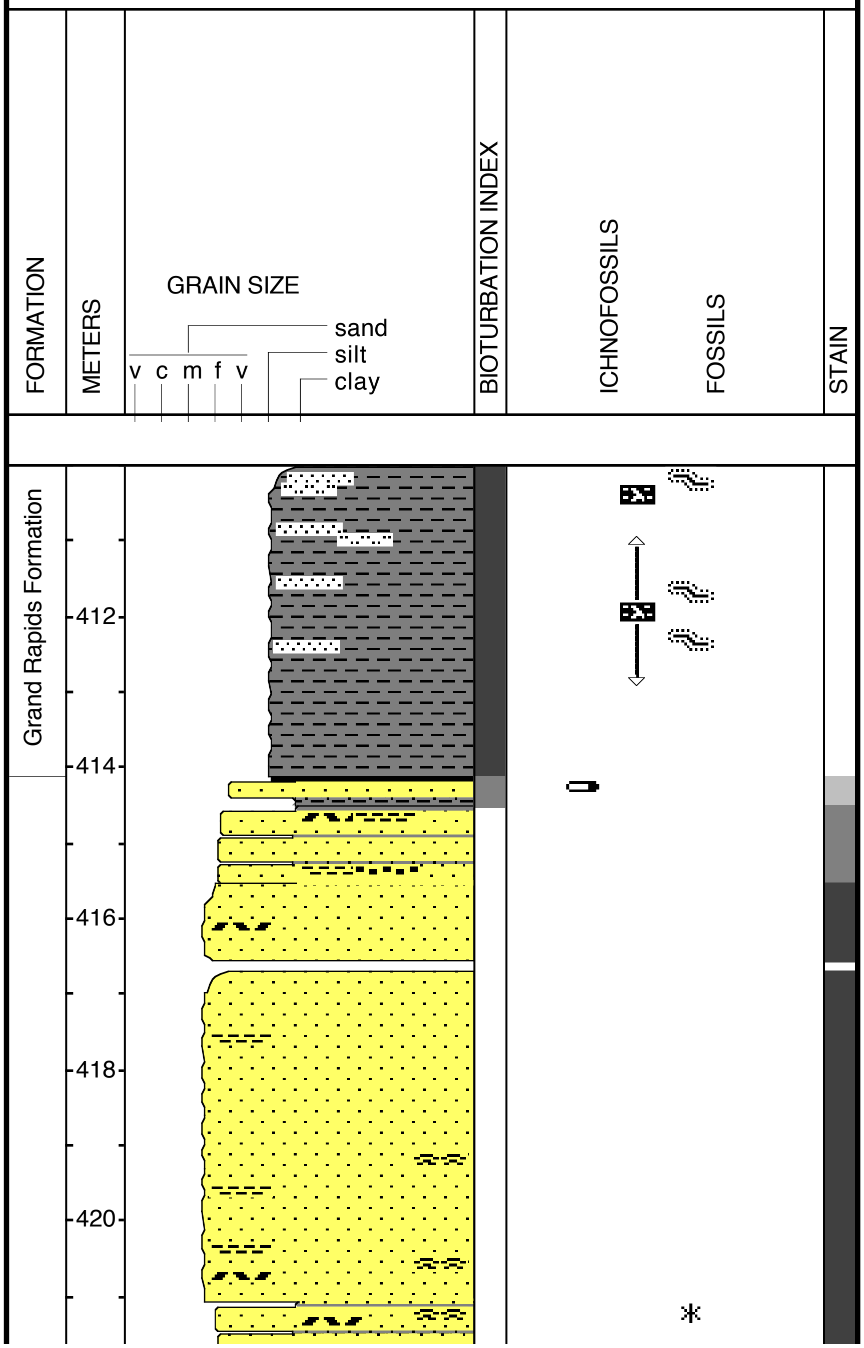
IMP 06 OV COLD LK

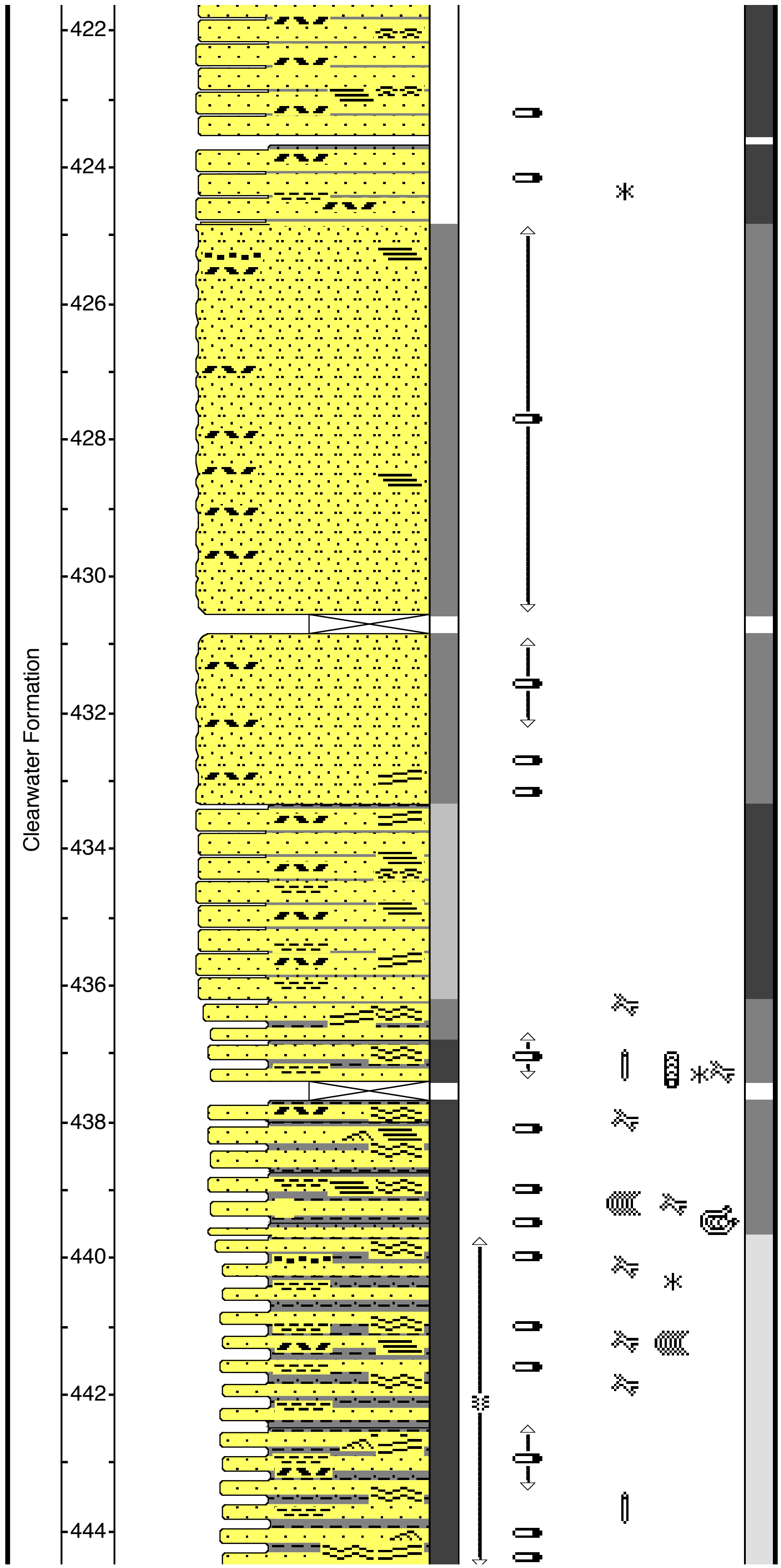
15 -21-65-03w4

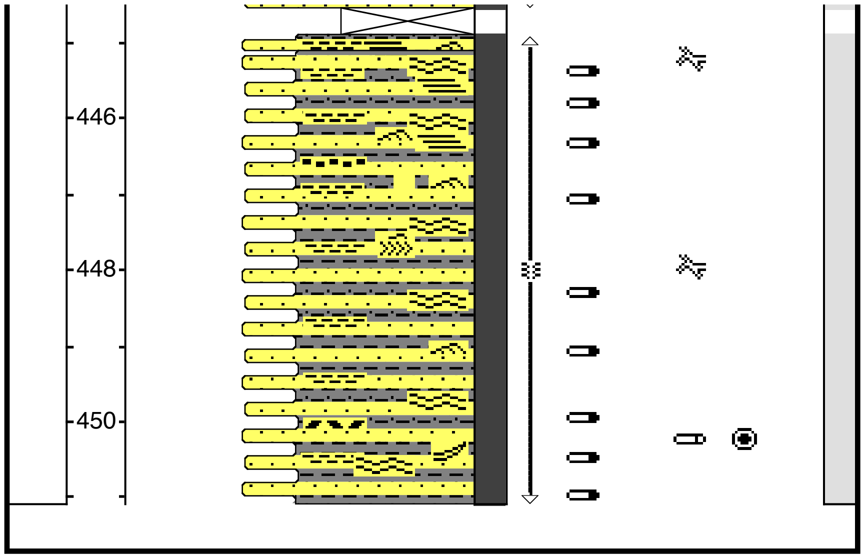
Date Logged: February 17th 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed, oil stained, recovery good




Clearwater Formation
422
424
426
428
430
432
434
436
438
440
442
444

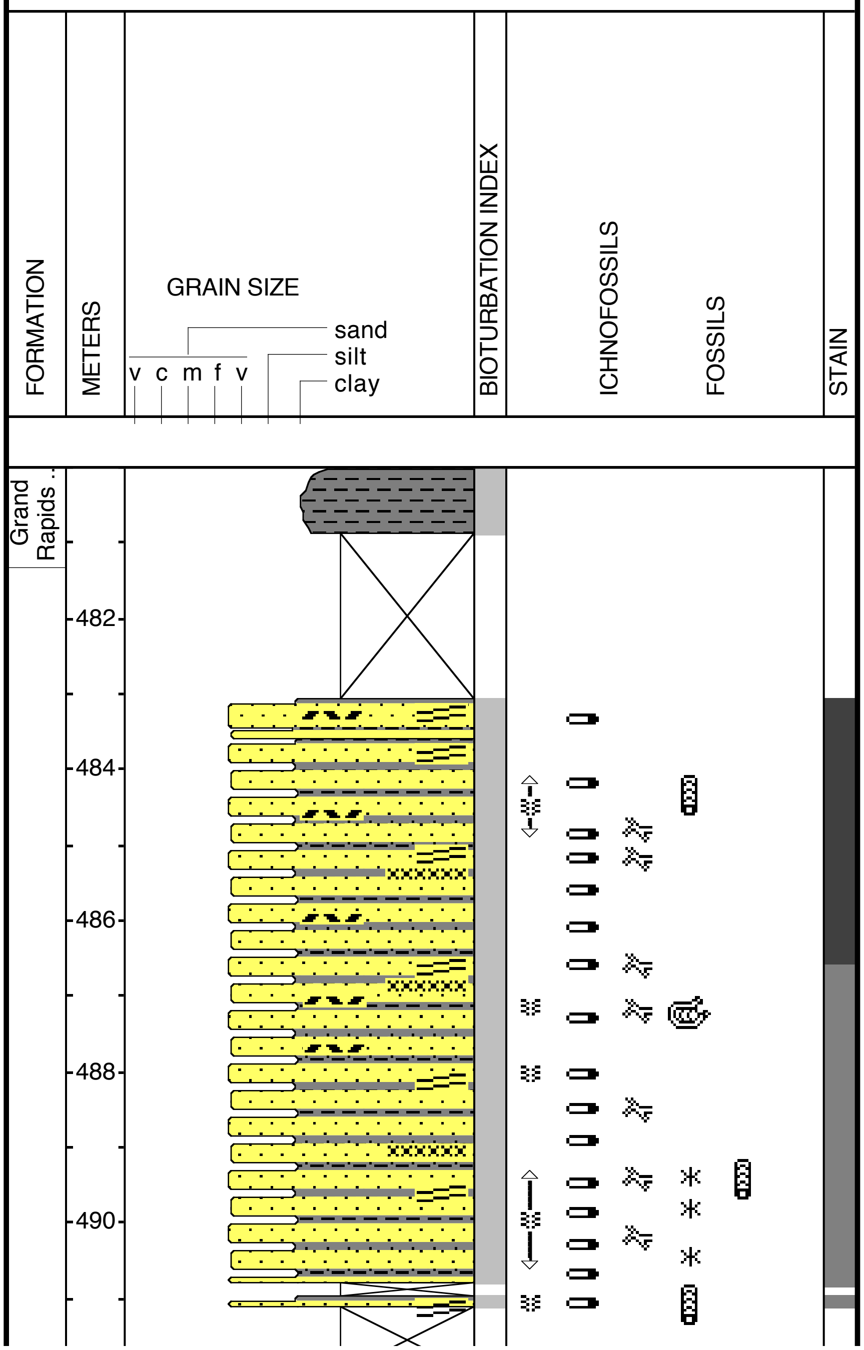

446
448
450

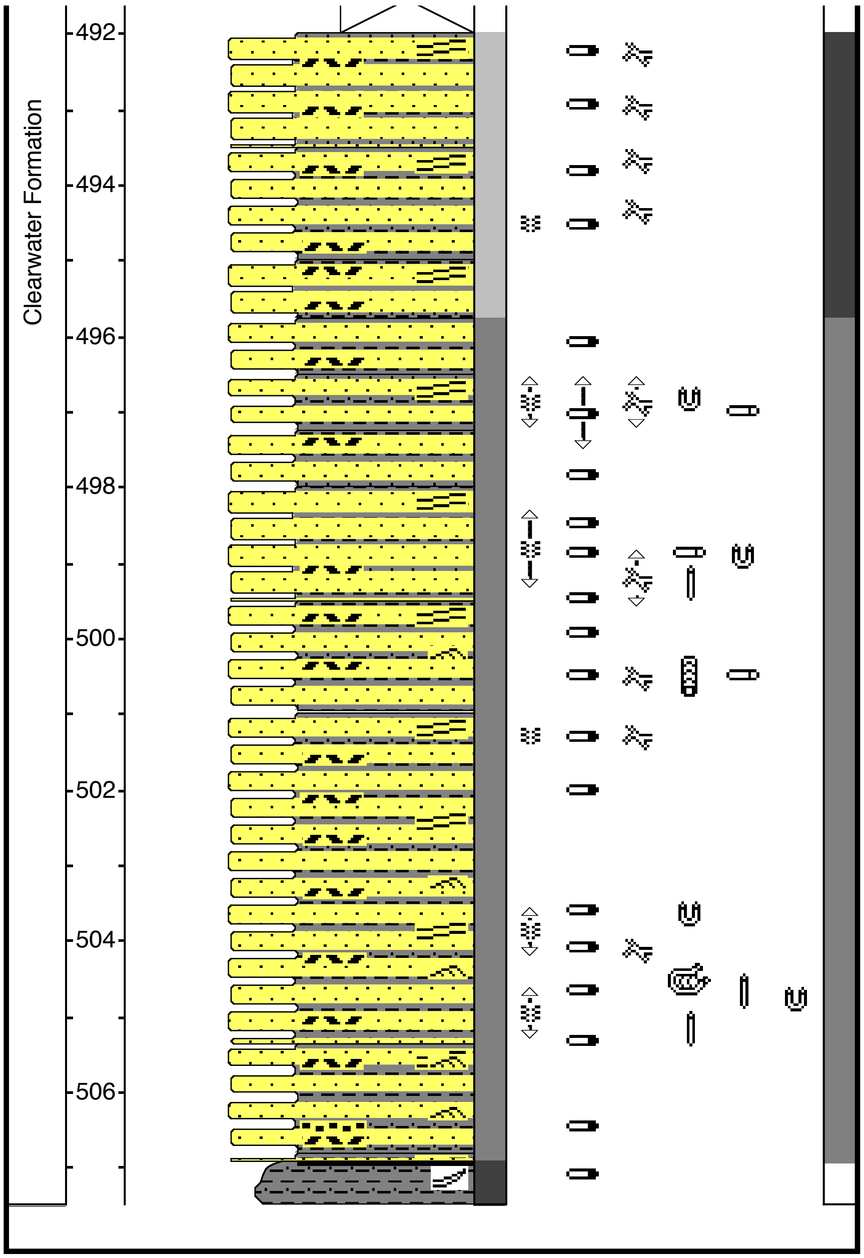
IMPERIAL 00/01 OV COLDLAKE
15-30-066-02w4

Date Logged: December 11th, 2009

Logged by: Carolyn Currie

Remarks: 3.5" slabbed core, oil saturated, v. good recovery, includes Grand Rapids shale above




Clearwater Formation
492
494
496
498
500
502
504
506