AER/AGS Open File Report 2017-08

Lithostratigraphy, Palynology, and Biostratigraphy of the Athabasca Oil Sands Deposit, Northeastern Alberta

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This body of work is the result of nearly two decades of work with the Alberta Geological Survey (AGS) and the Alberta Energy Regulator (AER) (and its predecessors). Although it is impossible to thank all of the government workers that helped with this regional work on the oil sands, we would like to thank the long and dedicated help from some of the former and present staff at the AGS and the Alberta Energy Regulator: H. Berhane, D.K. Cotterill, and C.W. Langenberg (AGS) for their technical expertise; and to the late M. Protz (AER), who always has helped to get the "formatting" right for public release.

Summary

The Athabasca Oil Sands Area of northeastern Alberta extends from approximately Township 70 to Township 104 and from Range 1, west of the 4th Meridian (Alberta-Saskatchewan border) to Range 18, west of the 4th Meridian. The Athabasca Oil Sands are hosted within the Wabiskaw–McMurray succession, which has complex lithofacies relationships within individual stratigraphic units. The complexity of the lithofacies tied to fragmentary preservation of different units makes it challenging to develop appropriate geological models for the characterization of the Wabiskaw–McMurray stratigraphy.

Decades of work by different geologists at the Alberta Geological Survey (AGS) have been done on the regional lithostratigraphy of the Wabiskaw–McMurray succession of the Athabasca Oil Sands Area. Tied with the regional lithostratigraphy has been the systematic sampling of fine-grained material for biostratigraphic analysis, to aid in correlation of units and delineation of paleoenvironments. Much of this biostratigraphic work is largely scattered within government files as unpublished material. The purpose of the present work is to release the biostratigraphic analyses in the public domain, and to provide geological interpretations that integrate the litho- and biostratigraphic results. The present report is written to give context for this stratigraphic data – a documentation of the compilation and analytical methods; reviews of the basic descriptions; and a summary of their interpretations. A series of digital files accompany this report, including stratigraphy of sampled cores and outcrops; well information for the sampled cores; compilation of historical palynological records (pre-1999) from AGS files; compilation of palynological reports done by and for the AGS (1999–2017); new palynofacies analysis and biostratigraphic charts for 31 cores and 10 outcrops; and, sedimentological and lithostratigraphic descriptions of cores and outcrops sampled for palynology.

This compilation work serves as a basis for understanding the geological framework of the Athabasca Oil Sands Area, from both a litho- and biostratigraphic viewpoint.

1 Introduction

The Athabasca Oil Sands deposit of northeastern Alberta is notorious for its complex facies relationships and fragmentary preservation, which has resulted in much discussion in the literature regarding the definition of mappable units, the identification of stratigraphic surfaces (i.e., ‘picks’), regional correlations, and the interpretation of the geological framework. The lithostratigraphy has evolved over the years. These lithostratigraphic revisions combined with changing description and interpretation of palynofacies has resulted in a need to standardize both the lithostratigraphic designations as well as the biostratigraphy and palynofacies descriptions of reservoir and non-reservoir units within the deposit. Such standardization will aid in the basic description of the geological framework for the Athabasca Oil Sands.

The present report integrates the regional lithostratigraphic and biostratigraphic (palynological) studies done by or for the Alberta Geological Survey (AGS) during the approximately two decades of previous work. By using an integrated approach, the results from the palynology help in identifying regional sedimentological trends and sequence boundaries for the different lithostratigraphic packages. The relative biostratigraphic age-dating of different stratigraphic packages aids in paleoenvironmental interpretations and in the future development of a 3D model for the Athabasca Oil Sands Area.

The regional study area extends from approximately Township 70 (southern edge) to Township 104 (northern edge) and from Range 1 to approximately Range 18, west of the 4th Meridian (Figure 1). The detailed lithostratigraphy and palynology apply to units from just above the Wabiskaw Member down to the sub-Cretaceous unconformity (Figure 2).

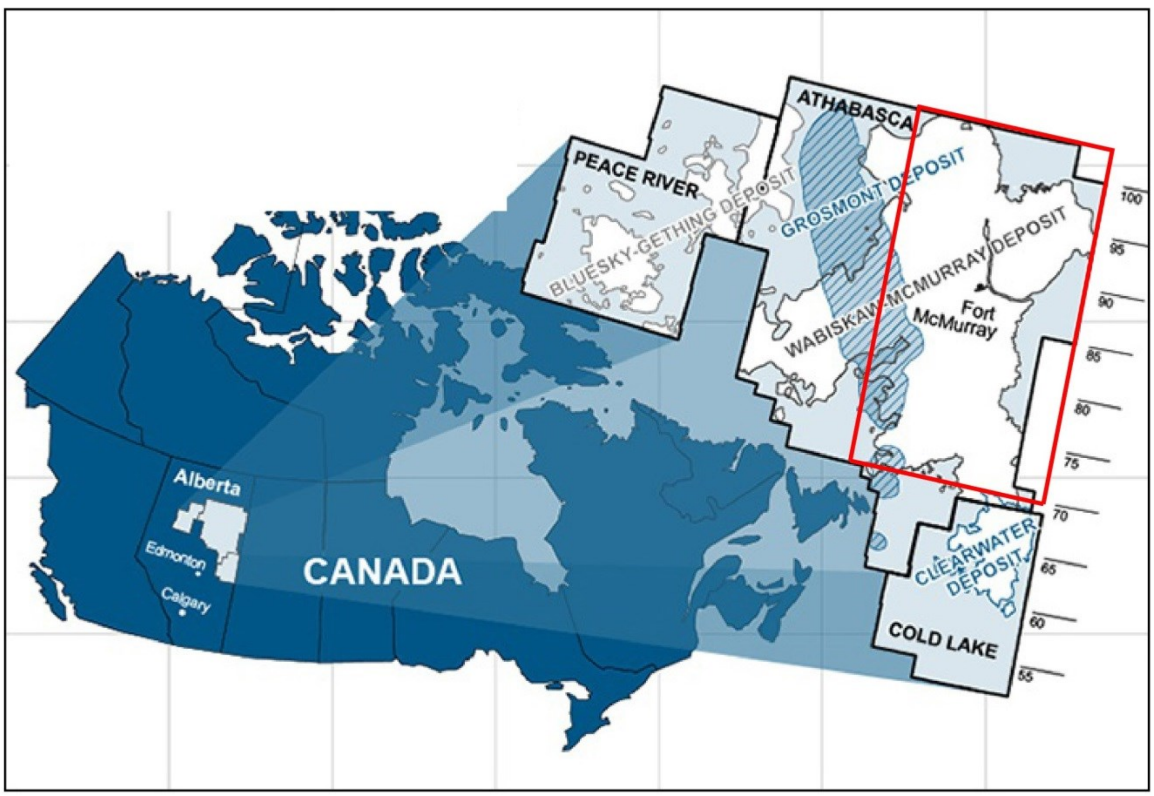


Figure 1. Location of the Athabasca Oil Sands Area. The main study area is from about Township 70 in the south (numbers on the right side) to Township 104; and from Range 1, west of the 4th Meridian (Alberta-Saskatchewan border) to about Range 18, west of the 4th Meridian (red rectangle) (modified from Alberta Energy Regulator, 2017).

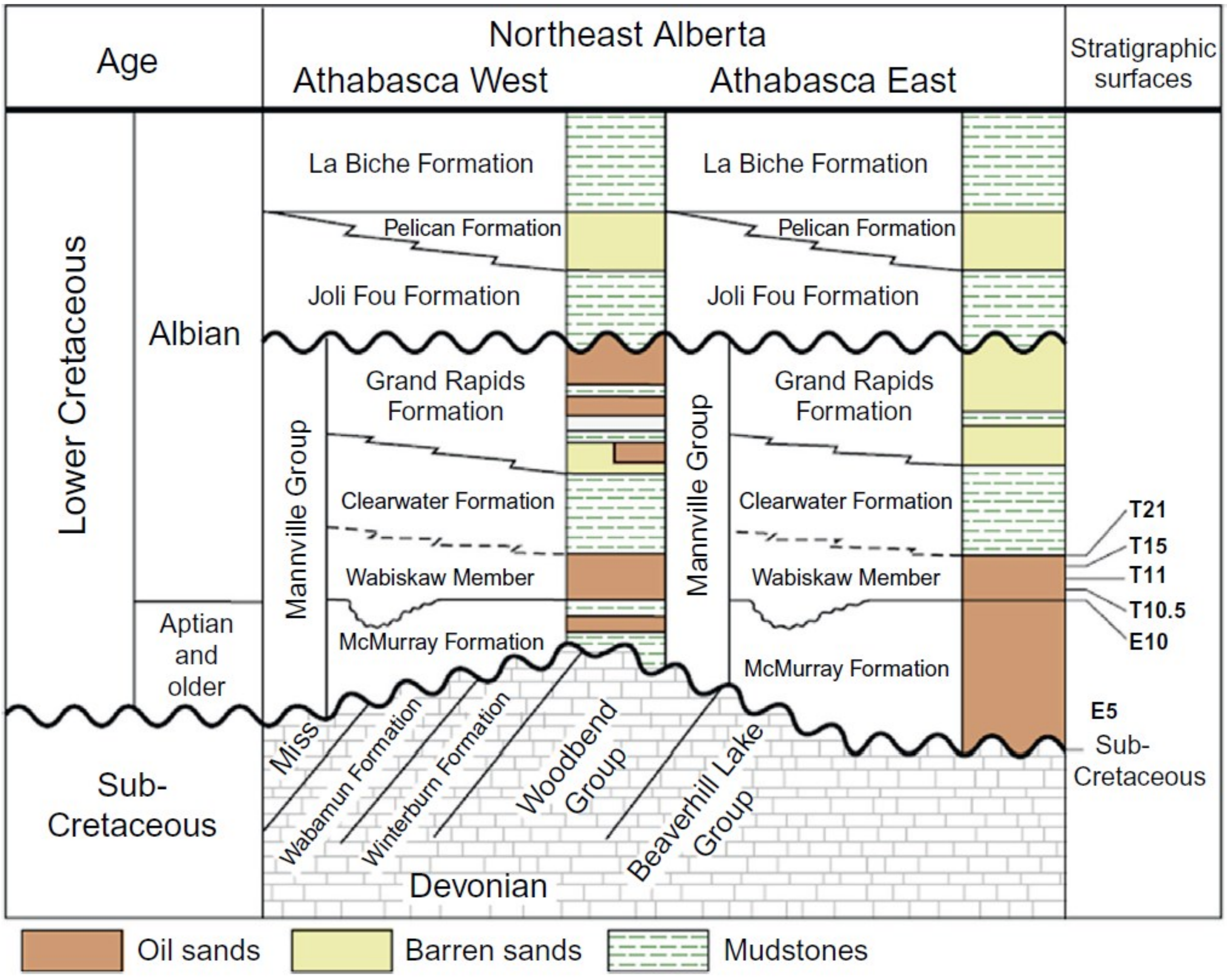


Figure 2. Schematic cross-section, northeastern Alberta. The stratigraphy examined in the present study is from just above the Cretaceous Wabiskaw Member (Clearwater Formation) (T21) to the sub-Cretaceous unconformity (modified from Hein et al., 2001).

2 Previous Work and Statement of the Problem

Previous work on the Lower Cretaceous Wabiskaw–McMurray succession is very extensive—from government, industry, and academic perspectives. Regional overviews of the Athabasca Oil Sands deposit are given by Alberta Energy and Utilities Board (2003), Caplan (2002), Hein (2006a), Hein et al. (2013a, b), Mathison (2003), Mattison (1987), and McPhee (1987, 1994). Carrigy and Kramers (1973) present an historical overview of exploration and development of the Alberta oil sands, which was updated by Hein (2000, 2015, 2016a). Hein et al. (2013a) and Hein and Parks (2016) give a retrospective of previous government work on the Athabasca Oil Sands, starting with the initial reserves estimates in the 1960s, continuing with AGS work for the Alberta Oil Sands Technology and Research Authority (AOSTRA) in the 1990s, and culminating with the omnibus "Gas-over-Bitumen" hearing by the Alberta Energy and Utilities Board (2003). It is beyond the scope of this report to repeat these reviews, with relevant stratigraphic and sedimentological work discussed below.

Over the last decade and a half, much Alberta government work has considered the regional lithostratigraphy and depositional facies of the McMurray Formation and associated stratigraphic units (Hein, 2006a, b, 2015; Hein and Cotterill, 2006, 2007; Hein et al., 2000, 2001; 2006a, b; 2008; Hein and Marsh, 2008; Langenberg et al., 2002, 2003; Marsh and Hein, 2008). From the Alberta government staff perspective, this regional work showed that the lower McMurray to top Wabiskaw Member deposits record an overall regional marine transgression, locally complicated by a number of different geological factors. Such factors resulted in the following confounding features of the Athabasca area:

- the preserved stratigraphy is complex;
- major preserved stratigraphic elements are separated by significant hiatuses, disconformities, and unconformities;
- different paleoenvironments, ranging from continental/fluvial to brackish estuarine, marginal marine to fully marine, may be juxtaposed to one another in outcrop or between wellbores in the subsurface, or stacked within a single wellbore, where recognition of breaks in the section may be difficult;
- no single depositional model accounts for the entire succession;
- in areas of decreased accommodation space (for major parts of the Athabasca Oil Sands Area) significant reworking of older units (from Devonian to Lower Cretaceous) occurred at different times, including cannibalization of earlier-deposited McMurray strata;
- recognition of fluvial, brackish, and marine-influenced settings and the realization that their distinction from one another is not straightforward, particularly in areas of mixed influences (i.e., tidally-influenced fluvial environments; fluvial-dominated tidal estuaries; marine-influenced coastal plains, etc.);
- local relative base-level controls are related to combinations of tectonics, dissolution of underlying Devonian salt and carbonate successions (with resulting subsidence, folding, and faulting), and eustatic changes in sea level; and
- much of the apparent local stratigraphy for the Wabiskaw–McMurray succession may not, in fact, be regionally correlative—with units in the south older than what appear to be similar facies in the north.

As discussed by Hein and Langenberg (2003) "There has been no regional work that demonstrates that what is mapped as lower-middle-upper McMurray in one area (e.g. Athabasca North) is actually either lithostratigraphically or chronostratigraphically correlatable to what has been mapped as lower-middle-upper McMurray in another area (e.g. Athabasca South)." One way to try and disentangle the fragmented preserved stratigraphy and to identify paleoenvironments is through the use of palynostratigraphy tied to the lithostratigraphy and sedimentology.

The Wabiskaw–McMurray succession is well known and documented for its rapid facies variation and general paucity of macrofossils to aid in biostratigraphic correlation (Hein et al., 2013a; Dolby et al., 2013). Fourteen large, vertebrate body-fossils have been found in the oil-sands mines over the previous two and a half decades (Tanke et al., 2013) (Figure 3). These large vertebrate fossils are mainly marine reptiles, including plesiosaurs and ichthyosaurs, and two terrestrial dinosaurs (armoured ankylosaur and nodosaur) (Bohach and Frampton, 2010; Chandler, 2014; Christian, 2011; Druckenmiller, 2006; Druckenmiller and Maxwell, 2010; Druckenmiller and Russell, 2006, 2008, 2009a, b; Druckenmiller and Zonneveld, 2002; Greshko, 2017; Henderson, 2013; Hill, 2012). Rare bones of ornithischian (bird-like) dinosaurs have been found in the McMurray Formation (Alberta Palaeo-Resources Ltd., 2007). Although many of these vertebrate remains are exceptionally preserved and represent spectacular fossil finds, the number of these large vertebrate finds is small and almost all have been recovered from the narrow stratigraphic interval at the contact between the Wabiskaw Member and the underlying McMurray Formation (Figure 3, solid dark pattern).

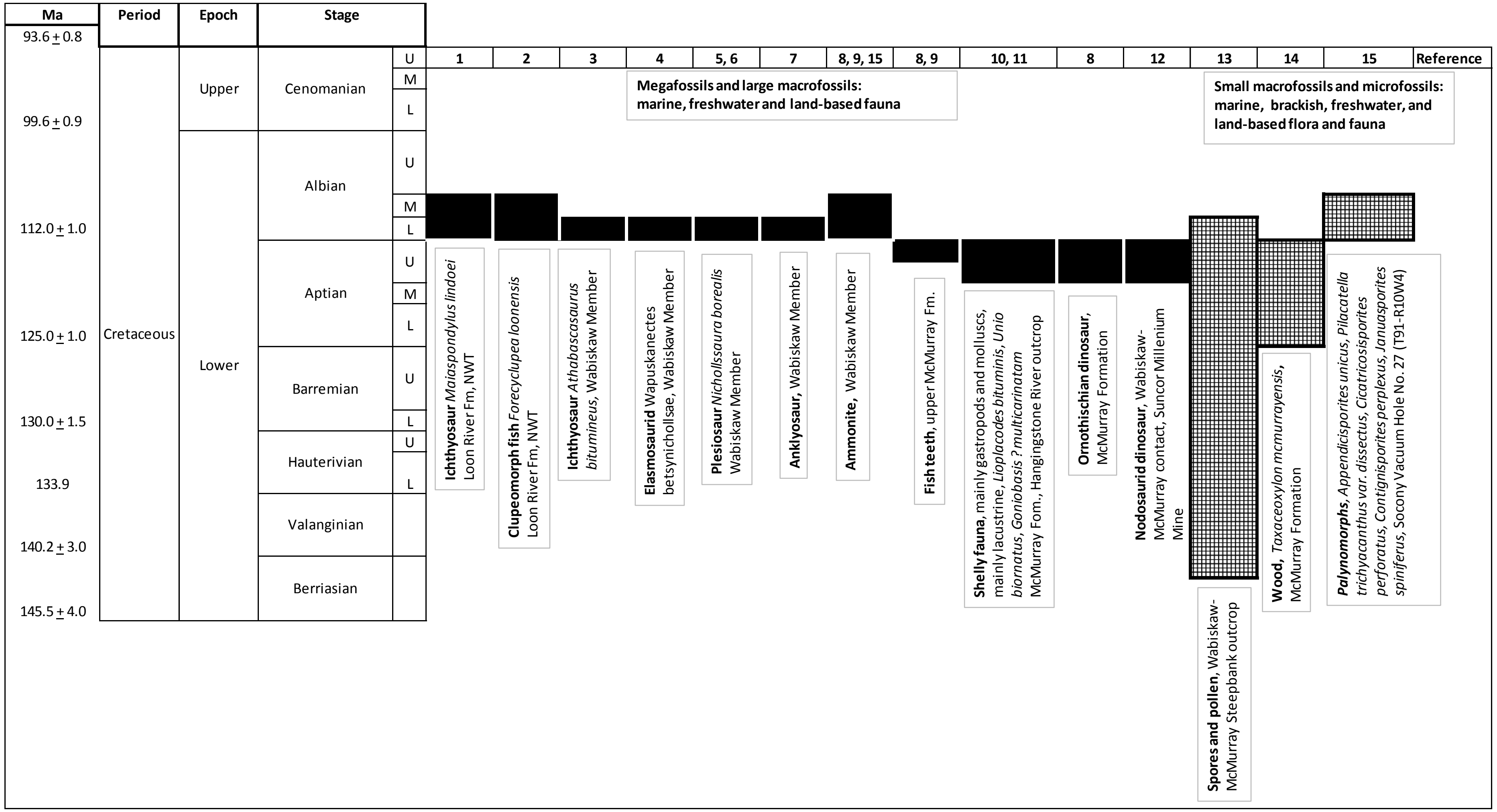


Figure 3. Schematic stratigraphic chart showing published records of mega-, macro-, and microfossils from the Lower Cretaceous succession in northeastern Alberta, corresponding to the Wabiskaw–McMurray (and associated) units. Most of the mega fossils and many of the large macrofauna are from a very narrow stratigraphic interval and time-range, recovered from sideritized cemented and concretionary beds along the Wabiskaw–McMurray contact. Smaller macrofossils and microfaunal/microfloral remains have a wider stratigraphic range; thus, being potentially more useful for regional assessment and correlation. References are: 1) Maxwell and Caldwell (2006); 2) Vernygora et al. (2015); 3) Druckenmiller and Maxwell (2010); 4) Druckenmiller and Russell (2006); 5) Druckenmiller and Russell (2008); 6) Druckenmiller and Russell (2009b); 7) Hill (2012); 8) Alberta Palaeo-Resources (2007); 9) Carrigy (1963); 10) Russell (1932); 11) Mattison (1987); 12) Greshko (2017); 13) Burden (1984); 14) Roy (1972); 15) Vagvolgyi and Hills (1969); and 16) Mellon and Wall (1956).

Compared to the rare larger macro- and megafossils described above, what is more commonly found in the Wabiskaw–McMurray successions are the smaller macro- and microscopic plant fossils, invertebrate fossils, and trace fossils (Figure 3, plaid pattern). The smaller macro- and microfossils have a longer stratigraphic range than the larger macrofossils and megafossils. Small macroscopic invertebrate fossils and plant remains include: ammonites (Wabiskaw Member only), mummified and petrified wood remains, pelecypods and gastropods (Alberta Palaeo-Resources Ltd., 2007; Carrigy, 1959, 1966; Hein et al., 2000, 2001; Mattison, 1987; Mattison and Pemberton, 1988; McLearn, 1933; Roy, 1972; Russell, 1932), and fish teeth, which have also been recovered from all levels of the McMurray Formation (Carrigy, 1963; Alberta Palaeo-Resources Ltd., 2007). Trace fossils are prolific in the Wabiskaw Member, becoming less common in the upper and middle McMurray, and rare in the lower McMurray Formation. The trace fossils vary in size from <1 mm size *Planolites* to large dinosaur foot prints (Brekke, 2015; Gingras et al., 2016; Harris et al., 2016; Hein et al., 2000, 2001; MacEachern and Gingras, 2007; Mattison, 1987; Mattison and Pemberton, 1988; Schchepetkina et al., 2016, among others). Microscopic plant and invertebrate animal fossils are common to very abundant in the Wabiskaw–McMurray succession. Microfossils and other organic remains include: acritarchs, algae, dinoflagellate cysts (called 'dinocysts'), foraminifera, pollen and spores (Burden, 1982, 1984; Brideaux, 1971; Carrigy, 1959, 1963; Demchuk et al., 2005, 2008; Dolby, 2014; Dolby et al., 2013; Harding, 1990; James, 1977; Mellon and Wall, 1956; Norris et al., 1975; Playford, 1971; Pocock, 1976; Singh, 1964, 1971, 1975; Sweet, 2002; Vagvolgyi, 1964; Vagvolgyi and Hills, 1969).

The problem with many of the large vertebrate and smaller macrofossils is that they may not record the paleoenvironmental conditions of the sites where the fossils are preserved. Wood logs and other detritus, dinosaur carcasses, shells, etc. may be transported by storm surges and offshore flood currents long distances into marine settings (up to 200 km). Conversely, marine macrofossils, such as shells, may be transported back onshore during transgressive flooding events. Furthermore, smaller molluscs (including pelecypods) tend to be relatively insensitive to paleosalinity fluctuations. Macrofossils are not ubiquitous; they are most commonly recovered from sideritized units within the middle and upper McMurray Formation and the overlying, basal Wabiskaw Member (Clearwater Formation), being much less common in the lower and pre-McMurray units.

One occurrence of a prominent silica-cemented horizon with root traces and coaly debris was reported from the lower McMurray Formation (within the so-called 'Beaver River Sandstone,' near Fort MacKay, AB, Hein et al., 2000, 2001). Another prolific site was near Tar Island, near the Suncor Mine tailings pond, on the Athabasca River, north of Fort McMurray. At the Tar Island site, over 100 specimens of petrified and mummified wood of the new species, *Taxaceoxylon mcmurrayensis*, were found and described (Roy, 1972). Some of the preserved wood had distinct growth rings, spiral thickenings of the tracheid walls, and other conspicuous and well preserved features. Elsewhere, mummified and petrified wood remains are relatively uncommon in the McMurray Formation (Hein et al., 2000, 2001). Only rare agglutinated foraminifera, molluscs, fish teeth, spores, and pollen grains were recovered from the upper McMurray Formation (Carrigy, 1963). No ammonites have been recovered from the McMurray succession, although the *Freboldiceras* ammonite genus occurs in the Grand Rapids Formation (Stelck and Kramers, 1980). Calcareous foraminifera, pelecypods, and sponge spicules were recovered from the Clearwater Formation above the basal Wabiskaw Member (Carrigy, 1959; 1963; James, 1977; Mellon and Wall, 1956). In general, fossil assemblages of the lower and middle McMurray successions are dominated by spores and pollen grains.

Palynology is another avenue to better understand the regional biostratigraphy of the Wabiskaw–McMurray succession. Palynology refers to the microscopic analysis (largely under transmitted light) of the total particulate organic matter which is found in ancient or modern sedimentary deposits (Tyson, 1995). The term ‘palynology’ was originally coined by Hyde and Williams (1944) for the microscopic analyses of all organic-walled microfossils, which are particularly resistant to aggressive chemical treatments, such as dissolution by peroxide and/or hydrochloric (HCl) and hydrofluoric (HF) acids (Riding and Kyffin-Hughes, 2004). In 1961, Tschudy called these chemically-resistant organic-walled microfossils by the then new term “palynomorphs.” Palynomorphs include a wide range of microscopic plants and animals—such as acritarchs, algae, dinoflagellate cysts, fungi, spores, and pollen—from continental, brackish, and fully-marine settings. Palynomorphs do not include wood detritus and fragments, plant cuticles, or amorphous organic material (Riding and Kyffin-Hughes, 2004).

Palynomorphs vary widely in type and relative abundance and have been used successfully for paleoenvironmental, paleoclimatic, and biostratigraphic work. Previous studies have shown that palynomorphs are helpful in the i) distinction of continental from brackish and/or marine settings; ii) determination of proximal-distal trends in sedimentary studies; iii) identification of sequence boundaries, particularly in fine-grained sediments where information is not conclusive; iv) subdivision of local paleoenvironments within the continental to marine settings; and, v) interpretation of paleoclimatic conditions and changes in the geological record (Akyuz et al., 2015; Atta-Peters and Kyorku, 2013; Atta-Peters et al., 2013; Dalseg et al., 2016; Dickey, 2013; Follows and Tyson, 1999; Horton, 2013; Houben, 2013; Looy et al., 2014; Pieñkowski and Waksmundzka, 2009; Thomas et al., 2013; Tyson and Follows, 2000; Volik et al., 2013, among others). For these reasons, it was thought that, along with the regional lithostratigraphic and sedimentological work on the Wabiskaw–McMurray units, there should be a systematic sampling (and resampling) of finer-grained mudstones for palynological analysis within the lithostratigraphic units that were described.

Little of this regional palynological work has been published. To date, one palynological report (Dolby, 1999) was included as an appendix in Hein et al. (2000); with generalizations from the palynology discussed in Hein et al. (2013a).

3 Purpose

The purpose of the present report is to compile and disseminate in the public domain the results of palynological analyses that were conducted along with regional characterization studies of the Athabasca Oil Sands deposit, and to present a regional geological model that integrates both the palynostratigraphy and lithostratigraphy. These data and interpretations will aid in the development of a regional 3D geological framework for the Athabasca Oil Sands deposit, which is presently being developed by the AGS as part of its bedrock mapping program.

4 Methods

Lithostratigraphic methods and facies descriptions have been well documented in Hein et al. (2000, 2001), with the major findings discussed below (see Section 5). Palynological sampling and analysis were conducted along with this lithostratigraphic work over a time period of ~18 years, from ~1998 to 2016 (Dolby, 1999, 2000, 2001, 2006, 2017). Stratigraphic information for the sampled cores and outcrops is given in Appendix 1. Information on the wells from which drill core was sampled is given in Appendix 2. The palynological data from the Dolby reports to the AGS, along with historical records from the AGS, were compiled and are being released as appendices in this report (Table 1; Appendices 3 and 4). Biostratigraphy based on new palynofacies analysis of all available samples (from Dolby reports to AGS in Appendix 4) is given as summary biostratigraphic charts and tables of the individual counts per sample in Appendix 5. Available descriptions of core and outcrop sections are in Appendix 6. Other outcrop and core descriptions have been published previously in Hein et al. (2000, 2001). Stratigraphic picks for wells associated with sampled cores are listed in Appendix 7.

Table 1. Summary of palynological records and analyses used in the present compilation. Stratigraphy of the sampled cores and outcrops is given in Appendix 1, with other information for the sampled cores in Appendix 2. Most of palynological analyses were done on core samples (327, or 86%); less commonly on outcrop samples (54, or 14%). One sample was from the Syncrude North Mine (Appendix 1, Table 2). Emphasis is on the McMurray succession (287, or 75%) and Wabiskaw Member (67, or 18%), which is the focus of this study. A small number of samples were taken from the overlying Clearwater Formation and underlying, mainly weathered pre-McMurray clastics and Devonian carbonate (~2% each), along the sub-Cretaceous unconformity, for comparison purposes. In the northern part of the study area, it is difficult to subdivide the McMurray Formation and it is designated as "undifferentiated." For the distribution of samples in respect to the relief on the sub-Cretaceous unconformity and the subcrop edges of underlying units refer to Figure 5 and Figure 6, respectively. For sample location with respect to bitumen resources see Figure 7.

Data Source	Clearwater Formation	Wabiskaw Member	McMurray Formation Undifferentiated	Upper McMurray Formation	Middle McMurray Formation	Lower McMurray Formation	Pre-McMurray Units	Devonian Carbonate (weathered)	Subtotal
Core Appendix 1 Table 1 (# cores = 56)	11	67	7	43	107	76	10	6	327
Outcrop Appendix 1 Table 2 (# outcrops = 18)	0	0	0	4	49	0	1	0	54
Mine Site Appendix 1 Table 2 (# mine = 1)	0	0	0	0	1	0	0	0	1
Totals	11	67	7	47	157	76	11	6	382

Summary results for the main types of palynomorphs are discussed below. Since many of the palynomorphs are not familiar to non-specialists, a brief description of the type of palynomorphs is given prior to the discussion of the results for the Wabiskaw–McMurray succession. This will help the reader understand what the different types of organic microfossils are and their paleoenvironmental and biostratigraphic significance. General palynological indicators of the degree of marine influence, as listed in Appendices 3 and 4, follow designations used by Leckie et al. (1990) (Table 2). Their ordinal classes for the relative ranking of freshwater to fully marine paleosalinities were first used in the historical records of the AGS and were carried forward in the beginning palynological reports done in this work (Dolby 1999, 2000, 2001). Inclusion of these ordinal classes here allows general comparison of the historical records with those presented here for the present regional litho- and biostratigraphic analysis.

Table 2. General palynological indicators of degree of marine influence. The numbers on the left are the "Paleoenvironmental Codes" listed in the palynological species lists in Appendices 3 and 4 (used with permission from D. Leckie, from Leckie et al., 1990).

CODE	ENVIRONMENT	DESCRIPTION
1	CONTINENTAL	Palynoflora composed of land-derived microspores, megaspores and pollen.
2	SLIGHTLY BRACKISH	Introduction of saline water into an essentially freshwater environment (e.g. coastal lakes with outlets to the sea, inlets, upper estuaries and interdistributary channels). Contains rare specimens of ceratioid dinocysts (e.g. *Nyktericysta*, *Vesperopsis* and *Balmula*) and a few acritarchs. Land-derived spores and pollen abundant.
3	BRACKISH	Marginal marine conditions found in bays, estuaries, lagoons and barrier-associated backwaters. Increase in salinity. Dinocyst species diversity low. Certain species of ceratioid and peridinoid dinocysts (e.g. *Luxadinium primulum*, *Palaeoperidinium cretaceum*) appear in abundance. Assemblages often monospecific. Land-derived spores and pollen abundant.
4	NEARSHORE MARINE	Inner neritic, shallow marine environment. Dinocyst diversity higher due to increased salinity, but assemblages still dominated by land-derived spores and pollen.
5	OPEN MARINE	Outer neritic, offshore marine environment. Close to the shelf margin. Fully saline. Dinocyst diversity high. Land-derived spores and pollen reduced in quantity. Assemblages dominated by dinocysts.

Some of the palynological techniques and data analysis approaches have evolved over time. For example, historical records at the AGS mainly recorded dominant palynomorph types, with less common indication of individual genus or species (Appendix 3); whereas the palynological analysis during this present (2016–2017) project recorded general types, as well as relative abundance of genera and species (Appendix 5). The earlier-analyzed samples were processed using traditional methods, including dissolving of non-chemically-resistant organic materials with hydrochloric acid (HCl), hydrofluoric acid (HF), and nitric acid (HNO_3). Such methods tend to be expensive and require laboratory training for handling hazardous materials and require special protocols for their disposal. In the present work, earlier-processed samples were either reprocessed (if sufficient material remained) or were resampled and reprocessed using relatively non-destructive techniques. In addition to the changes in laboratory processing, there has also been a shift in the field of palynology to go beyond the simple cataloguing of individual genus and/or species of palynomorphs, and to describe a larger-scale palynofacies designation. Palynofacies, similar to lithofacies or other biofacies, goes to a more holistic description of the community of palynomorphs. For example, Demchuk et al. (2008) demonstrated that specific palynofloral distributions (or palynofacies) can be used to ascertain different paleoenvironments and paleosalinities for the McMurray Formation in the Surmont area (Township 83, Ranges 6 and 7, west of the 4th Meridian) of north-central Alberta (Figures 4, 5, and 6). This palynofacies scheme was developed after most of the present palynology work was done (Dolby, 1999 to 2006). Starting in 2015, the palynology was reassessed using a palynofacies scheme similar to that of Demchuk et al. (2008) and Dolby et al. (2013) (Figure 4), the results of which are discussed later (see Section 7, Palynofacies and Biostratigraphy). All samples in the Dolby palynological reports (1999 to 2017) (Appendix 4) were either re-analyzed; or if insufficient material was available, the cores were resampled for reanalysis. Samples for the AGS historical records (Appendix 3) no longer exist; hence, palynofacies could not be assigned to the compiled records from those studies.

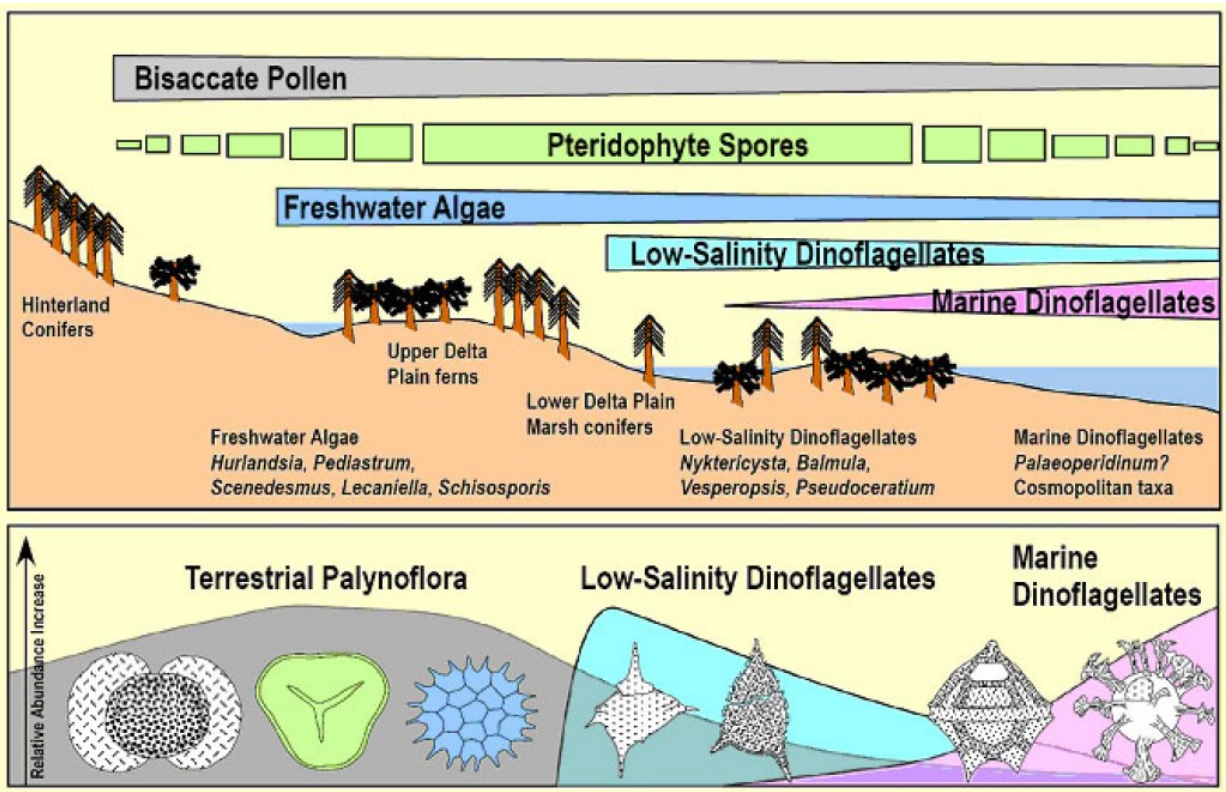


Figure 4. Idealized palynofacies pattern of palynoflora from the continental hinterland (left) through transitional and into fully marine settings (right). Upland paleoenvironments are dominated by terrestrial palynoflora, including bisaccate pollen, pteridophyte spores, and freshwater algae. Low-salinity dinoflagellates, including *Vesperopsis* and *Nyktericysta*, represent the landward encroachment of marine (tidal) waters; whereas the more marine dinoflagellates, such as *Oligosphaeridinium* and other cosmopolitan taxa, are abundant in offshore, neritic paleoenvironments (and deeper). The distribution of the relative frequencies of these palynofacies within the different paleoenvironments may be altered by such geological factors as climate, increased fluvial activity, and changes in sea level (relative base level). At Surmont, AB, the low-salinity dinoflagellates are those envisaged for much of the deposition of the middle McMurray. By contrast, the underlying lower McMurray would be more continental, hinterland and freshwater palynofacies; and the overlying Clearwater Formation would be fully marine palynofacies (used with permission from G. Dolby, from Demchuk et al., 2008, modified from Michoux, 2002).

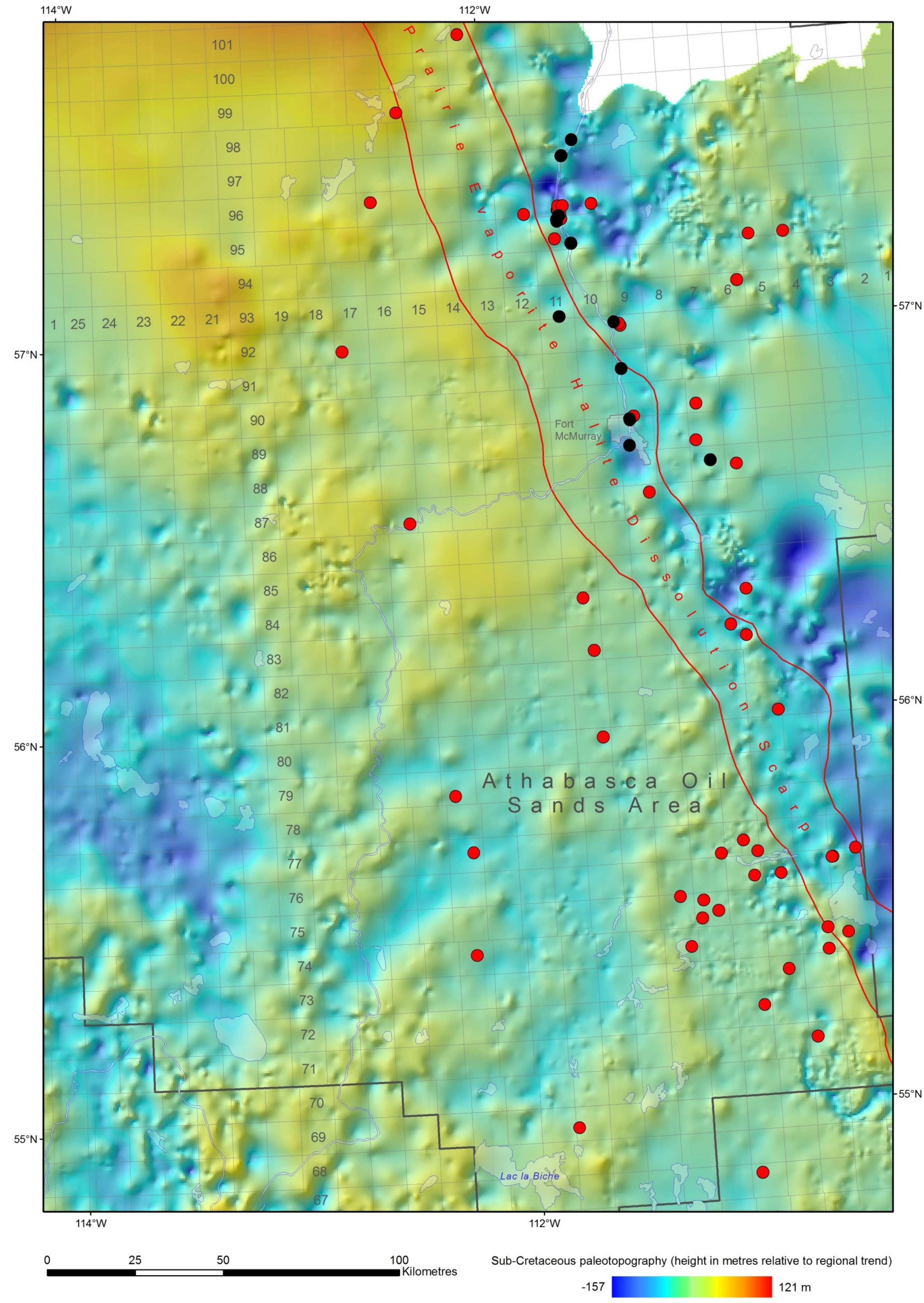


Figure 5. Outcrop (black dots) and subsurface core samples (red dots) located on a map that shows the regional paleotopographic relief on the sub-Cretaceous unconformity (height in metres relative to the regional trend on the unconformity), from Township 67 to 101, Ranges 1, west of the 4th Meridian to Range 2, west of the 5th Meridian. The red lines represent the area directly influenced by dissolution of the underlying Devonian Prairie Evaporite Formation (modified from Peterson et al., 2016).

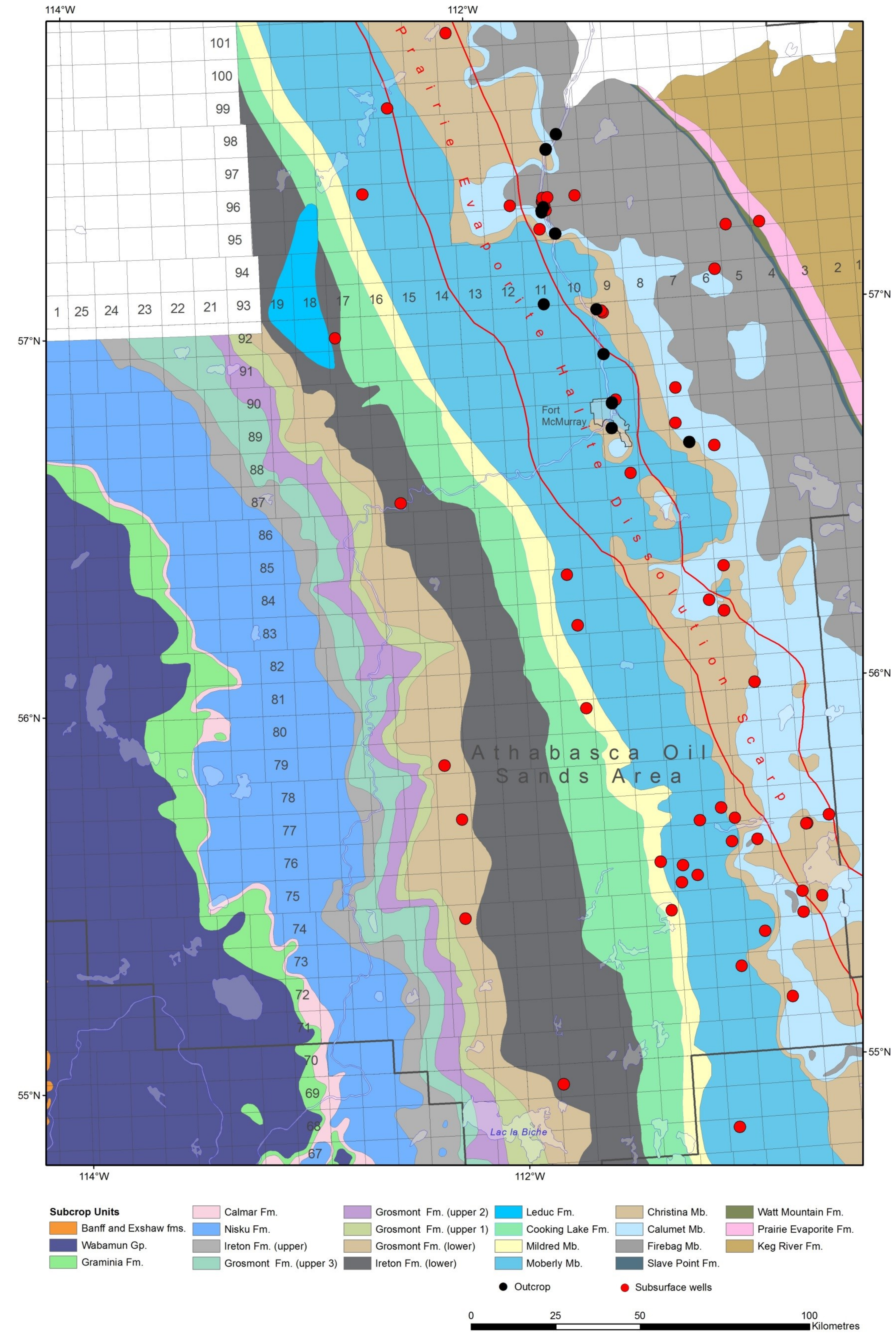


Figure 6. Outcrop (black dots) and subsurface core samples (red dots) located on a map that shows the subcrop edges of the different stratigraphic units from the Devonian Keg River Formation to the Mississippian Banff Formation, northeastern Alberta, from Township 67 to 101, Range 1, west of the 4th Meridian to Range 2, west of the 5th Meridian. The red lines represent the area directly influenced by dissolution of the underlying Devonian Prairie Evaporite Formation (modified from Hauck et al., 2017).

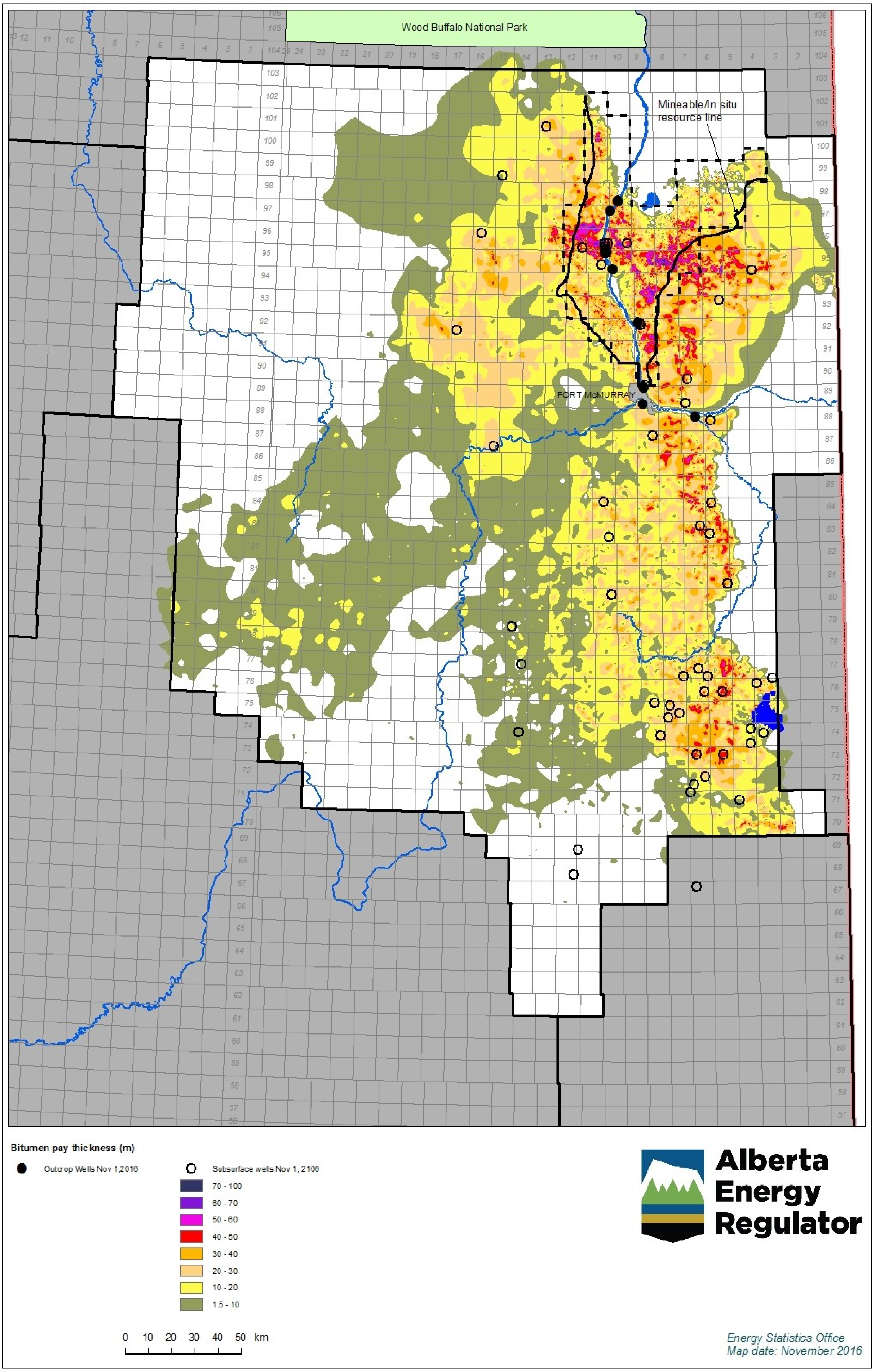


Figure 7. Outcrop (black dots) and subsurface core samples (open circles) located on a map that shows bitumen resource isopach (minimum thickness = 1.5 m; minimum pay cut off bitumen saturation = 3 weight per cent) within the Wabiskaw–McMurray succession (modified from Alberta Energy Regulator, 2015, their appendix E, figure AE).

For the present study, palynological analyses were done on outcrop and core samples using slides made from the >10 µm sieved, oxidized, and stained organic-matter fraction. On average, for each slide an initial count of 200 palynomorphs was done to ascertain the overall composition of the palynofloral assemblages, recording the main palynomorph types and their relative abundances. This was followed by analyzing the rest of the slide, with a systematic logging of remaining species and genera. In doing this detailed logging some of the superabundant and abundant genera and species, such as the bisaccate pollen and small inaperturate pollen (see later descriptions), were ignored to overcome the "masking" effect of the predominant palynomorphs. Raw biostratigraphic occurrence data, stratigraphic picks, and other data were managed using the StrataBugs© v. 2.0 software, which utilizes a taxonomic database, along with biostratigraphic groups, and relative frequency designations for each well (Athersuch et al., 2013).

After initial data entry, representative digital wireline logs were incorporated into the database and viewed with the biostratigraphic data to aid in the development and designation of type palynofacies schemes and holotype wells for the different stratigraphic subdivisions. Reworked palynomorphs were recorded as such; and, where possible, kerogen types and the degree of sorting were noted. The proportions and degree of sorting of the organic macerals was determined to help with environmental interpretations. Unfortunately, many of the organic residues were unavoidably contaminated with an oily or waxy substance from the heavy-oil and bitumen in the samples, which obscured the macerals. Slides were rescanned for a palynofacies designation after the initial species and genera determinations were done; and all earlier slides were rescanned, where available. Rare macrofossils (megaspores and shells) were also noted. All of the historical palynological data were entered into a master spreadsheet (using Excel); from which histograms were generated for the main types of palynomorphs (see Section 6, Palynology). The palynological results for representative outcrops and cores are given as biostratigraphic charts, which were generated using StrataBugs© (see Appendix 5).

5 Lithostratigraphy

5.1 Lithostratigraphic Nomenclature

The Wabiskaw–McMurray lithostratigraphic nomenclature has evolved over the decades and remains mainly informal. Carrigy (1959) first subdivided the Wabiskaw–McMurray into a lower fluvial, middle fluvial-estuarine, and upper marginal-marine to marine units. In the 2000s Hein and others, using regional litho- and biostratigraphic work, stated that distinctions of the middle from the upper McMurray are not possible on a regional scale; thus, proposing that the term 'middle' be abandoned, and that only lower versus upper McMurray be distinguished (Flach and Hein, 2001; Hein and Dolby, 2001; Hein et al., 2000, 2001). More recently, Ranger et al. (2008) introduced the following member designations for the McMurray Formation: Daphne member (lower McMurray), Steepbank member (middle McMurray), and Chard member (upper McMurray). Neither proposal—i.e., i) removing the middle McMurray and only using lower and upper McMurray by Hein and others; nor, ii) using the Daphne, Steepbank, and Chard member designations by Ranger and others—have been adapted by industry, academia, or government workers. Currently, the more commonly used designations are those applied by the Alberta Energy and Utilities Board (2003), although this is not always done in individual lease areas.

In the following description, the terms lower, middle, and upper adjectives are used to describe the original informal members of Carrigy (1959), with additional descriptors used as needed to conform to Alberta government designations (Alberta Energy and Utilities Board, 2003; Hein and Cotterill, 2006; Hein et al., 2013a). In all cases in the present report the informal member terminologies use "lower case" formats, except as labels in figures and tables.

The following equivalencies apply for the McMurray Formation (Figure 8):

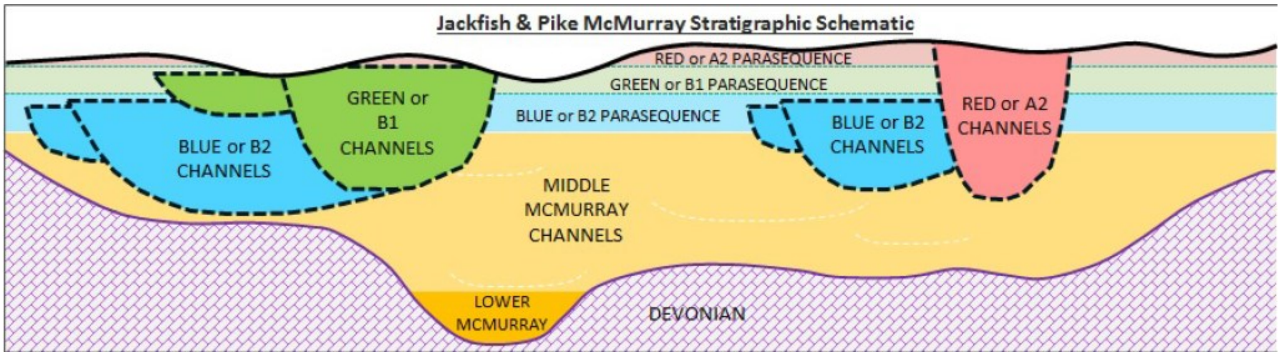


Figure 8. An interpretive stratigraphic cross-section for the Jackfish and Pike leases of the southern Athabasca Oil Sands Area, showing the informal lower, middle, and upper McMurray designations (Blue or B2, Green or B1, and Red or A2). An unconformity-based deep incised-valley system (influenced by a long period of karstification and erosion at the top of the Devonian carbonates, see Figures 5 and 6) is filled by lower McMurray braided-fluvial sandstones. The middle McMurray is fluvial-estuarine, and the topmost, upper McMurray units are fluvial-estuarine to marginal marine. The colour coding for the upper McMurray is from Ranger and Pemberton (1997) and the alpha-numeric designations are from the Alberta Energy and Utilities Board (2003; also in Hein and Cotterill, 2006) (from Baniak and Kingsmith, in press, their figure 3).

upper McMurray = A1, A2, B1, B2 parasequences with respective valley and/channel cut-and-fills (A, B1, B2 channels) of the Alberta Energy and Utilities Board (EUB) (2003) regional geological study. Prior to the EUB regional geological study, Ranger and Pemberton (1997) called these the red, green, and blue parasequences and channels (see also Hein, 2015). The topmost A1 parasequences and channels of the Alberta Energy and Utilities Board (2003, also in Hein et al., 2013a) were not identified by Ranger and Pemberton (1997). The upper McMurray is the Chard member of Ranger et al. (2008). Most recently, Baniak and Kingsmith (in press) have used both the colour and alphanumeric designations for the upper McMurray deposits in the Jackfish and Pike lease areas of the southern Athabasca Oil Sands Area (Figure 8).

middle McMurray = McMurray Channel and McMurray C Channel of the Alberta Energy and Utilities Board (2003); elsewhere, commonly referred to as middle McMurray by most workers (Ranger and Pemberton, 1997; Baniak and Kingsmith, in press). The middle McMurray is the Steepbank member of Ranger et al. (2008).

lower McMurray = McMurray Channel and McMurray C Channel of the Alberta Energy and Utilities Board (2003); elsewhere, commonly referred to as lower McMurray by most workers (Ranger and Pemberton, 1997; Baniak and Kingsmith, in press). The lower McMurray is the Daphne member of Ranger et al. (2008).

5.2 Previous Work and Definition of Lithofacies and Lithofacies Associations

Descriptions of the lithofacies and their associations for the McMurray Formation in the Athabasca Oil Sands Area have been previously published as follows:

1) an atlas of individual lithofacies descriptions, with representative core and outcrop photographs and interpretations (Hein et al., 2000);
2) a comprehensive field guide, with lithofacies designations, representative outcrop photographs and measured sections (Hein et al., 2001);
3) local field guides to the McMurray outcrop area, with measured sections and outcrop photographs (Barson et al., 2000a, b; Hein and Cotterill, 2007);

4) detailed lithofacies description and interpretations for the McMurray deposits in the subsurface of the Steepbank River (Langenberg et al., 2002; Hein and Langenberg, 2003); Clarke Creek (Langenberg et al., 2003); Lewis-Ft. McMurray (Hein, 2006b; Hein et al., 2006a); and, Firebag-Sunrise (Hein, 2006b; Hein et al., 2006b) areas;
5) regional, mappable lithofacies associations in the Athabasca Oil Sands Area, with their descriptions and interpretations (Hein et al., 2013a; Alberta Energy and Utilities Board, 2003);
6) overviews of the Wabiskaw–McMurray succession, with discussions of regional geological influences (Langenberg et al., 2002; Hein and Langenberg, 2003; Hein and Cotterill, 2006; Hein, 2016b), and tidal influences on deposition within the “middle” McMurray succession (Hein, 2015).

Hein et al. (2013a) and Hein (2015) presented compilations and full discussions of this previous work on definition of lithofacies, lithofacies associations, and lithostratigraphic frameworks used for the McMurray Formation in the Athabasca Oil Sands Area (Tables 3–5 and Figures 9 and 10). A brief discussion is given below of the major lithostratigraphic units, with representative photographs of the characteristic lithofacies in the accompanying figures.

Table 3. Lithofacies description, McMurray Formation, Athabasca Oil Sands Area, with indication of the relative abundance in the fluvial lower McMurray; fluvial-estuarine "middle" McMurray; and, marginal-marine, fluvial-estuarine upper McMurray successions. Although the previous recommendation by Hein and Langenberg (2003) that the "middle" McMurray terminology be abandoned, in general most workers have not followed suite. * Note: The "middle" listed here is strictly speaking the fluvial-estuarine upper part of the McMurray C Channel succession or the stacked fluvial-estuarine channel and point bars in the McMurray Channel successions (see Figure 10). For brevity and clarity, these are called the "middle" McMurray here to refer to the main bitumen-bearing part of the McMurray Formation. VC, very common; C, common; M, moderate; UC, uncommon; R, rare; VR, very rare; X, absent (modified from Hein, 2015).

#	Description	Average Bed Thickness (Range [m])	Interpretation	Lower McMurray	Middle McMurray	Upper McMurray
1	Pebbly, coarse-grained, trough cross-bedded sandstone	0.75 (0.5 to 3)	Traction transport and deposition from three-dimensional pebbly sand dunes	VC	C	R
2	Pebbly to fine-grained sandstone, graded beds	0.75 (0.25 to 1)	Mass transport and deposition from debris flows and other mass flows, derived from or near high slope channel edges	UC	VR	X
3	Carbonaceous to coaly, rooted, silty mudstone	1.5 (0.2 to 5)	Suspension fallout from flood flows into overbank settings, lakes, coal swamps	C	M	VR
4	Mottled, pedogenic with slickensides, argillaceous sandy lime-rich (calcareous) mudstone, variable amounts of clay and silt, weathered, rare roots	1.5 (0.2 to 4)	On sub-Cretaceous unconformity; lacustrine and pedogenic marl deposits	R	X	X
5	Fine to medium-grained, trough cross-bedded sandstone	0.75 (0.5 to 1+)	Traction transport and deposition from three-dimensional sand dunes	C	C	M
6	Fine grained to pebbly, planar-tabular cross-bedded sandstone	0.5 (0.2 to 2)	Traction transport and deposition from two-dimensional sand dunes, braid bar or mini-delta slip faces	C	C	M
7	Mud-clast breccia, sandy matrix, and syn-sedimentary convoluted sandstone and mudstone	0.5 (<0.1 to 5+)	Slumped and reworked mud and muddy sand clasts, which occur along cut-banks and channel edges	C	C	R
8	Massive sandstone and sandy siltstone, not bioturbated	1.5	High-energy current flow and/or flood-suspension flow deposits	C	C	M
9	(A) Very fine to fine-grained rippled sandstone (B) Very fine to fine-grained flaser rippled and herringbone cross-bedded sandstone	0.4 (<0.005 to 4+)	(A) Moderate energy traction current flow (B) Moderate energy current flow with suspension fall out from tidal currents (flasers) or bimodal switching tidal currents (herringbone)	C	VC - C	VC - C
10	(A) Bioturbated, sandy, low-angle inclined heterolithic cross-stratified sandstone and mudstone (B) Bioturbated, muddy, low-angle inclined heterolithic cross-stratified mudstone and sandstone	3 (1 to 40+)	Both due to bed traction deposition and suspension load deposition on meandering point bars: (A) More bedload transport and deposition; (b) More suspension transport and deposition	X	VC	M
11	Very fine-grained parallel laminated sandstone	0.5 (<0.2 to 2)	High-flow regime current bedload deposition	VR	R	M
12	(A) Bioturbated, rhythmically laminated sandstone and mudstone (B) Churned (intensely bioturbated) laminated sandstone and mudstone (C) Bioturbated, very fine to fine-grained sandy mudstone (D) Bioturbated, laminated to thickly interbedded silty mudstone and mudstone (E) Thinly laminated silty mudstone and mudstone	2 (0.2 to 3+)	Alternating current washovers and suspension fallout deposits on tidal flats and within subtidal environments: (D) and (E) with diminished or no bioturbation, indicating deposition in alternating aerobic/dysaerobic (D) or anaerobic (E) ponded bays, abandoned channels, and sloughs	X	M-C	M-C
13	(A) Churned (intensely bioturbated) very fine grained muddy sandstone (B) Churned (intensely bioturbated) muddy siltstone and silty mudstone	1.5 (0.3 to 8+)	Continuous sedimentation and well-oxygenated bottom conditions, within brackish bays, tidal flats, abandoned channels, and sloughs	X	M	C
14	Coaly, carbonaceous and/or rooted, sandy siltstone and silty mudstone; calcareous, concretions and/or pedogenic structures	0.3 (0.1 to 0.75)	Paleosols and rooted, vegetated overbank deposits	VR	UC	M
15	Coarsening-upward sequences from mudstone to siltstone/very-fine sandstone to sandstone	1 (0.5 to 3)	Crevasse splays on levees and other overbank areas, including within shallow bays, lakes and ponds	X	M	C
16	Very-fine to fine-grained, well sorted, wave-rippled and combined-flow rippled sandstone, some with minor ball-and-pillow structures or load casts with flame structures	0.25 (<0.01 to 0.75)	Rapid sedimentation from waves with some sediment loading and liquefaction, within marginal marine bays, shallow lagoons and lakes	X	X	M

Table 4. Log characteristics of different lithofacies associations within the McMurray Formation used within the Alberta Energy and Utilities Board (2003) regional geological model (from Hein et al., 2013a; Hein, 2015).

McMurray Unit	Gamma-Ray (API units)	Neutron Porosity (%)	Density Porosity (%)	Resistivity (ohm – m)	Thickness Range (m)
A1 sandstone	~75	30+	20–30	Variable	0.05–0.4
A1 mudstone	95–100	36–45	~22	Variable, 20+	0.1–0.3
A2 sandstone	~75	30+	20–30	Variable	0.05–0.4
A2 mudstone	~120	36–45	~22	~10	1–2
B1 sandstone	~75	30+	20–30	Variable	0.05–0.4
B1 mudstone	90–100	~45	~22	8–10	1–2
B2 sandstone	~75	30+	20–30	Variable	0.05–0.4
B2 mudstone	90–100	~45	~22	8–10	1–2
C Channel or McMurray Channel	25–45	30+	30+	Variable	Variable, from absent to 40+

Table 5. Definition of lithostratigraphic markers interpreted from wireline logs with quality codes (from Hein, 2015, modified from Wynne et al., 1994; Hein et al., 2000).

Pick	Type of Surface	Description	Quality Code
T21	Transgressive	Wabiskaw marker, top of Wabiskaw A unit	Excellent to very good
T11	Transgressive	Base of first regional marine shale in the Clearwater Formation, top of the Wabiskaw C unit	Very good to excellent
T10.5	Transgressive	Top of Wabiskaw D unit, incised-valley fill with maximum transgressive shale at the top (where preserved)	Excellent to very good
E10	Erosional, disconformity or unconformity	Top of McMurray Formation; where complete section is preserved this is the top of the Upper McMurray unit	Excellent to very good
E5	Erosional, disconformity or unconformity	Top of lower McMurray unit (where preserved and recognized)	Variable, very poor to fair
Pz	Sub-Cretaceous unconformity	Major erosional surface or hiatus at the top of the Devonian carbonate bedrock succession, base of the McMurray Formation	Variable, poor to fair, where karstic along the unconformity; where non-karstic, very good to excellent

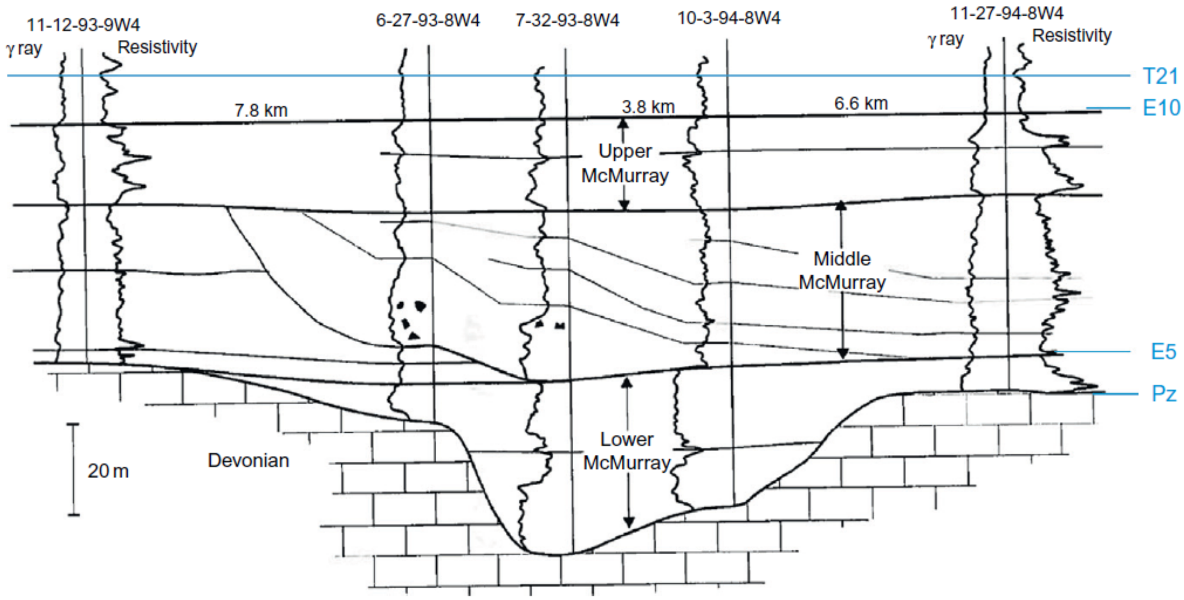


Figure 9. An interpretive wireline log cross-section showing the informal lower, middle, and upper McMurray designations. An unconformity-based deep incised-valley system (influenced by a long period of karstification and erosion at the top of the Devonian carbonates, Pz surface, see Figures 5 and 6) is filled by lower McMurray braided-fluvial sandstones. The "middle" McMurray large-scale fluvial-estuarine channel and meandering point-bar complexes (up to 40+ m deep) host the main bitumen reservoirs in the Athabasca Oil Sands deposit. The upper McMurray coastal plain to marginal-marine succession has thinner units with generally more continuous mudstones at the base of coarsening-upwards successions (also see Caplan and Ranger, 2001). Surfaces bounding the lower, "middle," and upper McMurray successions are regionally mappable unconformities/disconformities (Pz, E5, and E10, see previous Table 5)—an interpretation supported by recent biostratigraphic data (published previously by Dolby et al., 2013, for the Surmont area; and presented here for a more regional perspective of the Athabasca area). In areas of multiple channelling and erosion along these regional unconformities/disconformities it is impossible to distinguish the middle and upper McMurray successions from one another (see Figure 10), without correlation to regional coarsening-upwards successions. Such correlations are possible in areas of tight well-control; particularly in areas where such wells are tied into seismic surveys (see Baniak and Kingsmith, in press). However, detailed seismic-to-well correlations are generally not available in the public domain (from Hein, 2015, used with permission and modified from Cant and Abrahamson, 1996).

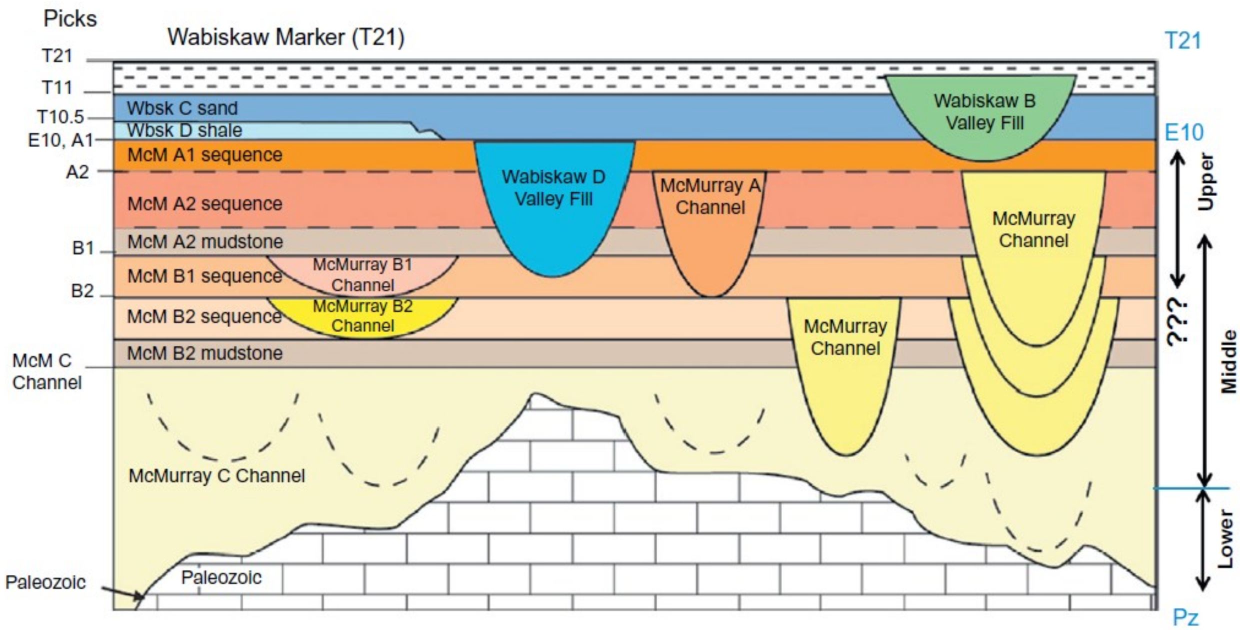


Figure 10. Stratigraphic model used in the Alberta Energy and Utilities Board gas-over-bitumen hearings, separating more regionally, continuous coastal-plain and marginal-marine successions, with regionally correlative mudstones (B2, A2, and Wabiskaw (Wbsk) D shale) and associated sandstones (B1, B2, A1, A2 Seq (sequence) and Wabiskaw (Wbsk) C Sand, from the underlying more channelized, discontinuous and cross-cutting units of the McMurray C Channel succession. The McMurray C Channel includes both the braided-fluvial channel sandstones of the lower McMurray and the overlying meandering fluvial-estuarine channel and point bar, interbedded sand- and mudstones of the middle McMurray succession (see Figure 9). Transgressive (T) and erosional (E) surfaces that are picked are the wireline log picks that have been used in regional mapping by the AGS studies (originally defined in Wynne et al., 1994, and adopted in Hein et al., 2000; see Table 5 and Figure 9). Distinction of middle and upper McMurray channelized units is impossible where stacked channels are superimposed upon one another, along with the presence of disconformities and unconformities that remove regionally correlative mudstones at the base of coarsening-upwards successions. This is shown schematically by stacked McMurray channels (yellow) on the right-hand side of the diagram (from Hein, 2015, modified from Alberta Energy and Utilities Board, 2003; Hein et al., 2013a). Note: McMurray C Channel is identified where regional correlatable mudstone(s) separate the upper McMurray from the middle and lower McMurray (left side of diagram). Where regional correlatable mudstone(s) is absent, then only McMurray Channel is identified (right side of diagram).

5.2.1 Pre-McMurray Clastic Succession

The pre-McMurray clastic succession sits unconformably upon weathered and karstic Devonian carbonate, and, where preserved, the top contact with the overlying McMurray Formation is disconformable or unconformable. The pre-McMurray succession consists of thin (<5 m), stacked paleosols, marls, karst-fills, and mudstones that are preserved as thin remnants along the sub-Cretaceous unconformity. Rare coaly and woody detritus is associated with this succession. In general, this unit is not recognizable on logs; and, is commonly included with the Devonian carbonate, when picks are based solely on wireline log interpretations. In the present study, all pre-McMurray clastic units were confirmed in outcrop or in core.

The best occurrence of the pre-McMurray clastic succession is the Fluvial Marl Section on the Athabasca River, north of Fort McMurray (Figure 11) (Hein et al., 2000). This section is located about 18 km downstream from the confluence of the Athabasca and Clearwater rivers on the east bank of the Athabasca River near McLean Creek. In this small outcrop (about 5 m high) is exposed a slumped section of paleosols (Lithofacies 4), muddy, sandy marl (Lithofacies 4), with interbedded carbonaceous mudstone (Lithofacies 3) and minor cross-bedded granule sand (Lithofacies 1). This outcrop is located within a paleotopographic low on the sub-Cretaceous unconformity. The pre-McMurray clastic succession is interpreted as a remnant of a continental succession that was emplaced in lakes and karst-holes on a weathered Devonian landscape. Most of the unit was removed with creation of the lower McMurray incised valleys and channels. The unit is sporadically preserved in outcrop and in the subsurface in isolated wells.

Figure 11. Marl deposit occupying a low on the sub-Cretaceous unconformity, Fluvial Marl Section, Athabasca River, north of Fort McMurray (Map Coordinates: 74D/14 Wood Creek, UTM 474746E, 6305712N). For full outcrop description see Hein et al. (2001)(from Hein et al., 2000, their figure 9.9.4b).

5.2.2 Lower McMurray Channel Successions

The lower McMurray channel successions have an erosional contact with the underlying pre-McMurray clastic succession; or are unconformable/disconformable upon weathered and karstic Devonian carbonate. The lower McMurray succession consists of a series of stacked incised-valley fill and channel complexes, which are mainly preserved in paleotopographic lows along the sub-Cretaceous unconformity (Figure 5, Figure 6, and Figure 11). In many wells, the lower McMurray succession contains the basal water leg and, in these cases, is not always cored. On wireline logs, the channel deposits tend to be blocky, porous sand (Figure 9), which may fine upwards into sandy-silty mudstone, mudstone, and rare coal. Distinction of the lower McMurray from overlying middle McMurray channel deposits is not straightforward. Where identifiable, this contact is placed at the E5 surface (Table 5, Figure 2 and Figure 9); where indistinguishable, the E5 surface is not picked; and the composite channel succession is identified as "McMurray Channel" or "McMurray C Channel" (Figure 10). In areas of low accommodation space, for example, in the subsurface areas southwest, west, and northwest of Fort McMurray (Figure 5), much of the underlying lower McMurray succession has likely been reworked into the overlying middle McMurray channel deposits; and, in these situations, the lower McMurray is not identifiable. In areas without core, interpretations based on wireline logs where there are stacked blocky sands on top of one another do not allow differentiation of the lower from middle channel sands. In core, the middle McMurray channel sands commonly contain bioturbated mud clasts, or bioturbated mud-clast breccias.

By contrast, bioturbation is relatively uncommon to rare in the lower McMurray succession—expressed, mainly as more isolated, small horizontal traces (*Planolites*) in pond or lagoonal deposits; or as root casts and/or insect traces in overbank successions. Mud clasts and mud-clast breccias within the lower McMurray channel deposits are commonly sideritized (after organic woody detritus), internally massive or laminated and lack burrows.

The most common lithofacies within the lower McMurray channel successions is the large-scale, trough cross-bedded pebbly-granule sand, followed by the smaller cross-bedded lithofacies, including trough, ripple and planar-tabular cross-bedded, or massive sand (Lithofacies 8) (Lithofacies 1, 5, 9A, 6, Table 3, Figure 12). Mud-clast breccia and slump deposits (Lithofacies 7) are common at the base of individual channel- or valley-fill successions, which tend to grade upwards into finer-grained cross-bedded or massive units. In some cases, inverse-to-normally graded pebbly to fine-grained sand (Lithofacies 2) is present along the high-gradient margins of channel and valley walls. Mottled, pedogenic, argillaceous sandy marl (Lithofacies 4) is rare, and tends to occur either within more isolated lows along the sub-Cretaceous unconformity; alternatively, some outliers of sandy and silty marl are preserved on Devonian bedrock highs. Parallel-stratified sand (interpreted as flood deposits, Lithofacies 11) and the pedogenic, coaly and rooted paleosols (Lithofacies 14) are very rarely preserved within the lower McMurray successions. The lower McMurray informal member is interpreted as a succession of braided fluvial complexes, dominated by bar-and-channel deposits, with less commonly preserved overbank floodplain deposits (Figure 13). The floodplain deposits include paleosols, sometimes rooted; lacustrine marsh, coal; and, flood deposits, including massive sands, sands with parallel lamination and/or with coarsening-upwards crevasse splays (Figure 12C–G).

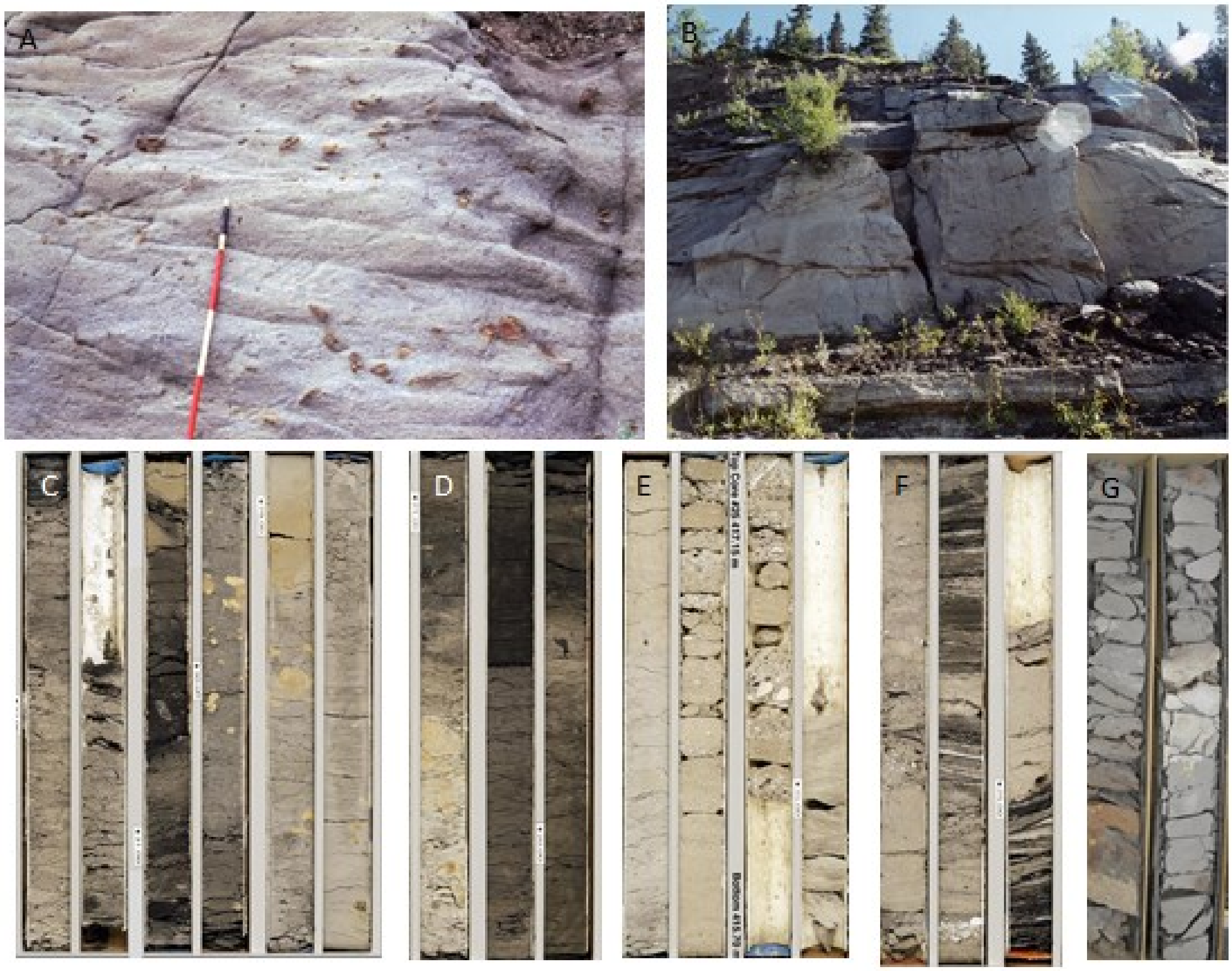


Figure 12. Lower McMurray outcrop and core photographs: A) Trough cross-bedded, pebbly sand (Lithofacies 1) with sideritized mud clasts (orange-brown) and cross-cutting bitumen-infilled fractures, outcrop upstream of Tar Island, Athabasca River (map coordinates: 74D/14 Wood Creek, UTM 472210E, 6313710N); B) Large-scale planar tabular cross-bedded sand (Lithofacies 6) (thickly bedded white sand), Crooked Rapids Section #2, Athabasca River (map coordinates: 74D/12 Cascade Rapids, UTM 446608E, 6272690N); C) Organic mudstone, with pedogenic mottling textures and dispersed coaly woody detritus (Lithofacies 14), locally sideritized (orange), core AB/03-16-077-05W4/0 (top ~428.2 m; base ~432.40 m, no lost core; empty sleeve); D) White pedogenic mudstone (Lithofacies 4), grading up into grey organic to coaly mudstone (Lithofacies 3), core AA/02-28-076-04W4/0 (top ~419.45 m; base ~423.95 m); E) White organic mudstone (Lithofacies 3), abruptly overlain by pebbly coarse sand (Lithofacies 1), core AA/02-28-076-04W4/0 (top ~414.90 m; base ~419.45, 1.45 m lost core in empty sleeves); F) White-tan organic mudstone, with pedogenic mottling (Lithofacies 14), abruptly overlain by cross-bedded sand, with coaly interlaminae (Lithofacies 5), core AA/03-09-077-05W4/0 (top ~424.75 m; base ~426.65 m); G) Sub-Cretaceous unconformity, sideritized (orange), with pedogenic mottled mudstones, dispersed coaly and woody debris (including bogen) (Lithofacies 3), core AA/16-17-101-13W4/0 (top ~1752 ft.; base ~1762 ft.). C–F) Each core slat is ~0.75 m in length; G) Each core slat is ~2.5 ft. long. Top is to the upper right, base is to the lower left on all core photographs. In A red scale bars are each 0.3 m long; total vertical face in B is about 10 m high.

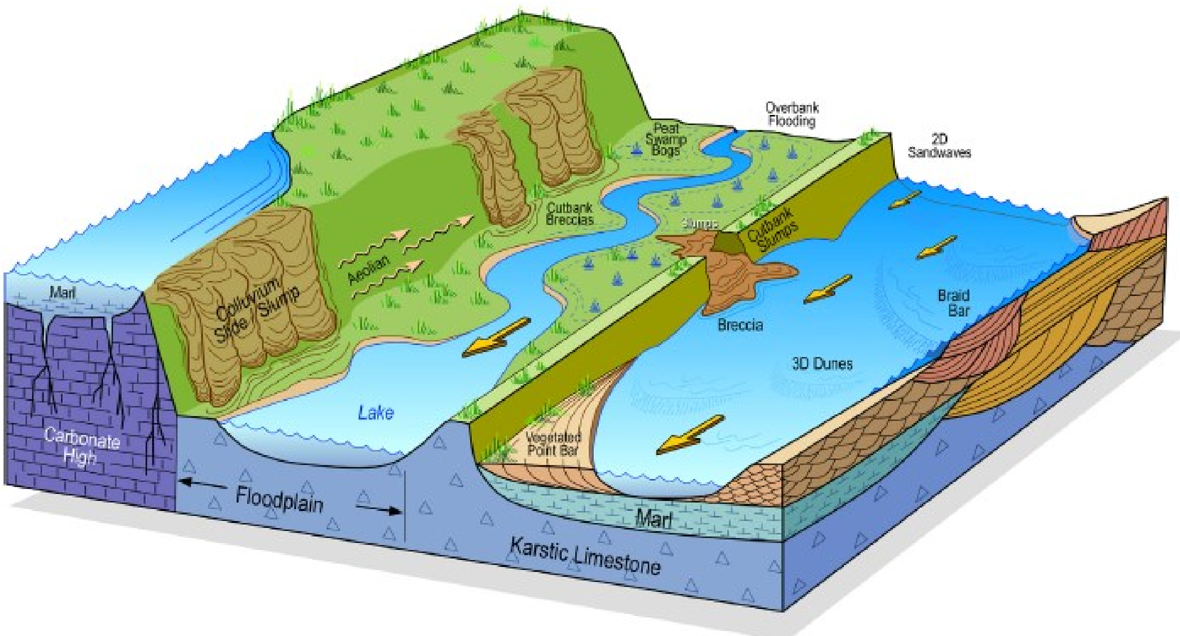


Figure 13. Schematic lithofacies model for the lower McMurray continental and fluvial deposits, Athabasca Oil Sands deposit, northeastern Alberta (from Hein et al., 2000, their figure 82).

5.2.3 Middle McMurray Channel-and-Point Bar Successions

The middle McMurray channel-and-point bar successions have an erosional contact with the underlying lower McMurray clastic succession; or are unconformable upon weathered and karstic Devonian carbonate. The middle McMurray succession consists of a series of thick (up to 40 m), meandering channel-and-point bar complexes, which form the main bitumen reservoir in the Athabasca Oil Sands Area (Figure 7). On wireline logs, the channel deposits tend to be blocky, porous sands, which fine upwards into low-angle inclined heterolithic-stratification (I.H.S.) of mudstone and sand (Figure 9), in some cases capped by thick laminated mudstone and/or rooted paleosols (Figure 9). Distinction of the middle McMurray channel deposits from the underlying lower McMurray channel deposits is not easy. Where identifiable, this contact is placed at the E5 surface (Table 5, Figure 2 and 9); where indistinguishable, the E5 surface is not picked (Figure 10, see above discussion). In core and outcrop, the middle McMurray channel sands commonly contain bioturbated mud clasts, or bioturbated mud-clast breccias (Lithofacies 7, Table 3, Figure 14A, Figure 14D, 15C, and 15D). Bioturbation is ubiquitous within the mudstone clasts, and is very common within the inclined heterolithic stratified (I.H.S.) units. The base of many of the middle McMurray channel deposits consists of mud-clast breccia and/or slump deposits (Figures 14A and 15C), which become finer-grained along with a change from clast-supported to matrix-supported breccia textures upsection. At the transition to the overlying point-bar successions, mud-clast breccia may align along the low-angle stratified beds of the lower point bar successions; alternatively, mud clasts may be dispersed within trough cross-bedded sand that occurs in the transition zone at the base of the point-bar successions (Figure 15C). Where complete channel-and-point bar complexes are preserved, there is a gradual fining-upwards succession from channel sand and mud-clast breccia, to inclined heterolithic stratified (I.H.S.) sand and mudstone, to thick sandy silty mudstone, interpreted as abandonment-fill mudstone (Figure 15A and 16B). Abandonment-fill mudstone may have coarsening-upward successions of crevasse-splay and levee deposits at the base, which fine upwards into oxbow-lake and abandonment-channel, fill mudstone. Rare flood deposits are preserved within the abandonment fills; and, in some cases, rooted paleosols and coals occur at the base or top of the abandonment-fill mudstone successions.

The most common lithofacies within the middle McMurray channel-and-point bar successions is the large-scale, trough cross-bedded pebbly-granule sand (Lithofacies 1, Table 3, Figure 15D), the bioturbated, sandy, low-angle inclined heterolithic stratified sand and mudstone (Lithofacies 10A, Figure 14B and 15A); and, the rippled very-fine to fine sand (Lithofacies 9A, Table 3, Figures 14B, 14C, and 15A). Mud-clast breccia and slump deposits (Lithofacies 7, Table 3, Figures 14A and 15D) are common at the base of individual channel-fill successions or at the transition zone between the channel and point-bar complexes. Within the channel and lower point-bar accumulations, other common lithofacies are small-scale trough and planar-tabular cross-bedded fine to medium sand (Lithofacies 5 and 6, Table 3, Figure 14C). Tidal influence is present within most of the middle McMurray succession, as shown by the presence of the I.H.S. units, some of which internally show rhythmic tidal laminations and tidal couplets (Lithofacies 12, Table 3, Figure 16A and E), along with flaser- and linsen- and herringbone bedding (Table 3, Figure 14E and 15B, also see Hein, 2015). Parallel-stratified sand (interpreted as flood deposits, Lithofacies 11), debris flow deposits (Lithofacies 2), and the pedogenic, coaly and rooted paleosols (Lithofacies 14, Figure 16C) are uncommon within the middle McMurray successions. Coarsening-upwards successions from mudstone to sand (interpreted as crevasse-splay deposits) are moderately common within the middle McMurray deposits, interpreted as reflecting more preservation of floodplain overbank shallow-bay and lacustrine deposits. The middle McMurray informal member is interpreted as a succession of fluvial-estuarine complexes, dominated by meandering channel-and-point bar deposits, with less commonly preserved overbank floodplain units (Figure 17). The floodplain deposits include parallel laminated or massive sand; coarsening-upwards crevasse splays; fining-upwards abandonment fill; and, oxbow-lake sandy mudstones and mudstone successions; with some rooted paleosols, marsh and coal beds.

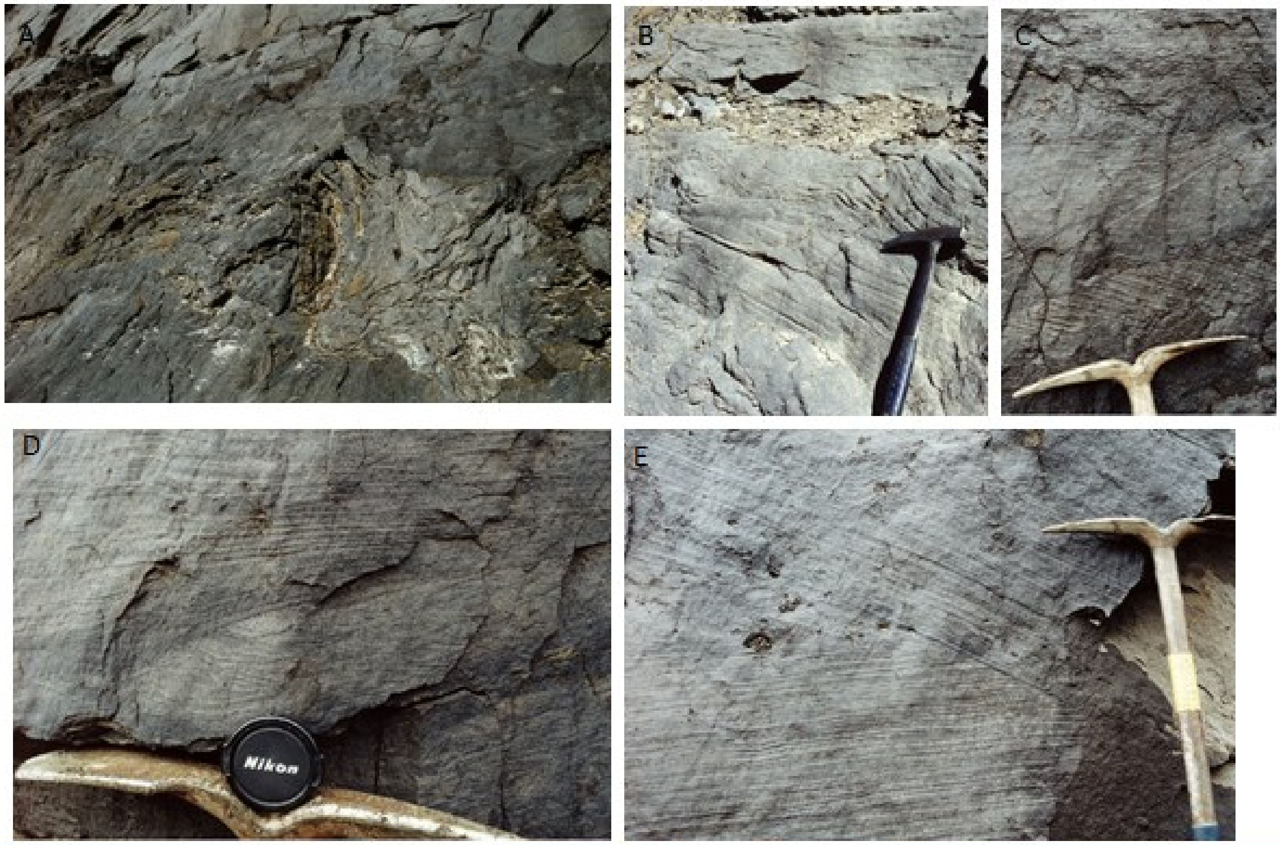


Figure 14. Middle McMurray outcrop photographs: A) Medium to coarse pebbly sand with large slump blocks and mudstone breccia clasts (Lithofacies 7), base of channel succession, Horse River Section #3 (map coordinates: 74D/11 Fort McMurray, UTM 475550E, 6283820N). Bed with the clasts is about 1 m thick; B) Sand with convolute lamination (Lithofacies 7)(near hammer head), interbedded between horizontal to low-angle cross-bedded sand (Lithofacies 11) at base and overlain by low-angle cross-bedded sand at top with superimposed ripples (Lithofacies 10A), Daphne Island East #4 (map coordinates: 74E/5 Bitumount, UTM 460230E, 6350370N); C) Medium to fine sand, with stacked planar-tabular (Lithofacies 6) and trough cross-beds (Lithofacies 5), some with opposing bottom-set ripples (Lithofacies 9A) and escape burrows, Dover River Section (near base of outcrop) (map coordinates: 74E/4 Fort MacKay, UTM 453070E, 6336004N); D) Fine sand, with climbing ripples, trough cross-bedding, Dover River Section (near base of outcrop) (map coordinates: 74E/4 Fort MacKay, UTM 453070E, 6336004N); E) Fine sand, with opposing large-scale planar-tabular cross-beds (Lithofacies 6 or large-scale Lithofacies 9B), the lower one with opposing ripples and escape burrows; Dover River Section (map coordinates: 74E/4 Fort MacKay, UTM 453070E, 6336004N). For full outcrop descriptions see Hein et al. (2001).

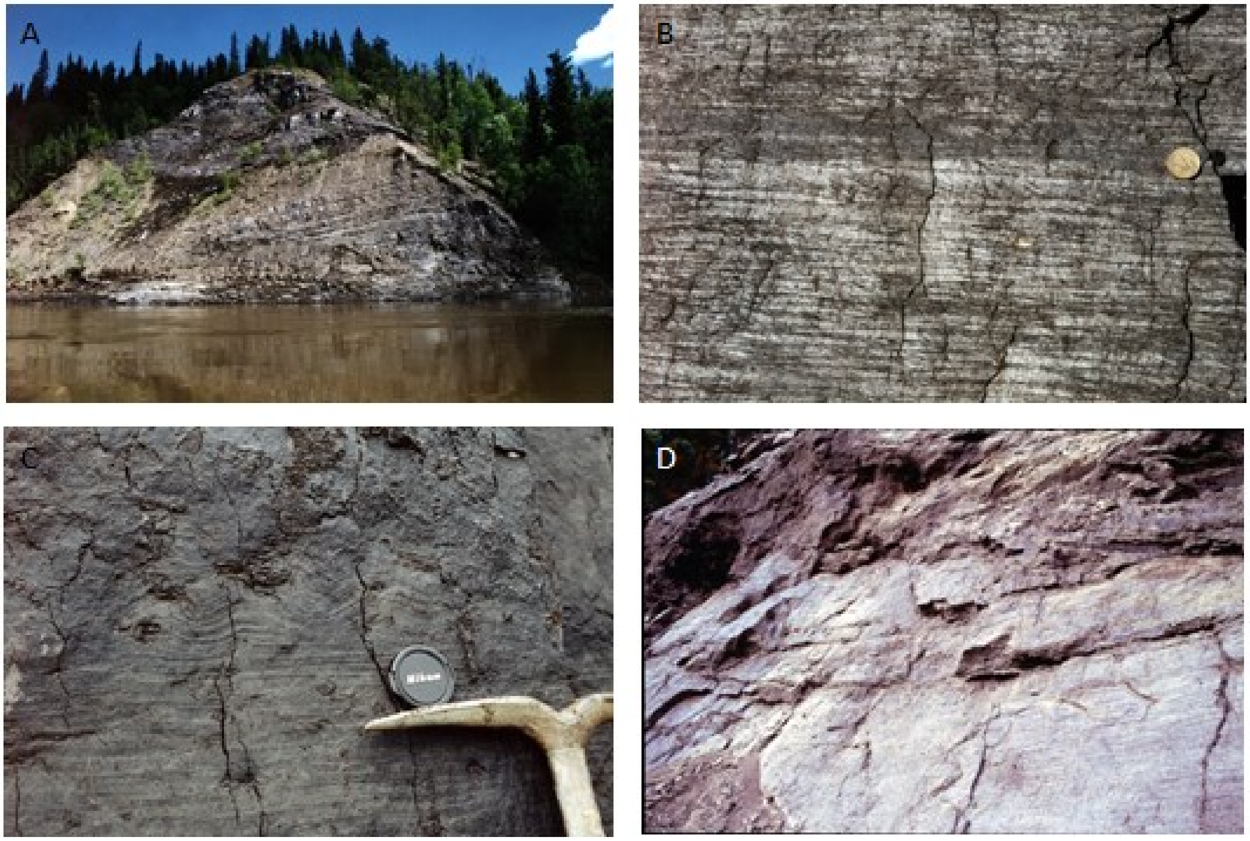


Figure 15. Middle McMurray outcrop photographs: A) Large-scale inclined heterolithic stratification (I.H.S.) (Lithofacies 10A) (base of outcrop, dipping to the left), cut by more recessive, trough cross-bedded sand (Lithofacies 5), which grades up to vertical-accretion abandonment-fill mudstone (Lithofacies 12D and 12E) at top of outcrop; downstream extent of McMurray Type Section #4, Athabasca River (map coordinates: 74D/11 Fort McMurray, UTM 476120E, 6291840N). Outcrop is ~15 m high; B) Fine sand with ripple-drift, current-ripple and small-scale trough cross-bedding (Lithofacies 9A and 5), superimposed on larger-scale on sandy I.H.S. beds (Lithofacies 10A), McMurray Type Section #1, Athabasca River (map coordinates: 74D/11 Fort McMurray, UTM 476166E, 6291060N). Dollar coin for scale; C) Convolute lamination at top of low-angle rippled sand deposit (Lithofacies 7 over Lithofacies 11), overlain by mudclast pebbly granule sand (Lithofacies 7), burrowed, Dover River Section (base of section) (map coordinates: 74E/4 Fort MacKay, UTM 453070E, 6336004N); D) Large-scale trough cross stratification in medium to pebbly sand (Lithofacies 1), with mudstone-intraclast breccias (Lithofacies 7) in the upper part of the photograph, Saline Creek Section #2 (map coordinates: 74D/11 Fort McMurray, UTM 478730E, 6283480N). Lowest bed is about 2 m thick. For full outcrop descriptions see Hein et al. (2001).

Figure 16. Middle McMurray outcrop and core photographs: A) Fine to medium sand with “pin-striped” tidal laminae on larger-scale trough cross-bedding (Lithofacies 12A), close-up photograph, MacKay River Amphitheatre Section #2 (south end) (map coordinates: 74E/4 Fort MacKay, UTM 459970E, 6338850N); B) Fine to medium sand, cross-bedded (Lithofacies 5), overlain by vertical-accretion abandonment-fill mudstone (dark unit at top) (Lithofacies 13), Horse River Section #3 (map coordinates: 74D/11 Fort McMurray, UTM 475550E, 62838204N); C) White rooted muddy sand to sandy mudstone (Lithofacies 14), interbedded with bitumen-saturated sand with organic and coaly interbeds (Lithofacies 14), bioturbated, core AA/10-17-077-05W4/0 (top ~357.55 m; base ~362.05 m); D) Interbedded clast-supported mudstone-clast breccia (Lithofacies 7) with massive medium sand (bitumen-saturated) (Lithofacies 8), AOSTRA AO83 core, AA/03-18-093-12W4/0 (top ~146.30 m; base ~150.80 m); E) Low-angle to horizontally-stratified fine sand and mudstone, with rhythmic interlaminae at varying scales (Lithofacies 12A), overlain by flaser-rippled, fine sand and mudstone (Lithofacies 9B), core AA/09-18-077-05W4/0 (top ~340.80 m; base ~345.35 m); F) Slumped inclined heterolithic stratified (I.H.S.) sand and mudstone, with contorted and over-steepened bedding and syn-sedimentary faults (Lithofacies 10B and 7), core AB/03-18-077-05W4/0 (top ~374.65 m; base ~380.55 m). Lost core (1.95 m) between 377.10 m and 379.05 m; no other missing core, only empty sleeves. C–F) Each core slat is ~0.75 m in length. Top is to the upper right, base is to the lower left on all core photographs. For full outcrop descriptions see Hein et al. (2001).

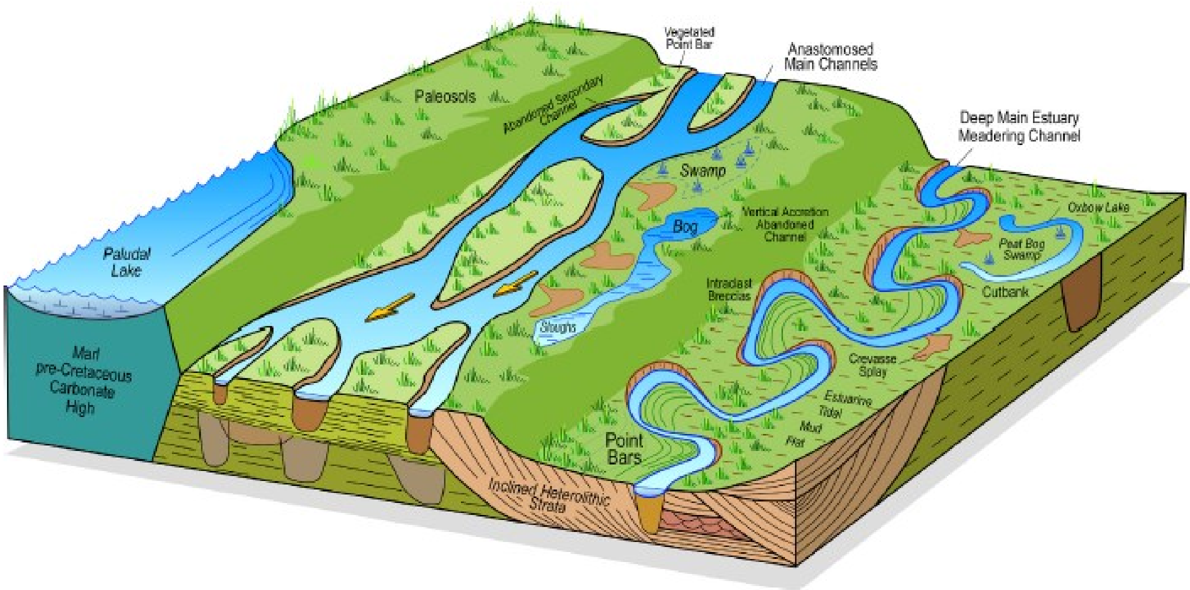


Figure 17. Schematic facies model for the middle McMurray fluvial-estuarine and estuarine deposits, including channels, point bars, abandonment fill oxbow lakes and overbank paleosols, colluvium and local lake sediments (from Hein et al., 2000, their figure 83).

5.2.4 Upper McMurray Tidal-Creek, Tidal-Flat, Bay-Fill and Marginal-Marine Successions

The upper McMurray tidal and marginal-marine successions have an erosional contact with the underlying middle McMurray clastic succession; or rest unconformably upon older units, including weathered and karstic Devonian carbonate. The upper McMurray succession consists of a series of thick (up to 20 m), meandering tidal-creek, tidal-flat, bay-fill and marginal-marine complexes, which form secondary bitumen accumulations, some with top gas and top water, in the Athabasca Oil Sands Area. On wireline logs, the tidal-creek deposits tend to be relatively thin and blocky, porous sands (Figure 9), which fine upwards into low-angle inclined or horizontally stratified mudstone and sand (tidal point-bar and tidal-flat deposits). In certain deposits there are more pervasive, coarsening-upwards mudstone to sand sequences, with rooted paleosol tops. Distinction of the upper McMurray tidal-creek deposits from the underlying lower McMurray channel deposits is not clear. The blocky channel sands tend to be thinner and mudstones at the base of the coarsening-upwards sequences tend to be thicker (up to 1.5 m) and laterally more persistent, compared to mudstones in the underlying middle McMurray informal member. Lithologically the units are the same. If successive mudstones are identified in the stacked coarsening-upwards sequences, they are identified from the top downwards as A1, A2, B1 and B2 (Figure 10). Where correlatable mudstones are removed by erosion associated with overlying channel successions, it is difficult to identify the associated stratigraphy without detailed and tight well control (ideally tied to seismic grids, where available).

The most common lithofacies within the upper McMurray tidal and marginal-marine successions are the small-scale, rippled, flaser and herringbone cross-bedded, very-fine to fine sand (Lithofacies 9A and 9B), the bioturbated, rhythmically interlaminated sand and mudstone (Lithofacies 12A), the bioturbated (churned) muddy sand (Lithofacies 13A); and, the coarsening-upwards mudstone to sandstone sequences (Lithofacies 15) (Table 3, Figure 18 and 19). Subject to the types of lithofacies and their vertical and lateral trends, the upper McMurray succession is interpreted as largely deposited within tidal and tidally-influenced, marginal-marine settings, including tidal creeks and bars, tidal flats, tidal bays, and offshore shoreface settings (Figures 20 and 21) (see Hein, 2015). Depending upon the local accommodation and amount of erosion from overlying units, up to three or more stacked coarsening-upwards successions may amalgamate to form the upper McMurray informal member (A1 to C Channel, Figure 10). In areas where the mudstones at the base of the coarsening-upwards successions are sufficiently thick (~2 m), there may be compartmentalization and separation of the bitumen reservoirs from the overlying top gas and top water reservoirs within the upper McMurray succession (Alberta Energy and Utilities Board, 2003; Hein et al., 2013a).

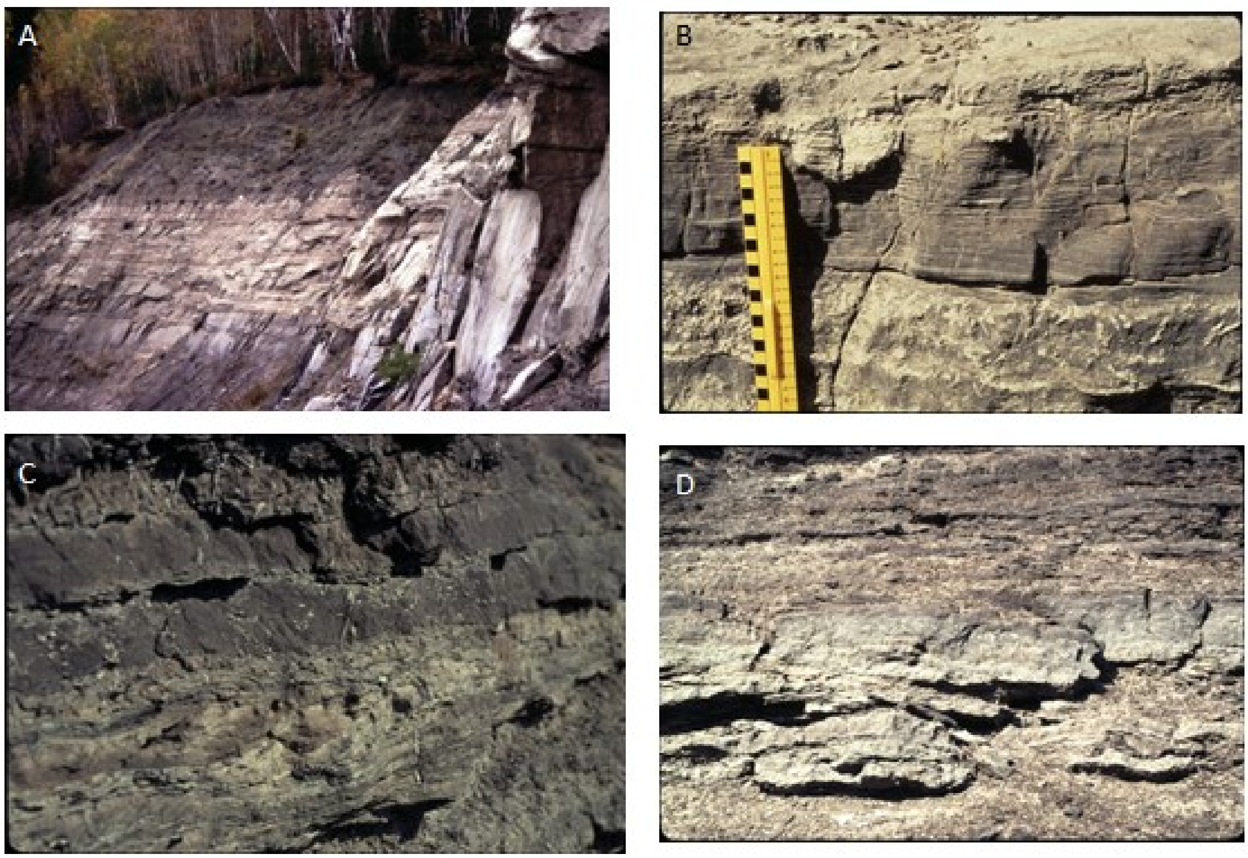


Figure 18. Upper McMurray outcrop photographs: A) White shoreface succession of fine-grained to very fine sand with parallel and low-angle intersecting low-angle truncations, overlying dark, bitumen-stained, middle McMurray channel succession, and underlying Wabiskaw D and Wabiskaw C units (dark), Horse River (Oxbow Lake) #3 Section (map coordinates: 74D/11 Fort McMurray, UTM 475550E, 6283820N); B) Light grey, muddy fine sand with *Cylindrichnus* and escape burrows (Lithofacies 13A), abruptly overlain by muddy and fine sand with parallel laminations, low-angle truncations, and ripples (Lithofacies 11, 12, and 9B), cut by *Skolithos* and vertical to oblique burrows, MacKay River Viewpoint Section (map coordinates: 74E/4 Fort MacKay, UTM 459990E, 6339151N). Dark marks on ruler are each 1 cm long; C) Burrowed muddy sand and sandy silty mudstone, with vertical *Skolithos* burrows, V-shaped *Cylindrichnus*, and vertical escape burrows, Amphitheatre Section #2 (upper part, south end) (Map Coordinates: 74E/4 Fort MacKay, UTM 459970E, 6338850N); D) Burrowed muddy sand overlying interbedded, burrowed sand and mudstone with inclined heterolithic stratification (I.H.S.) (Lithofacies 10A and 10B), Amphitheatre Section #2 (upper part, south end) (Map Coordinates: 74E/4 Fort MacKay, UTM 459970E, 6338850N). For full outcrop descriptions see Hein et al. (2001).

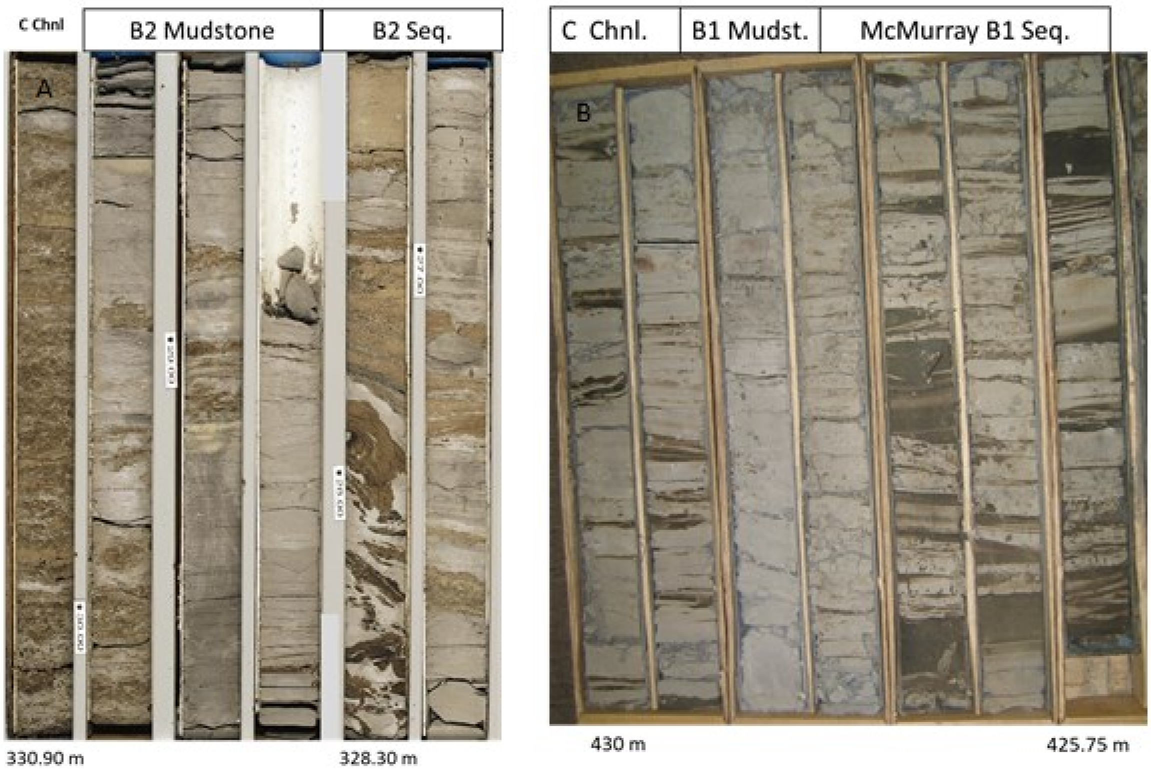
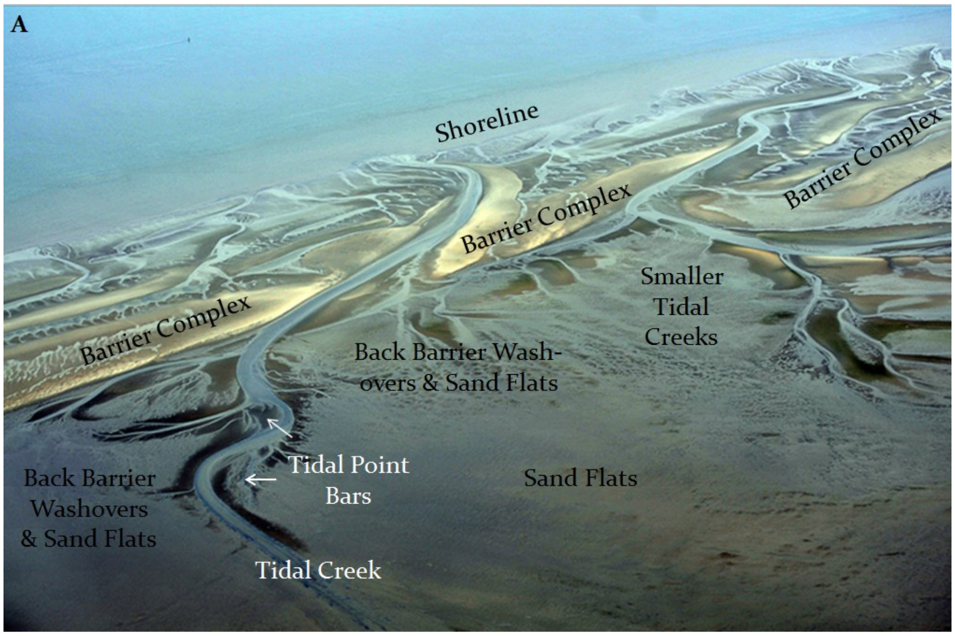


Figure 19. Upper McMurray core photographs: A) Coarsening-upwards succession (Lithofacies 15) of B2 mudstone and B2 sequence, abruptly overlying the top of a McMurray C Channel succession, core AA/13-08-077-05W4/0 (top ~336.80 m; base ~330.90 m.), empty sleeve, no lost core; B) Coarsening-upwards succession (Lithofacies 15) of B1 mudstone and B1 sequence, abruptly overlying the top of a McMurray C Channel succession, core 00/10-36-079-09W4/0 (top ~425.00 m; base ~430.00 m). Lost core: 0.10 m between 425.00 m and 425.75 m. Each core slat is ~0.75 m in length. Top is to the upper right, base is to the lower left on all core photographs.



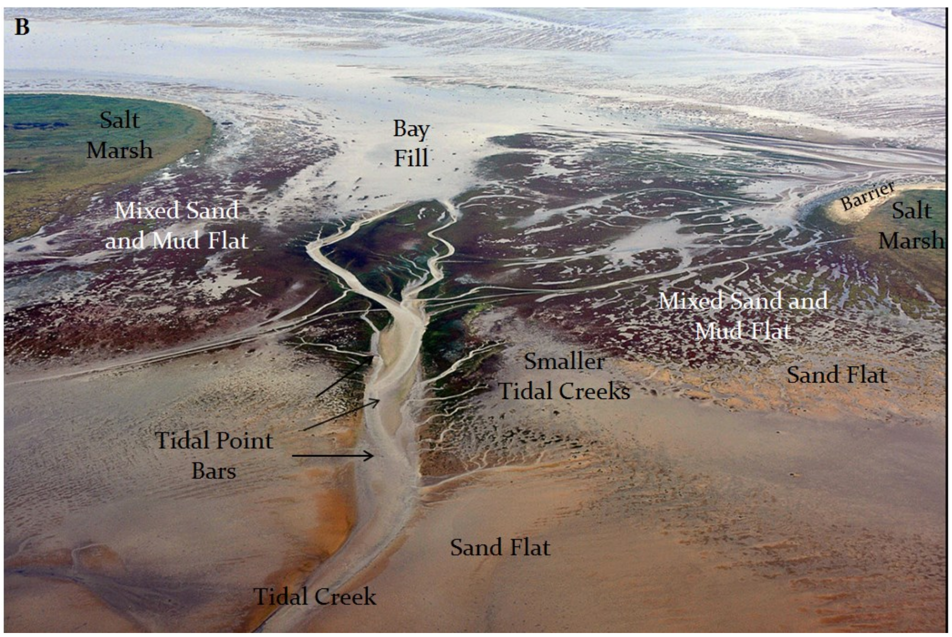


Figure 20. Aerial photographs of modern analogs for the upper McMurray tidal creek, point bar, tidal flat, and marsh deposits. A) Sand flats, tidal creeks, and tidal point bars in a sand-dominated back-barrier area of the North Sea; B) Mixed sand and mud tidal flats, tidal creeks, point bars, bay fills, and salt marshes of the North Sea. For discussion of tidal creek facies models see Dalrymple (1992). Sources of photographs: A) Fotoflug Nordsee, Priele im Watt vor Scharhörn, 4 September 2011, by Ralf Roletschek, https://commons.wikimedia.org/wiki/File:11-09-04-fotoflug-nordsee-by-RalfR-011.jpg; B) Fotoflug Nordsee, Nigehörn (links) und Scharhörn (rechts), 6 September 2011, by Ralf Roletschek, https://commons.wikimedia.org/wiki/File:11-09-04-fotoflug-nordsee-by-RalfR-024.jpg (from Wikimedia Commons; reproduced under Creative Commons Attribution-Share Alike 3.0 Germany license; labels added by F.J. Hein).

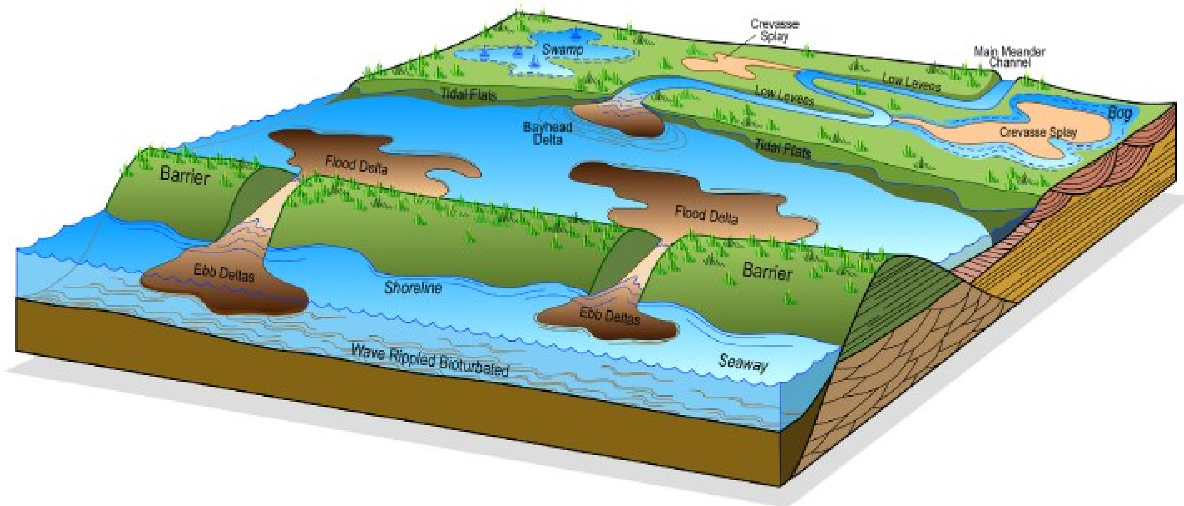


Figure 21. Schematic facies model for the upper McMurray and Wabiskaw estuarine, brackish-bay, and shoreface successions, Athabasca Oil Sands deposit, northeastern Alberta (from Hein et al., 2000, their figure 84).

5.2.5 Wabiskaw D Incised-Valley Fills and Marginal Marine Sequences

The Wabiskaw D unit sits disconformably to unconformably (E10 surface, Table 5, Figure 9 and 10) upon the McMurray Formation. In areas where the McMurray Formation is completely eroded, the Wabiskaw D unconformably overlies Devonian carbonate. The Wabiskaw D succession consists of a series of thick (up to 10 m) incised-valley fills, channel and marginal-marine complexes, which form secondary bitumen accumulations, some with top gas and top water, in the Athabasca Oil Sands Area. On wireline logs, the valley- and channel-fill deposits tend to be blocky, porous sands, which are capped by shaley mudstone or silty muddy shale (Figure 9). Distinction of the Wabiskaw D deposits from the underlying McMurray sediment is based on lithology of the sands and composition and appearance of the associated mudstone and shale beds. Typically, the Wabiskaw D sand is an immature litharenite, except in cases where quartz-rich McMurray sediment has been reworked and incorporated into the overlying Wabiskaw D valley- or channel-fill deposits. Wabiskaw D shale interlaminae are typically dark, steel-grey (or dark blue-grey) in colour, with a marked fissility. Bioturbation structures are prominent, consisting of large, more marine trace fossils, including: *Bergaugeria*, *Asterosoma*, *Thalassinoides*, large *Skolithos*, *Diplocriterion*, *Rosellia*, *Palaoephycus*, etc. These features contrast with the McMurray sediments, which are typically quartz-rich, have non-fissile silty or sandy silty mudstone interbeds, and have a restricted trace fossil assemblage, of smaller traces, including *Cylindrichnus*, *Skolithos*, *Gyrolithes*, *Planolites*, rare *Ophiomorpha*, among others (for further discussion of these differences see Hein et al., 2013a).

The Wabiskaw D deposits are either sand- or shale-dominated (Figure 22 or 23). Shale-dominated Wabiskaw D (also called the Wabiskaw D shale) has <5% sand. Typically the shale-dominated Wabiskaw D occurs at the top of the succession; less commonly at the base of the Wabiskaw D unit. On wireline logs, where the Wabiskaw D incised-valley fill appears to be shaly at the base, and the shale exceeds 5 m in thickness, there is a cleaning/coarsening-upwards profile on the gamma-ray logs. The shale component of the Wabiskaw D valley fill typically registers as a sharp deflection to the left on the neutron logs, a response that does not occur on the density logs.

Figure 22. Wabiskaw Member (Clearwater Formation) core photographs: A) Wabiskaw D valley fill abruptly overlying the McMurray Formation, core AA/11-03-078-06W4/0 (top ~355.05 m; base ~358.60 m). Lost core: 0.15 m between 356.55 m and 356.70 m; B) Wabiskaw C, Wabiskaw D shale, and Wabiskaw D valley-fill units, core AA/07-22-076-06W4/0 (top ~320.89 m; base ~324.12 m). Empty sleeves; no lost core. Each core slat is ~0.75 m in length. Top is to the upper right, base is to the lower left on all core photographs.

Figure 23. Clearwater shale and Wabiskaw Member core photographs: Clearwater marine shale, upper right, fissile with concretionary textures, gradationally overlying the top of the Wabiskaw Member. The Wabiskaw consists of the upper, greenish caste, heavily bioturbated Wabiskaw C muddy sand, underlain by interlaminated sand and mudstone of the Wabiskaw D valley-fill succession; core AA/08-20-076-06W4/0 (top ~320.47 m; base ~325 m). Each core slat is ~0.75 m in length. Top is to the upper right, base is to the lower left on all core photographs.

The most common lithofacies within the Wabiskaw D valley fill is mixed sand and shale, which typically has between 20% and 40% shale. The interbedding of the sand and shale is wavy—occurring as flaser- and/or linsen-bedding. Bioturbation is prominent and locally disrupts the primary sedimentary structures. The Wabiskaw D mixed sand and shale lithology is commonly capped by the Wabiskaw D shale. Regionally the Wabiskaw D shale reaches a maximum thickness of 2 m. The Wabiskaw D shale is identical to the shaly component of the underlying Wabiskaw D incised-valley fills; typically a dark steel-grey (or blue-grey) colour and a pronounced fissility. On logs the Wabiskaw D shale has a low resistivity response and a sharp deflection to the left on the neutron log (with no deflection on the density log). In core glauconite is present within the Wabiskaw D shale, where burrowing commonly brings it down from the overlying Wabiskaw C unit. Trace fossils within the Wabiskaw D shale include smaller *Planolites*, with some large borings and large vertical *Skolithos* burrows at the top contact with the overlying Wabiskaw C succession—interpreted as a disconformity as represented by a *Glossifungites* surface. The Wabiskaw D incised-valley fill and Wabiskaw D shale are interpreted as estuarine to marine drowned valley- and bay-fills that were cut and then later filled by a maximum transgression associated with the Clearwater Sea.

5.2.6 Wabiskaw C Marginal-Marine Sequences

The Wabiskaw C unit sits disconformably to unconformably upon the Wabiskaw D succession (T10.5 surface, Table 5, Figures 9 and 10). In areas where the Wabiskaw D is completely eroded, the Wabiskaw C unconformably overlies the underlying McMurray Formation (E10 surface, Figures 9 and 10). The Wabiskaw C sand succession consists of a series of thin (up to 5 m) incised-valley fills and marginal-marine shoreface complexes, which form secondary bitumen accumulations, some with top gas and top water, in the Athabasca Oil Sands Area. The sand component of the Wabiskaw C succession is typically a glauconitic, immature litharenite, comprising >50% of the unit (Figures 22 and 23). In some areas there are stacked Wabiskaw C sand and Wabiskaw C mudstone units, which form successive coarsening-upwards successions. Much of the Wabiskaw C sand and Wabiskaw C mudstone is thoroughly bioturbated, such that primary sedimentary structures are rarely preserved. Trace fossils include: *Diplocriterion*, *Asterosoma*, *Thallasinoides*, *Skolithos,* rare *Ophiomorpha,* and escape burrows, among others. On wireline logs, the Wabiskaw C sands tend to be blocky, porous sands capped by a fissile shaley mudstone or silty muddy shale (Figure 9).

The Wabiskaw C unit has an erosional contact with the underlying Wabiskaw D or McMurray Formation. Distinction of the Wabiskaw C deposits from the underlying Wabiskaw D or McMurray successions is based on lithology of the sands and composition and appearance of the associated mudstone and shale beds. Typically, both the Wabiskaw D and Wabiskaw C sands are immature litharenite. Glauconite is common in the Wabiskaw C; in the Wabiskaw D, only present where admixed from above due to burrowing down from the Wabiskaw C sand down into the Wabiskaw D sand. Wabiskaw D shale interlaminae are typically dark, steel-grey in colour, with a marked fissility. Mudstones within the Wabiskaw C succession are sandy and silty; lack the fissility of the Wabiskaw D shales; and, tend to be a light to medium green-grey colour. The Wabiskaw C sand and mudstone are interpreted as drowned valley- and bay-fill deposits to offshore marine lower shoreface deposits, which were emplaced by regressive events following the maximum Wabiskaw D transgression associated with the Clearwater Sea. In some areas, there are two younger units at the top of the Wabiskaw (the Wabiskaw B and the Wabiskaw A). The Wabiskaw B *sensu-stricto* only occurs in the southern part of the Athabasca Oil Sands Area. This unit was previously mapped by the regional geological study of the Alberta Energy and Utilities Board (2003) and was not re-examined during the present work. The topmost Wabiskaw A unit is mainly preserved along the northern and northwestern limits (Hein and Cotterill, 2006), does not host significant bitumen, and similarly was not examined during the present study. The top of the Wabiskaw Member is marked by a regional transgressive surface (T21, Table 5, Figure 9 and 10), above which are the marine shales of the Clearwater Formation (Figure 23). In some wells in the central and northern areas, coarsening-upwards cycles, equivalent to the Wabiskaw B are identified.

6 Palynology: Common Microfossils in the Wabiskaw–McMurray Succession and Associated Strata

The science of palynology needs some understanding of the terminology and classification schemes used to categorize and describe this organic material. The organic material and microfossils that were found in the mudstones and shales recovered from the Wabiskaw–McMurray succession (and associated strata, see Figure 2) fall into six major groups or genera. These include: acritarchs, algae, dinoflagellate cysts (also called ‘dinocysts’), fungi, spores, and pollen. Microphotographs of representative palynomorphs from the studied samples are given in Plate 1.

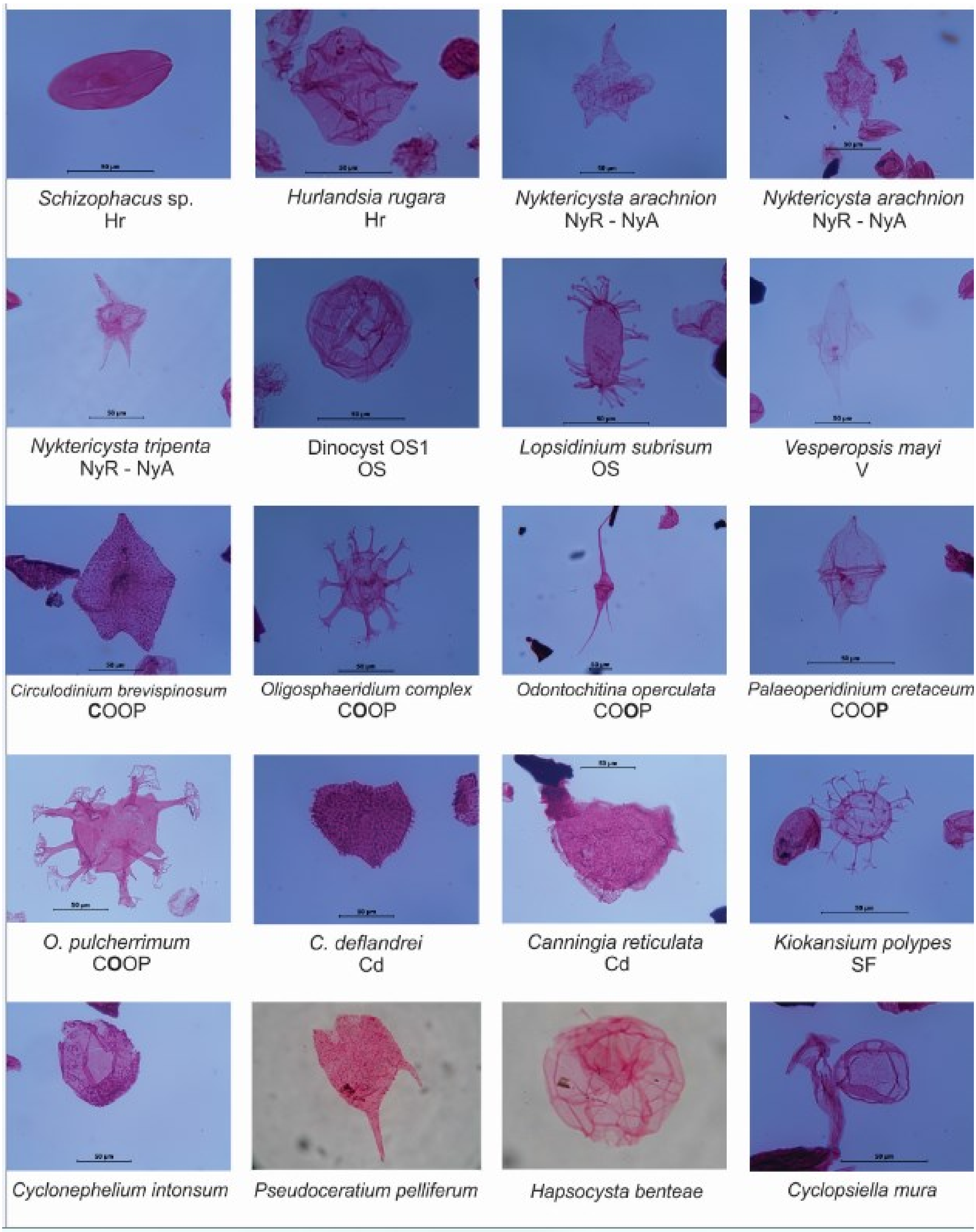


Plate 1. Typical palynomorphs from the Wabiskaw–McMurray succession, and associated strata, Athabasca Oil Sands Area. Refer to the explanation of the palynofacies concept and abbreviations described in Section 7 and illustrated in Figure 36.

6.1 Acritarchs

The name '*acritarch'* comes from the Greek *ákritos*, meaning confused or doubtful; and *arché*, meaning beginning or origin (http://dictionary.reference.com/browse/acritarch). Acritarchs are non-soluble organic structures of unknown biological (taxon) affinities, which have a central cavity surrounded by an organic wall (Evitt, 1963). Acritarchs range in age from the Precambrian to the Holocene. These microfossils have been interpreted as resting cysts of various types of organisms, most likely from eukaryotic unicellular organisms, such as algae, green algae (photosynthetic), or other genera related to dinoflagellates. Acritarchs commonly have complex ornamentations, such as external projections, hair-like spines and thick cell membranes. Although the biological affinity is unknown, acritarchs are classified into "form genera," which are quite useful for biostratigraphic and paleoenvironmental work (see external link: Commission Internationale de Microflore du Paléozoique (CIMP) Subcommission on Acritarchs (http://www.cimp.ulg.ac.be/Acritarchs.html). Most acritarchs are thought to be of marine origin.

In the study area, acritarchs are present within the Devonian carbonates beneath the sub-Cretaceous unconformity and some of these fossils were also reworked and emplaced within overlying Cretaceous units. Devonian samples were analyzed at the base of only three cores, since the emphasis of this work was on the Cretaceous succession. All three carbonate samples were taken just below the sub-Cretaceous unconformity, within a weathered and sometimes rooted and altered carbonate rock. For the carbonate samples that were analyzed, the acritarchs include *Leiosphaeridia* spp., *Micrhystridium* spp., and *Veryhachium* spp. (Tables 6 and 7; Appendices 4 and 5). All acritarch genera indicate marine conditions.

Table 6. Summary list of acritarch microfossils for different stratigraphic units from just above the Cretaceous Wabiskaw Member (Clearwater Formation) to the sub-Cretaceous unconformity (see Appendices 4 and 5). Note: two specimens are reworked in middle McMurray, well AB/16-02-096-11W4, depth 8.75 m). The reworked specimens were not included in the specimen count for each stratigraphic interval in Table 7. For palynofacies nomenclature and descriptions see Section 7 and Figure 36.

Core Location UWI	Sample Depth (m)	Stratigraphic Unit (Palynofacies)	Acritarchs (# of specimens) Total # of specimens = 138
100/11-08-075-08W4/00	406.05 m	Wabiskaw A (OS)	*Cyclopsiella* spp. (1)
	406.86 m	Wabiskaw A (OS + COOP)	*Cyclopsiella*? *mura* (6) *Cyclopsiella* spp. (11)
100/15-35-076-04W4/00	352.00 m	Wabiskaw D (OS)	*Cyclopsiella*? *mura* (2)
100/06-15-076-06W4/00	342.70 m	Middle McMurray (COOP + OS)	*Cyclopsiella* spp. (1)
1AA/03-12-081-06W4/00	202.66 m	Clearwater (Cd)	*Cyclopsiella*? *mura* (1)
	204.48 m	Wabiskaw A (Cd)	*Cyclopsiella*? *mura* (1)
	210.47 & 208.80 m	Wabiskaw B (Cd)	*Cyclopsiella*? *mura* (1)
	212.72 m	Wabiskaw C (COOP)	*Cyclopsiella* spp. (1)
	215.55 m	Wabiskaw D (COOP + OS)	*Cyclopsiella*? *mura* (1)
	217.53 m	Wabiskaw D (OS)	*Cyclopsiella* spp. (1)
	222.06 m	Upper McMurray (OS)	*Cyclopsiella*? *mura* (3)
	202.66 m	Clearwater (Cd)	*Pterospermopsis* spp. (1)
	208.80 m	Wabiskaw A(Cd)	*Pterospermopsis* spp. (3)
1AA/05-17-083-06W4/00	307.65 m	Wabiskaw A (Cd)	*Cyclopsiella*? *mura* (1)
	308.40 m	Wabiskaw A (Cd)	*Cyclopsiella*? *mura* (1)
	307.65 m	Wabiskaw A (Cd)	*Pterospermopsis* spp.(1)
	311.40 m	Wabiskaw B (COOP)	*Pterospermopsis* spp. (1)
1AB/10-29-092-09W4/00	21.82 m	Wabiskaw C (COOP)	*Cyclopsiella* spp. (3)
100/05-17-092-17W4/00	232.65 m	Wabiskaw C (OS)	*Cyclopsiella* spp. (4)
	242.92 m	McMurray (OS)	*Cyclopsiella* spp. (4)
1AA/10-26-093-06W4/00	257.34 m	Wabiskaw C (SF)	*Cyclopsiella*? *mura* (2) *Cyclopsiella* spp. (12) *Pterospermopsis* spp. (1)
	259.48 m	Wabiskaw D (COOP + OS)	*Cyclopsiella*? *mura* (12)
1AA/06-36-095-11W4/00	67.69 m	Devonian	*Leiosphaeridia* spp. (3) *Micrhystridium* spp. (4) *Veryhachium* spp. (23)
1AB/16-02-096-11W4/00	5.1 m	Wabiskaw D (COOP)	*Leiosphaeridia* spp. (1)
	8.75 m	Middle McMurray (Hr)	*Leiosphaeridia* spp. (1) reworked *Micrhystridium* spp. (1) reworked
1AA/03-28-096-16W4/00	355.9 m	Wabiskaw A (Cd equivalent)	*Pterospermopsis* spp. (1)
	388.62 m	Upper McMurray (OS)	*Cyclopsiella*? *mura* (1)
1AA/11-09-099-15W4/00	435.63 m	Wabiskaw D (OS)	*Cyclopsiella* spp. (26)
	428.35 m	Wabiskaw C (SF)	*Cyclopsiella*? *mura* (1)

Table 7. Summary list of acritarch microfossils (excluding reworked fossils) for different stratigraphic units from just above the Cretaceous Wabiskaw Member (Clearwater Formation) to the sub-Cretaceous unconformity (see Appendices 4 and 5).

Stratigraphic Unit	Acritarch	Number of Specimens
Clearwater Formation	*Cyclopsiella? mura*	1
	Pterospermopsis spp.	1
Wabiskaw Member	*Cyclopsiella*? *mura*	28
	Cyclopsiella spp.	59
	Leiosphaeridia spp.	1
	Pterospermopsis spp.	7
McMurray Formation undifferentiated	*Cyclopsiella* spp.	4
Upper McMurray Formation	*Cyclopsiella? mura*	4
Middle McMurray Formation (excluding the two reworked specimens)	*Cyclopsiella spp.*	1
Lower McMurray Formation	None recorded	0
Pre-McMurray succession	None recorded	0
Devonian unit – just below sub-Cretaceous unconformity	*Leiosphaeridia* spp.	3
Unconformity – weathered bedrock at the contact of the Devonian and Cretaceous units	*Micrhystridium* spp.	4
	Veryhachium spp.	23
Total Number of Specimens		136

6.1.1 Acritarch Discussion

Associated with the creation of the sub-Cretaceous unconformity in the Athabasca Oil Sands Area was a long period of non-deposition, weathering, and erosion, with removal of any formerly deposited Jurassic and older sediment, prior to the initial transgressions associated with Lower Cretaceous deposition. Acritarchs within the Devonian carbonates record the marine settings of the original carbonate facies, some of which are reworked and resedimented higher upsection into the Cretaceous units.

Most commonly acritarchs are not recovered in the Cretaceous clastic units. In some cores, rare to very rare acritarchs are within the McMurray to Clearwater successions, with a very limited number of reworked acritarchs, including *Leiosphaeridia* spp., *Micrhystridium* spp.; *Veryhachium* sp., and other undifferentiated forms. The *Leiosphaeridia* spp., *Micrhystridium* spp., and *Veryhachium* spp. have all been recovered from the Devonian succession, beneath the sub-Cretaceous unconformity (Table 7), where the frequency ranges from present or rare (1–2 specimens per sample) to abundant (>15 specimens per sample).

For the Cretaceous units, from historical AGS records (Appendix 3), only in a single sample from the marine Wabiskaw C unit, acritarch frequency increased to being common (core location 07-18-069-12W4, depth 451.1 m). In the same well, the acritarch genus *Pterospermella* was also recorded. *Petrospermella* sp. was recorded in only two other core samples—the 07-26-080-11W4 (Clearwater Formation, depth 1362–1364 ft.) and in the 04-08-089-07W4 (Clearwater Formation, depth 348 m), where large *Petrospermella* sp. were noted. Like the *Leiosphaeridia* acritarchs, the *Petrospermella* acritarchs indicate shallow-water marine conditions. This genus may be indicative of regressive events. In the present study, no acritarchs were recovered from the pre-McMurray and lower McMurray units (Table 7), with the most common occurrences in the Wabiskaw Member and Clearwater Formation samples (Tables 6 and 7). Middle McMurray samples have reworked *Leiosphaeridia* spp. and reworked *Micrhystridium* spp. specimens along with rare Cretaceous forms of *Cyclopsiella* spp. Elsewhere, most records of reported *Cyclopsiella* are from Tertiary rocks; the only Cretaceous records of the genus so far are from southern England and here. Although the occurrence of acritarchs within the Wabiskaw–McMurray succession is commonly rare (1 to 3 specimens per sample), in some wells the frequency of acritarchs becomes more common (4 to 10 specimens per sample) or very common (11 to 20 specimens per sample). The most common acritarch taxa are *Cyclopsiella* spp., *Cyclopsiella*? *mura*, and *Pterospermopsis* spp., generally within the upper McMurray, Wabiskaw, and Clearwater units (Tables 6 and 7).

6.2 Algae

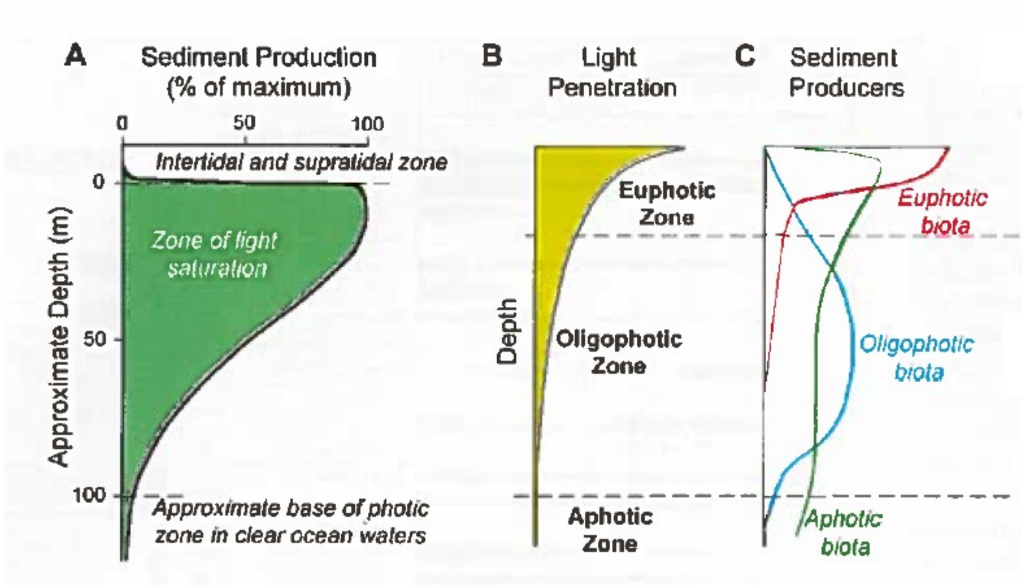
The term' *algae*' refers to a large and diverse group of photosynthetic organisms, which range in age from the Precambrian to the Holocene; they include the dinoflagellate cysts, which will be discussed separately. One definition of the group is that chlorophyll is the main photosynthetic pigment within their cells and that algae lack a protective cover of cells around their reproductive cells. Algae have different modes of reproduction, including asexual cell division and other complex forms of sexual reproduction. Algal species vary widely in size, from microscopic, single-celled organisms, such as diatoms; to large, multicellular organisms, such as kelp or brown algae, which may grow up to 50 m or more in length. Algae are mainly aquatic; and are freshwater or marine. Most algae do not have larger cell tissues or other structures that are typical of land or sea plants, such as leaves, roots, stomata, xylem, and phloem. The majority of algae derive their energy from photosynthesis, although some may also get their energy through uptake of organic carbon. Because algae largely rely on photosynthesis for their energy, the presence of algal fossils is usually indicative of shallow-water, clear and non-turbid conditions. Certain algae, including the *Botryococcus* genus, form larger colonies that are held together by biofilms. *Botryococcus* colonies are able to produce high levels of hydrocarbons representing typically around to 30–40% of their dry weight (Metzger and Largeau, 2005). Algal blooms (including *Botryococcus*) form in areas with elevated values of nutrients, such as nitrogen and phosphorous (Labib et al., 2012). Algal blooms result in high levels of organic carbon, which accounts for the high organic and hydrocarbon content of many fine-grained source rocks, such as oil-shales.

Some micro-remains of green algae include decay-resistant substances from the algal cells in their vegetative state (*Botryococcus* and *Pediastrum);* whereas other algal fossil remains are from thick-walled resting cells (spores), which some algae (such as *Zygnemataceae)* produce to survive unfavourable environmental conditions, including desiccation or alternating flooding and drying-out cycles. The process of producing zygospores is called conjugation—a survival mechanism that first evolved in green algae in the Carboniferous for survival during drying-out phases of ephemeral ponds on land (Martín-Closas, 2003). The algal genus *Tetranguladinium* has a stratigraphic range from the middle Permian to the Holocene; with a preference for freshwater environments in humid, warm temperate to subtropical-tropical climates, with common drying-out seasons (Lindström, 2013).

Fossils of the algal family Zygnemataceae are limited to their resting cell state (spores). Zygnemataceous spores have been identified from Carboniferous (or older) to Holocene age (van Geel, 1978, 1979; van Geel and Grenfell, 1996). Zyngnemataceous zygospores are associated with sediments from shallow, clean (non-turbid), oxygen-rich, freshwater ponds, which may experience periodic drying-out or desiccation events. Zygnemataceae are very common algae; and include important biologic components of many freshwater settings, including lakes, ponds, and streams; or near the margins of lakes, in flowing water, or in stagnant bogs. Optimal conditions are 15–20° C and pH 7.0–8.0. Their zygospores usually develop in the spring, under clean (non-turbid), shallow, fresh- and oxygen-rich waters (van Geel, 1976, 1978).

The *Botryococcus* colonies and *Pediastrum* spp. represent the vegetative stage of the Chlorophyta. *Botryococcus* colonies are usually found dominantly in mesotrophic conditions (Figure 24C and D) (Reynolds et al., 2015), mainly open, clear (non-turbid) and freshwater settings. *Botryococcus* colonies are very common in freshwater bogs, oligotrophic lakes, temporary ponds, lagoons, and estuaries, generally within temperate to tropical latitudes (Guy-Ohlson, 1992, 1998; Medeanic, 2006). Under more saline conditions (brackish to normal marine), the *Botryococcus* algae are stressed and growth forms are drastically reduced and/or reproduction stops.

Pediastrum spp. have been reported from sediment that originated in stagnant or slowly-flowing fresh waters (eutrophic to mesotrophic, Figure 24C and D), with open water surfaces, such as in freshwater ponds or in paleo-sinkholes (paleo-cenotes) (Blokker et al., 1998). *Pediastrum* fossils occur in a wide range of depositional environments, but their presence is mainly taken as an indicator of freshwater settings in temperate to warm climates (Zamaloa and Tell, 2005). In reviews of Early Cretaceous freshwater phytoplankton it is generally considered that *Botryococcus* and *Pediastrum*, along with other genera, developed in mesotrophic to eutrophic lakes (Figure 24D) (Batten, 1996; Batten and Lister, 1988). *Lecaniella* microfossils resemble the conjugate zygospores of the Zygnemataceae; and, similarly have been widely reported from shallow, mesotrophic freshwater deposits, including small temporary pools, lakes and paleo-sinkholes. A summary of the algal microfossils within the Clearwater to pre-McMurray successions in the study area is listed in Tables 8 and 9.



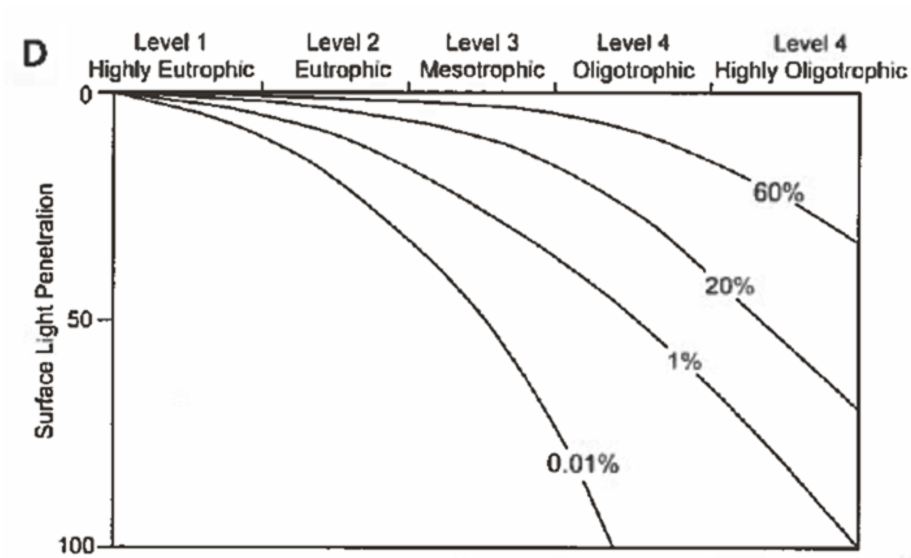


Figure 24. Sediment production in the carbonate factory: A) Schematic curve showing biogenic carbonate sediment production relative to depth, mainly based on green algae and corals; B) Zonation of the upper part of the ocean water column according to light penetration; C) Distribution of euphotic, oligophotic, and aphotic biotas; D) Estimated depths of photosynthetically active surface light penetration as a function of tropic resource decline. Isolines are for optimal growth; 1% base of euphotic zone (used with permission from B. Jones, 2010, after Hallock, 1987; Mutti and Hallock, 2003; Pomar, 2001; Schlager, 1998).

Table 8. Summary list of algal remains for different stratigraphic units from just above the Cretaceous Wabiskaw Member (Clearwater Formation) to the sub-Cretaceous unconformity (see Appendices 4 and 5). For palynofacies nomenclature and descriptions see Section 7 and Figure 36.

Core Location UWI	Sample Depth (m or ft.)	Stratigraphic Unit (Palynofacies)	Algae (# of specimens) Total # specimens = 258
100/11-08-075-08W4/00	406.05 m	Wabiskaw A (OS)	*Lecaniella* spp. (1)
	478.5 m	Middle McMurray (Hr)	*Lecaniella foveata* (1) *Schizophacus parvus* (1)
100/10-30-076-04W4/00	340.5 m	Wabiskaw A/Wabiskaw B contact (Cd)	*Schizophacus parvus* (2)
	390.5 m	Middle McMurray (Hr* Overbank)	*Schizophacus reticulatus* (12)
100/15-35-076-04W4/00	354.45 m	Middle McMurray (Hr* Swamp)	Cyst OS1 (1)
100/06-15-076-06W4/00	342.7 m	Middle McMurray (COOP +OS)	*Schizophacus parvus* (1)
102/10-01-077-07W4/00	1130 ft.	Middle McMurray (Hr* Overbank)	*Schizophacus parvus* (3)
	1151 ft.	Middle McMurray (Hr Overbank)	*Schizophacus parvus* (6) *Schizophacus reticulatus* (2) Zygnemataceous spores (1)
	1194 ft.	Pre-McMurray (Hr*)	*Schizophacus parvus* (1) Zygnemataceous spores (1)
100/11-15-077-07W4/00	1089 ft.	Middle McMurray (Hr)	*Schizophacus parvus* (1) *Schizophacus reticulatus* (1)
	1150 ft.	Middle McMurray (Hr)	*Schizophacus* spp. (3)
	1155 ft.	Middle McMurray (Hr)	*Schizophacus* spp. (2)
	1195 ft.	Lower McMurray (Hr)	*Schizophacus reticulatus* (1)
100/11-01-077-08W4/00	1053 ft.	Middle McMurray (NyA)	*Lecaniella foveata* (1)
	1116 ft.	Lower McMurray (Hr*)	*Schizophacus parvus* (1)
1AA/03-12-081-06W4/00	201.96 m	Clearwater (Cd)	*Lecaniella* spp. (1)
	202.66 m	Clearwater (Cd)	*Lecaniella* spp. (1) *Schizophacus* spp. (2)
	217.53 m	Wabiskaw D (OS)	*Schizosporis* spp. (1)
	241.70 m	Middle McMurray (COOP flood into NyR)	Cyst OS1 (2) *Lecaniella* spp. (1) *Schizophacus* spp. (5) *Tetranguladinium* spp. (1)
1AA/05-17-083-06W4/00	309.90 m	Wabiskaw B (COOP)	*Schizosporis* spp. (1)
	339.40 m	Middle McMurray (Hr*)	*Lecaniella* spp. (1) *Schizophacus* spp. (4)
	345.00 m	Middle McMurray (Hr)	*Schizophacus* spp. (2)
	346.45 m	Middle McMurray (Hr)	*Lecaniella* spp. (1) *Schizophacus* spp. (2) *Tetraporina* spp. (1)
100/10-26-083-07W4/00	397.00 m	Middle McMurray (Hr + OS Flood)	*Pediastrum* spp. (1) *Schizophacus* spp. (1) *Schizosporis* spp. (1)
1AA/02-04-090-09W4/00	81.99 m	Middle McMurray (Hr*)	*Schizophacus parvus* (1) Zygnemataceous spores (1)
	115.21 m	Middle McMurray (Hr)	Cyst OS1 (1) *Schizosporis* reticulatus (1)
	121.34 m	Lower McMurray (Hr)	*Schizophacus parvus* (2)
1AE/01-29-092-09W4/00	69.3 m	Middle McMurray (Hr*)	*Lecaniella foveata* (1) Zygnemataceous spores (1)
	87.72 m	Lower McMurray (Hr*)	*Lecaniella foveata* (4)
	106.83 m	Pre-McMurray (? Karst)	*Lecaniella foveata* (1) Zygnemataceous spores (1)
	116.74 m	Pre-McMurray (? Karst)	*Schizophacus laevigatus* (1)
1AB/10-29-092-09W4/00	27.75 m	Upper McMurray (Hr*)	*Lecaniella foveata* (1)
	30.00 m	Middle McMurray (Hr*)	*Lecaniella foveata* (1) *Schizosporis* reticulatus (1)
	34.75 m	Middle McMurray (Hr*)	*Schizosporis* reticulatus (1) Zygnemataceous spores (1)
	42.30 m	Middle McMurray (Hr*)	*Pediastrum* spp. (1)
	53.5 m	Middle McMurray (Hr)	*Schizophacus parvus* (1)
	59.00 m	Middle McMurray (Hr*)	*Schizophacus parvus* (1) Zygnemataceous spores (1)
	61.68 m	Middle McMurray (Hr)	Botryococcus colony (1) *Schizosporis* reticulatus (1)
	83.5 m	Pre-McMurray (? karst)	*Lecaniella foveata* (1) Zygnemataceous spores (1)
	85.6 m	Pre-McMurray (? karst)	*Lecaniella foveata* (1) Zygnemataceous spores (1)
100/05-17-092-17W4/00	232.65 m	Wabiskaw C (OS)	*Schizophacus* spp. (5)
	242.92 m	Wabiskaw D (OS)	Cyst OS1 (1)
	248.20 m	? Middle McMurray (Hr)	*Lecaniella* spp. (1) *Schizophacus* spp. (5)
	254.45 m	? Middle McMurray (Hr)	*Tetraporina* spp. (2)
	259.29 m	Pre-McMurray (? Overbank)	*Tetraporina* spp. (1)
	260.45 m	Pre-McMurray (? karst)	*Tetraporina* spp. (8) Zygnemataceous spores (8)

Table 8 continued.

Core Location UWI	Sample Depth (m or ft.)	Stratigraphic Unit (Palynofacies)	Algae (# of specimens) Total # specimens = 258
1AA/10-26-093-06W4/00	257.34 m	Wabiskaw C (SF)	*Lecaniella* spp. (1)
	264.00 m	Middle McMurray (NyA + minor COOP Flood)	*Lecaniella* spp. (1) *Scenedesmus* spp. (1) *Schizophacus* spp. (1)
	264.03 m	Middle McMurray (NyA)	*Schizophacus* spp. (1)
1AA/10-05-095-05W4/00	244.55 m	Middle McMurray (NyA)	*Lecaniella foveata* (1)
1AA/04-14-095-11W4/00	49.20 m	Middle McMurray (Hr* Overbank)	*Schizophacus parvus* (11) *Schizosporis* reticulatus (4)
	62.05 m	Lower McMurray (Hr*)	*Lecaniella foveata* (1) *Schizophacus parvus* (13) Zygnemataceous spores (2)
1AA/06-36-095-11W4/00	7.70 m	Middle McMurray (NyR Overbank)	*Schizophacus parvus* (2)
	33.2 m	Middle McMurray (? Hr*)	*Schizophacus parvus* (1)
	46.3 m	Middle McMurray (Hr*)	*Schizophacus parvus* (1)
	49.59 m	Pre-McMurray (Hr*)	*Schizophacus parvus* (3) Zygnemataceous spores (2)
1AA/05-01-096-11W4/00	4.7 m	Middle McMurray (Hr*)	*Schizosporis* reticulatus (1)
	6.80 m	Middle McMurray (Hr)	*Schizophacus parvus* (2) Zygnemataceous spores (2)
	17.10 m	Middle McMurray (Hr*)	*Schizophacus laevigatus* (1) *Schizophacus parvus* (2)
	26.10 m	Middle McMurray (Hr)	*Schizophacus parvus* (1)
	39.10 m	Middle McMurray (? Hr*)	*Schizophacus parvus* (1)
	54.70 m	Lower McMurray (Hr* Overbank)	*Schizosporis* reticulatus (2)
	59.6 m	Pre-McMurray (? Hr - ? NyA)	*Schizophacus parvus* (1) *Schizosporis* reticulatus (1)
1AB/16-02-096-11W4/00	5.1 m	Wabiskaw D (COOP)	*Lecaniella* spp. (1)
	8.75 m	Middle McMurray (Hr)	*Lecaniella foveata* (1) *Schizophacus parvus* (1)
	35.70 m	Middle McMurray (Hr* Overbank)	*Schizophacus parvus* (1) *Schizosporis* reticulatus (3)
	59.40 m	Lower McMurray (Hr* Overbank)	*Schizophacus parvus* (1)
	72.8 m	Lower McMurray (Hr* Overbank)	*Schizophacus parvus* (1) *Schizosporis* reticulatus (1) Zygnemataceous spores (2)
	76.00 m	Lower McMurray (Hr* Overbank)	*Lecaniella foveata* (1) Zygnemataceous spores (1)
	79.80 m	Lower McMurray (Hr* Overbank)	*Lecaniella foveata* (3) *Schizophacus parvus* (2)
1AA/09-11-096-11W4/00	40.90 m	Middle McMurray (Hr)	*Schizophacus parvus* (5)
	101.4 m	Lower McMurray (Hr)	*Lecaniella foveata* (1) *Schizophacus parvus* (1)
	111.20 m	Pre-McMurray (Hr*)	*Schizosporis* reticulatus (1) Zygnemataceous spores (1)
1AD/09-12-096-11W4/00	33.10 m	Upper McMurray (Hr*)	*Schizosporis* reticulatus (1) Zygnemataceous spores (1)
	39.60 m	Upper McMurray (Hr Overbank)	*Lecaniella foveata* (1) *Schizophacus parvus* (4)
	70.75 m	Middle McMurray (Hr)	*Schizophacus parvus* (1)
	93.70 m	Lower McMurray (Hr Overbank)	*Schizophacus parvus* (1) *Schizosporis* reticulatus (2)
1AA/09-02-096-12W4/00	88.39 m	Middle McMurray (Hr*)	*Schizosporis* reticulatus (2)
1AA/03-28-096-16W4/00	387.43 m	Upper McMurray (OS)	*Schizophacus* spp. (1)
	388.62 m	Upper McMurray (OS)	*Lecaniella* spp. (1)
	393.63 m	Middle McMurray (NyR/NyA)	*Lecaniella* spp. (1)
	398.25 m	Middle McMurray (NyR)	*Schizosporis* spp. (1)
1AA/11-09-099-15W4/00	428.35 m	Wabiskaw C (SF)	*Lecaniella* spp. (1)
	432.43 m	Wabiskaw D (OS)	*Lecaniella* spp. (1) *Schizophacus* spp. (10) Zygnemataceous spores (2)
	435.63 m	Wabiskaw D (OS + COOP)	*Lecaniella* spp. (1) *Schizophacus* spp. (1)
	444.4 m	Middle McMurray (Hr)	*Schizophacus* spp. (2) *Schizosporis* spp. (1)
1AA/16-17-101-13W4/00	1741 ft.	Middle McMurray (NyR)	*Pediastrum* spp. (1)

Table 9. Summary list of algal remains (excluding dinocysts) for different stratigraphic units from just above the Cretaceous Wabiskaw Member (Clearwater Formation) to the sub-Cretaceous unconformity (see Appendices 4 and 5).

Stratigraphic Unit	Algae	Number of Specimens
Clearwater Formation	*Lecaniella* spp.	2
	Schizophacus spp.	2
Wabiskaw Member	Cyst OS1	1
	Lecaniella spp.	6
	Schizophacus parvus	2
	Schizophacus spp.	16
	Schizoporis spp.	2
	Zygnemataceous spores	2
Upper McMurray Formation	*Lecaniella foveata*	2
	Lecaniella spp.	1
	Schizophacus parvus	4
	Schizophacus spp.	1
	Schizoporis reticulatus	1
	Zygnemataceous spores	1
Middle McMurray Formation	*Botryococcus* colonies	1
	Cyst OS1	4
	Lecaniella foveata	6
	Lecaniella spp.	6
	Pediastrum spp.	3
	Scenedesmus spp.	1
	Schizophacus laevigatus	1
	Schizophacus parvus	45
	Schizophacus reticulatus	15
	Schizophacus spp.	28
	Schizosporis reticulatus	14
	Schizoporis spp.	3
	Tetraporina spp.	3
	Tetranguladinium spp.	1
	Zygnemataceous spores	6
Lower McMurray Formation	*Lecaniella foveata*	11
	Schizophacus parvus	23
	Schizophacus reticulatus	1
	Schizoporis reticulatus	5
	Zygnemataceous spores	5
Pre-McMurray succession	*Lecaniella foveata*	3
	Schizophacus laevigatus	1
	Schizophacus parvus	5
	Schizophacus reticulatus	2
	Tetraporina spp.	9
	Zygnemataceous spores	15
Total Number of Specimens		258

6.2.1 Algae Discussion

Most of the algal remains are from those units for which a freshwater environment is interpreted, including the fluvial and estuarine floodplain, overbank, marsh, swamp; and, for units along the sub-Cretaceous unconformity, including paludal lakes and lacustrine karst (cenotes). Most species, such as *Schizophacus* spp., *Lecaniella foveata*, and Zygnemataceous spores, are long ranging; their absence is likely due to local paleoenvironmental conditions. *Botryococcus* colonies are reported from middle McMurray and pre-McMurray samples; Zygnemataceous spores are reported from all units from pre-McMurray through Wabiskaw; *Tetranguladinium* sp. is rare within the middle McMurray; and, *Schizophacus* spp. range from rare to very abundant from pre-McMurray to Clearwater units, with very common to very abundant frequencies within the middle McMurray samples. *Pediastrum* spp. were recovered from the middle McMurray samples. A new species (Cyst OS1) is recorded from the middle McMurray and Wabiskaw samples. *Schizoporis* spp. are present in the lower McMurray through Wabiskaw samples; and, *Tetraporina* spp. are common in the pre-McMurray samples, rarely present in the middle McMurray (Table 9).

6.3 Dinoflagellate Cysts (Dinocysts)

The name '*dinoflagellate'* comes from the Greek *dinos*, meaning rotation or eddy; and *flagellum*, from Latin, meaning whip, in reference to the dinoflagellate cells' two characteristic flagella (Figure 25) (http://dictionary.reference.com/browse/dinoflagellate). The full name reflects the fact that flagella propel the cell forward in a rotating motion. Dinoflagellate cysts (dinocysts) are found in Middle Triassic to Holocene sediments. The vast majority of dinocysts are found in marine sediment; but they are also known from nonmarine Cretaceous to Holocene strata.

Dinoflagellates are microscopic, single-celled aquatic organisms that belong in the phylum Dinoflagellata. Dinoflagellates have two flagella: a transverse flagellum, which encircles most of the cell, and a longitudinal flagellum, which is inserted in the midventral region and trails posteriorly. Dinoflagellates are both photosynthetic (autotrophic) or predatory on diatoms or other dinoflagellates (heterotrophic); some are both (mixotrophic).

Dinoflagellates are the major component of the marine phytoplankton. Dinoflagellates reach optimal growth with increased sunlight, increased temperature, and increased nutrients within the water column (Taylor, 1987). Dinoflagellate blooms may form locally in areas of enrichment of nutrients, such as in areas of marine upwelling. They tolerate a wide range of temperatures (1–35°C.); and salinities (from freshwater, to brackish, to fully marine); and, as such, may be useful for reconstruction of paleo-oceanographic conditions and paleo-circulation patterns.

Dinoflagellates have a complex life cycle involving both asexual and sexual reproduction, and often with several life-cycle stages. Most dinoflagellates have a motile (swimming) stage; some have a non-motile cyst stage, with the cyst sometimes being preservable in the fossil record (Figure 26) (Bravo and Figueroa, 2014). In the cyst stage, dinoflagellates remain dormant in or on the bottom sediment until conditions for excystment prevail. During excystment, a new motile cell exits the cyst and the empty cyst remains in the sediment (Figure 26). Almost all dinoflagellate fossils are cysts (dinocysts) (Evitt, 1963).

Motile dinoflagellate cells may be unarmoured or armoured; in the latter, the outermost part of the cell (cortex) encompasses a series of separate cellulosic plates, which are arranged in a pattern called tabulation. Tabulation is variable and is the most critical feature in classifying dinoflagellates. Fossil and extant dinoflagellates are classified in a single system (Fensome et al., 1993).

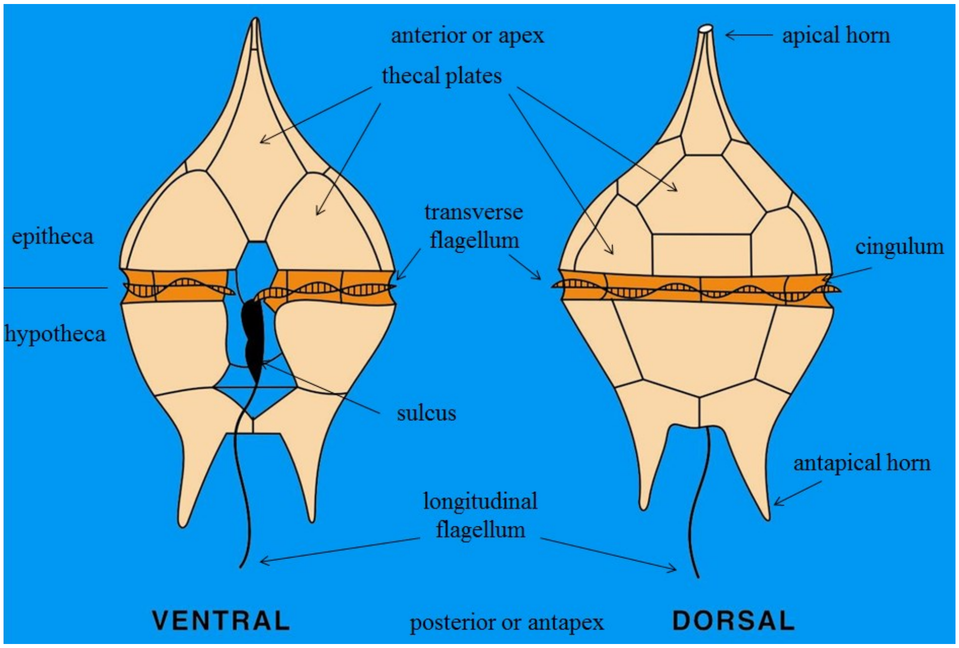


Figure 25. Schematic sketch of the main features and terminologies used to describe a thecate, motile dinoflagellate (used with permission and modified from Fensome et al., 1996, after Evitt, 1961 and 1963).

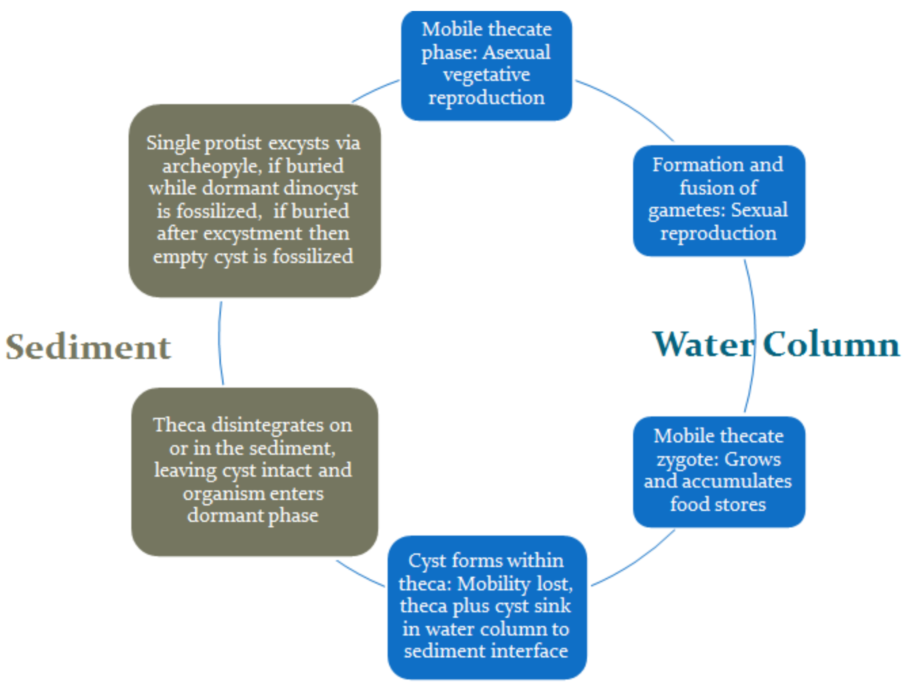


Figure 26. Schematic simplified life cycle of a cyst-forming dinoflagellate. The motile stage is in the water column (right); the non-motile stage is on the sedimentary surface or just below the sediment-water interface (right). If the dinocyst is buried while in the dormant phase, the organism cannot escape and the cyst may fossilize prior to excystment. If the organism exits the cyst (excysts) prior to burial, then only the empty cyst remains to be buried and fossilized (see discussion in Tyson, 1995).

During excystment an opening (called the archeopyle) is created, mainly by the loss of one or more thecal plates in the cyst (Figure 25). Some dinocysts may become fossilized prior to excystment if they become more deeply buried on the seafloor (or lake-bottom for freshwater types).

In general, most dinoflagellates are marine and have a variety of forms and ornamentations (see Downie and Sarjeant, 1965; Fensome et al., 1993; MacRae et al., 1996; Wall et al., 1977). Freshwater (or hyaline) dinoflagellates form 'glassy' (or clear, also called hyaline) cysts or have delicate, thin-walled, cysts. Dinocysts are classified according to various structures and features, primarily according to the tabulation and archeopyle types; then according to wall structure, shape, ornamentation, and composition and opacity of the wall of the cyst (i.e., calcareous and translucent vs. non-calcareous and transparent). (Figure 27) (Downie et al., 1961; Downie and Sarjeant, 1965; Fensome et al., 1993, 1996; Sarjeant, 1982; Williams et al., 1978).

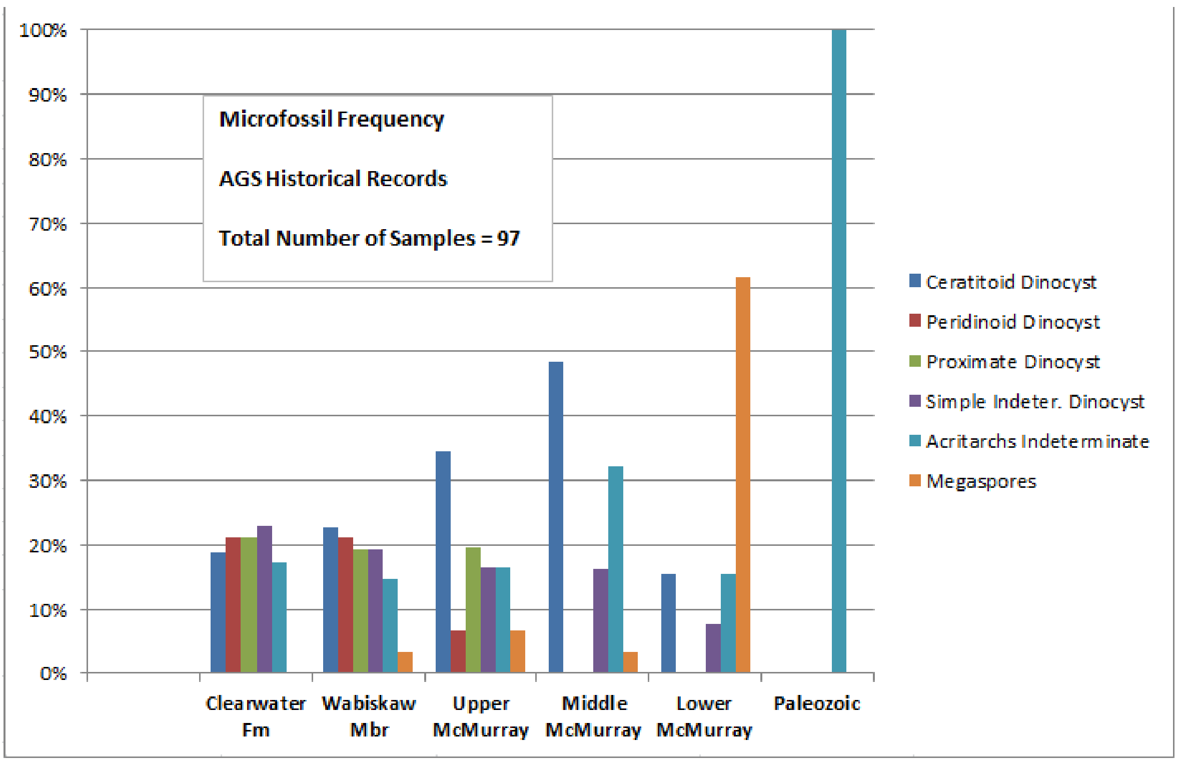


Figure 27. Composite histogram showing the frequency of the main types of microfossils by stratigraphic level within the Athabasca Oil Sands Area. This compilation is based on 97 mudstone-sample analyses from unpublished historical records in government files at the AGS (Appendices 1 and 3, pre-1999). For each sample a count of 200 specimens was made to determine the overall composition of the microfossil assemblage.

In the AGS historical records (Appendices 3 and 4) six major types of dinocysts were recorded: ceratioid; chorate; hyaline; peridinoid; proximate-gonyaulacoid; and, simple, indeterminate. Additionally, a final type (called the 'unassigned') was created for those undefined forms, which do not fall under existing classification schemes.

- Ceratioid dinocysts first appeared in Late Jurassic time and declined through the Late Cretaceous (Harding and Hughes, 1990). Modern ceratioid dinoflagellates do not produce cysts that are resistant to geochemical processes associated with diagenesis and are not considered 'fossilizable' (Harding and Hughes, 1990). Ceratioid dinocysts have a rhomboidal central form, with the development of broad-based horns. The tabulation pattern of ceratioid dinocysts is similar to that of the modern *Ceratium* genus (Bint, 1986; Wall and Evitt, 1975).

- Chorate dinocysts are nearly spherical bodies, with prominent projecting parts (called processes) and crests. The chorate dinocysts develop within the original motile cell and are connected to the original motile cell wall by the different processes. After the cyst is developed the original cell wall (theca) disintegrates, leaving the spherical form with projections and crests. In these cysts the ornamentations have a maximum height exceeding 30% of the minimum diameter of the central body. There may be a slight correspondence between dinocyst ornamentation and that of the original motile theca (Sarjeant, 1982).

- Proximate dinoflagellates form the cyst wall immediately within the theca, such that the cyst wall is in contact with the wall of the original motile cell. Proximate dinocysts tend to lack surficial ornamentation; if outgrowths occur, their maximum height is less than 10% of the minimum diameter of the central body (Sarjeant, 1982).

In general there is a lack of information on the distribution of fossil dinoflagellates from freshwater settings, compared to the wealth of information regarding both recent and fossil marine dinoflagellate taxa (Drljepan, 2014; Mertens et al., 2012; Tardio et al., 2006). Hyaline dinocysts are clear (transparent or nearly so, also called glassy), thin-walled; and, along with the simple, indeterminate, thin-walled types, are considered freshwater in origin. Other freshwater types include the *Peridinium* dinoflagellate genus. Most cysts from the peridinoid dinoflagellates are ellipsoidal, oval, circular, or have a 'peanut' shape. In some cases vestigial thecal patterns are preserved on the cyst wall.

Studies of the modern Lake Kineret (Sea of Galilee, Israel) and Lake Nero di Cornisello, Italy, indicate that locally *Peridinium* populations can tolerate a wide range of freshwater settings. The Sea of Galilee is in a semi-tropical climate, with hot summers and cool, rainy winters, and has been naturally eutrophic for a long time (Berman, 1972). In Lake Kineret, during certain months, the *Peridinium* populations may reach extremely high levels, which impart a brown-red colouration to the water (called a 'red tide').The red-tide event results in a "flood" of deposition of cysts on the lake floor sediment. By contrast, Lake Nero is a high-alpine lake, with low alkalinity, with freshwater input due to precipitation and runoff from small rivulets during the warm 4 to 5 months of summer; with no input during the remaining seven to eight months when the lake surface is frozen (Tardio et al., 2006, 2009).

Differentiation of fossil freshwater dinocysts from fossil marine dinocysts is not always straightforward (Batten and Lister, 1988; Mudie et al., 2004). In 2013 an example of a calcareous dinocyst was reported from a new freshwater dinoflagellate species (Craveiro et al., 2013). Prior to this discovery, most calcareous cysts were thought to have been produced by marine peridinoid dinoflagellates, from cold through tropical marine settings. The oldest freshwater dinocysts are from Lower Cretaceous (Barremian-age) deltaic pond deposits, from the English Wealden, which comprise an assemblage from the ceratioid group (including *Nyktercysta* and *Balmula* genera) (Batten, 1985, 1989; Martín-Closas, 2003).

6.3.1 Dinocyst Discussion

Using the AGS historical records, a summary of the main types of dinocyst microfossils (along with acritarchs and megaspores) within the Clearwater to pre-McMurray successions for the Athabasca Oil Sands Area is shown in Figure 27. Individual species lists and frequencies per sample are in Appendix 3.

Overall, the frequency of different dinocyst types in most of the Clearwater, Wabiskaw and upper McMurray samples range from ~3% to ~20% of palynomorph content. Exceptions include floods of ceratitoid dinocysts in the upper and middle McMurray samples, which exceed 30% in the upper McMurray and approach 50% in the middle McMurray samples. Peridinoid and proximate dinocysts were not recorded in the middle and lower McMurray samples. In comparison to the acritarchs and megaspores, the dinocysts show a more uniform frequency distribution within the different stratigraphic units. The one Paleozoic sample only contained acritarchs. The acritarch frequency likely reflects an influence of reworked Devonian material up into the overlying Cretaceous successions, as shown by the ubiquitous presence of acritarchs throughout the units, as well as the marine influence within the successively more transgressive record from lower McMurray to Clearwater time.

At the beginning of the litho- and biostratigraphic regional work (which began in 1997), it was hoped that palynological analyses, including a specific breakdown of the different dinocyst types (Figure 27), would help determine and map sedimentary units deposited in freshwater, brackish and/or marine water. Initial palynological work did follow these designations, but it was concluded (using a broader distribution of samples) that the dinocyst classification as described above was not sensitive enough to ascertain paleosalinities within the Wabiskaw–McMurray succession. For this reason, all available sample slides were recounted and reanalyzed with regard to a breakdown of dinocysts according to the following broad types: brackish, freshwater, marine and indeterminate. These results are included along with individual biostratigraphic charts per well in Appendix 5. Results will be discussed in the section on palynofacies (Section 7), with consideration of the main different types of dinocysts, along with the occurrences of other palynomorphs, such as spores and pollen, and microfossils, such as acritarchs, fungi, megaspores, and wood.

6.4 Fungi

Fungi are a major group of parasitic and saprophytic (living on dead or decaying material) organisms which lack chlorophyll, and includes mildew, molds, mushrooms, and certain bacteria. A small number of cores had Fungae spp. recorded in the palynomorph analyses. These include 30 specimens of *Multicellaesporites* spp. from the upper McMurray unit in the 00/15-35-076-04W4 core (depth 354.45 m, palynofacies Hr*); one specimen of *Multicellaesporites* spp. from the middle McMurray unit in the 100/11-15-077-07W4 core (depth 1155 ft., palynofacies Hr); and, rare (1–3) specimens from the upper and middle McMurray units in the AB/10-29-092-09W4 core (depths 27.75–34.75 m, palynofacies Hr*; and 61.68–69 m, palynofacies Hr* and Hr) (Appendix 5). No fungi were recorded in the pre- or lower McMurray successions.

6.5 Spores, Megaspores, and Pollen

The word '*spore*' comes from New Latin *spora* or Greek *sporá,* both meaning 'seed,' 'to sow', or 'sowing' (http://dictionary.reference.com/browse/spore). Spores are part of the life cycle of many algae, fungi, bacteria, protists, and seedless, nonflowering plants. Spores originated in the Late Ordovician period and extend to the Holocene. Pollen range in age from Carboniferous (Mississippian and Pennsylvanian) to Holocene.

The spore is a unicellular reproductive body that can grow into a new organism without merging with another cell; and, as such, is haploid (i.e., has only one set of chromosomes). A spore can develop into a sporeling, whereas gametes need to fertilize to produce zygotes, which then develop into sporophytes. Under favourable conditions, spores develop into multicellular gametophytes (Figure 28). Two different gametophytes merge to form a zygote, which then forms a new sporophyte. Seed-bearing plants are heterosporous, producing spores of two sizes and types – the larger "female" (megaspore) and the smaller "male" (microspore). Megaspores develop into female gametophytes, which eventually produce eggs. Microspores develop into male gametophytes or pollen grains. Pollen is produced by seed-bearing plants—both gymnosperms and angiosperms (flowering plants).

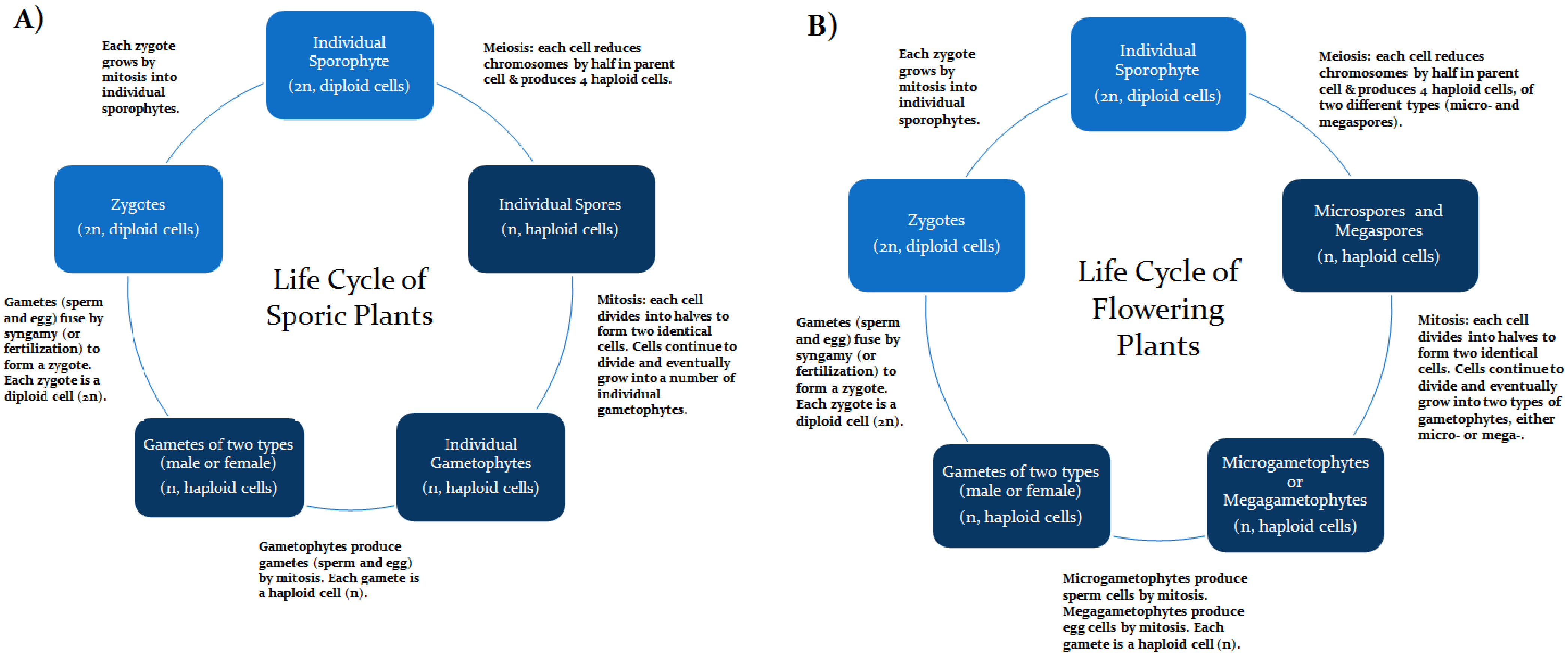


Figure 28. Simplified schematic life cycle of plants: A) Sporic plants. Alternation occurs between spore-forming sporophytes, which reproduce asexually and gamete-producing gametophytes that reproduce sexually. In modern ferns, the sporophyte is a diploid (2n) plant that through meiosis produces haploid (n) spores from sacs underneath the leaves. These are ejected and fall to the ground, which if damp enough, germinate into gametophytes (haploid, n stage). Two gametophytes join to form a zygote (2n stage), which then grows into an individual sporophyte, and the cycle is repeated; B) Flowering plants. These differ from sporic plants in that they produce two types of spores, which grow into two different types of gametophytes that produce either sperm or egg cells. In modern plants what we see as a flowering plant is the sporophyte. Spores in the sporic plants, microspores (male in flower plants), and megaspores (female in flowering plants) are all found as microfossils in palynological analyses.

The field of palynology encompasses both geological and biological perspectives, and classifications and their use(s) depend, in part, upon the purpose of the palynological work. In most geological studies the aim of palynological analyses is to aid in deciphering the biostratigraphy, that is, the relative age and correlation of different stratigraphic units, using the fossils and/or microfossils present in the different strata. Using Linnaean nomenclature, biologists classify forms into a basic "species" taxon, followed by genus, family, order, etc. The fossil record is inherently incomplete; such that palynologists may not have sufficient empirical evidence or understanding to subdivide spores, megaspores or pollen beyond the generic level. As discussed by Jansonius (1981) generic grouping of ancient spores or pollen may include fossils from plants that are not directly related to one another. If no difference is seen in the morphological features of the preserved spores or pollen, then there can be no basis for further subdivision of the genera. In biostratigraphic work on ancient spores and pollen, classifications are largely based on morphological features of the spores and pollen grains, including: i) size and shape of the body of the grains; ii) presence of an aperture(s), or absence (inaperturate); iii) if present, the number, shape (length and breadth, round, oval or slit-like) and location of the aperture(s) (polar, zonal, global) (Figure 29); iii) type and thickness of wall; iv) type and pattern of wall stratification, markings, sculpture or ornamentation; v) presence or absence of air sacs attached to a central body; vi) if present, number of air sacs (or bladders), most commonly one or two (bisaccate); rarely, three.

In the present study, eight major types of spores and pollen were recorded: i) angiosperm pollen; ii) bisaccate pollen; iii) *Classopollis* spp.; iv) gymnosperm pollen; v) megaspores; vi) pteridophyte spores; vii) schizaceous spores; viii) the species *Taxodiaceaepollenites hiatus* (because of its environmental implications, discussed later*)*; along with numerous genera and species that are listed for each sample in Appendix 5. A description of some of the important temporal (age-related) and environmental implications of the presence of the major types of plants, spores and pollen are given next.

- Angiosperm pollen comes from flowering and fruit-bearing vascular plants in which mature seeds are protected by ovules which are enclosed in an ovary, which upon fertilization develop into fruit. Fossil evidence indicates that angiosperms first evolved in the Lower Cretaceous (~125 million years ago), in which the use of flowers and sugary nectar attracted insects for pollination, and fruit consumption by animals resulted in seed dispersal. By Middle Cretaceous (~100 million years ago) there was rapid diversification of angiosperms. Today most plant species (~80%) are angiosperms, which dominate temperate and tropical environments (Bond, 1989). Angiosperms include herbaceous plants, roses, shrubs, grasses and deciduous hardwood trees such as oak, maple and dogwood, that have broad leaves which change colour and die in the autumn. Other angiosperms, including rhododendron, live oak and magnolia do not lose their leaves with the seasons.
- Bisaccate pollen originate from coniferous trees, including spruce, pine, and podocarpus, among others. Pollination of conifers depends upon the wind. Bisaccate grains consist of a central body, with two attached bladders. Bisaccate grains may be indicative of long-distance transport, and its presence represents a hinterland (upland) contribution (Dolby et al., 2013). Bisaccate grains range in age from Pennsylvanian (Late Carboniferous) to the recent.
- *Classopollis* spp. pollen is Mesozoic pollen, largely spherical in shape that has a thickened girdle along the equator, and a proximal tetrad scar. The plants that produced this pollen prefer arid to semi-arid paleoenvironments (Filatoff, 1975); hence, the presence of pollen of this type in significant numbers indicates an arid/semiarid hinterland contribution.

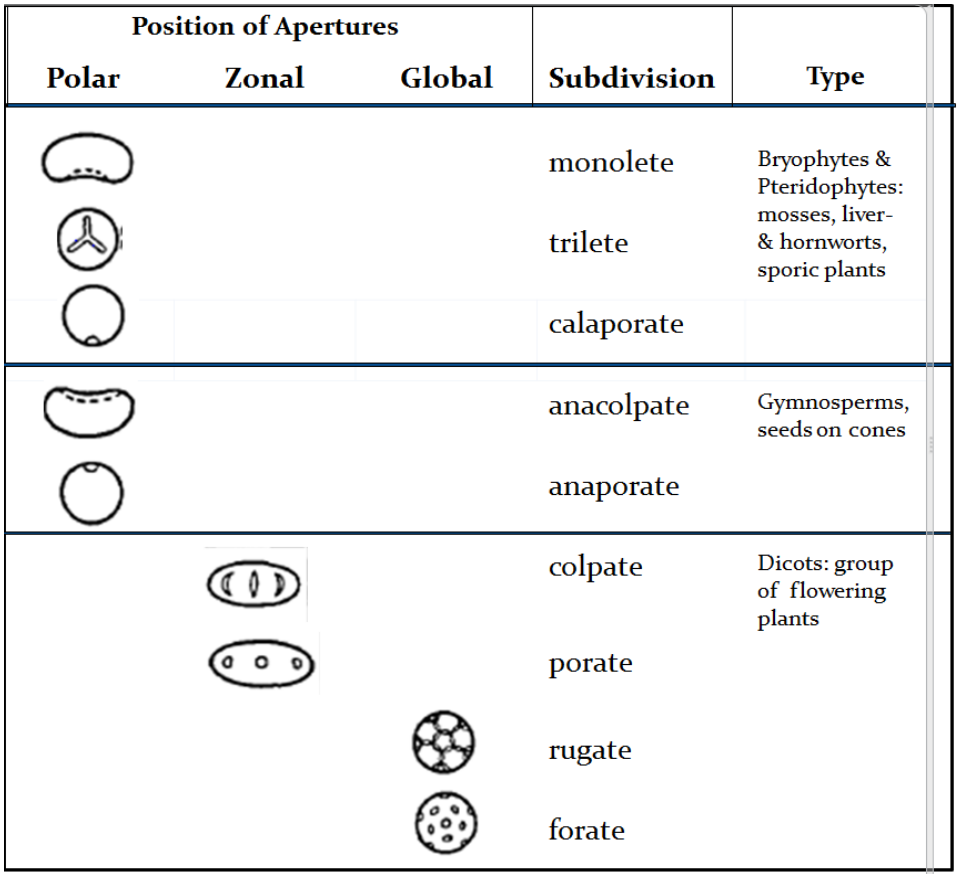


Figure 29. Classification of pollen and spore morphology based on apertures (from Erdtman and Vishnu-Mittre, 1958; modified from earlier classifications of Faegri and Iversen, 1950; Iversen and Troels-Smith, 1950; and Erdtman, 1952). For other descriptions of pollen analysis, see Hoen (2016, updated from Punt et al., 1994, and Reitsma, 1970).

- Gymnosperm pollen comes from seed-bearing plants, in which the seeds are not protected by fruit or by an ovary. Gymnosperms include gingkoes, cycads and conifers. The seeds may develop on scales or leaves, at the ends of stalks, or within cones. Gymnosperms are all woody plants, are perennials, and have a relatively long reproductive cycle (compared to angiosperms). The maximum growth rate of gymnosperms is slower than the maximum growth rate of angiosperms; and, in well-lit, well-watered environments, gymnosperm seedlings may be uncompetitive (Bond, 1989). In modern day environments (dominated by angiosperms) gymnosperms are very common to dominant in high-latitude, high-elevation settings with nutrient-deficient soils (Bond, 1989). In past environments, when angiosperms were not predominant, gymnosperms may have had a wider geographic range. Gymnosperms range in age from the late Carboniferous to the recent.
- Pteridophyte spores come from free-sporing vascular plants (with a xylem and phloem) that lack flowers and seeds, and reproduce by spores. The group includes ferns and horsetails (monilophytes, related to seed plants) as well as club mosses, spike mosses and quillworts (lycophytes). Since this group includes two unrelated phylogenetic groups, the term is considered to be an ‘informal’ designation. Pteridophytes can occur in a variety of alluvial settings; where abundant to predominant, pteridophyte spores indicate a nearby swamp or marsh paleoenvironment (Dolby et al., 2013).

- Schizaceous spores are from ferns that occur in paleoenvironments with alternating flooding and drying-out cycles (Dolby et al., 2013).
- *Taxodiaceaepollenites hiatus* (TCT pollen) belongs to the Taxodiaceae group, and along with other inaperturate (i.e., lacking apertures) pollen, is indicative of lowland, floodplain swamp settings (Dolby et al., 2013).

A summary of the main types of spores and pollen types within the pre-McMurray to Clearwater successions in the study area are given in the histograms in Figure 30 through Figure 35. Individual species lists and frequencies per sample are in Appendix 5.

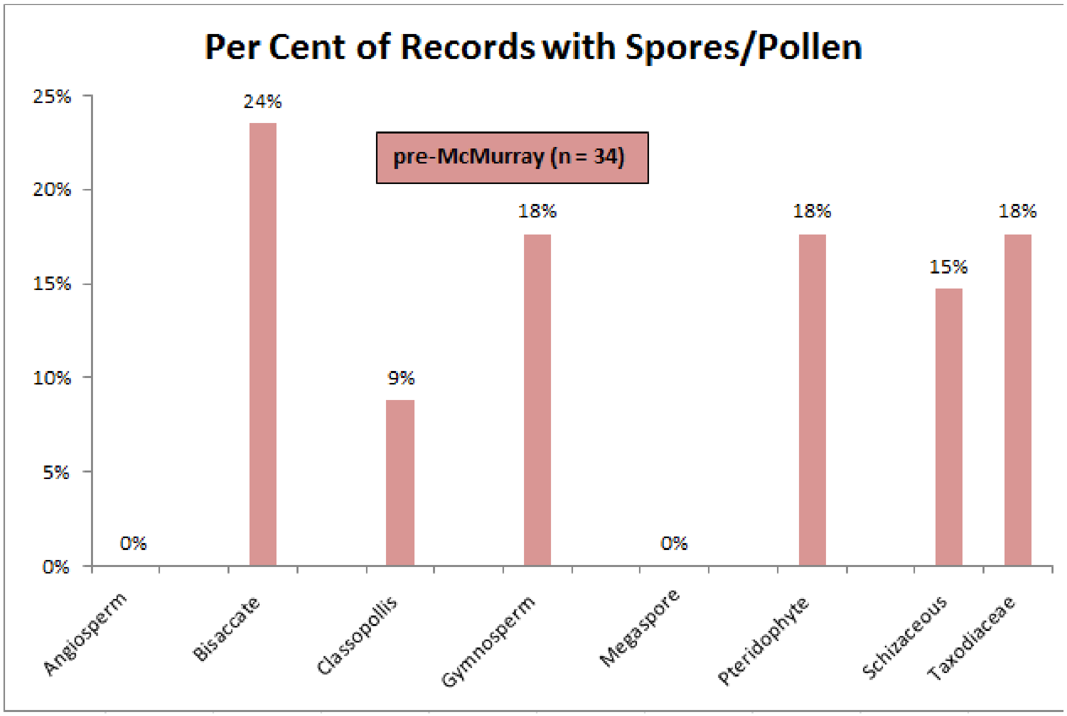


Figure 30. Histogram of the relative frequency of different spore and pollen types in the pre-McMurray succession; n is the number of records. A record refers to an instance where the presence of a specific spore/pollen type was noted (without necessarily saying how many specimens were counted in each sample). Histograms are presented in this way because not all of the palynological records indicated the number of specimens per sample; in some cases, only the presence was noted (see Appendix 5).

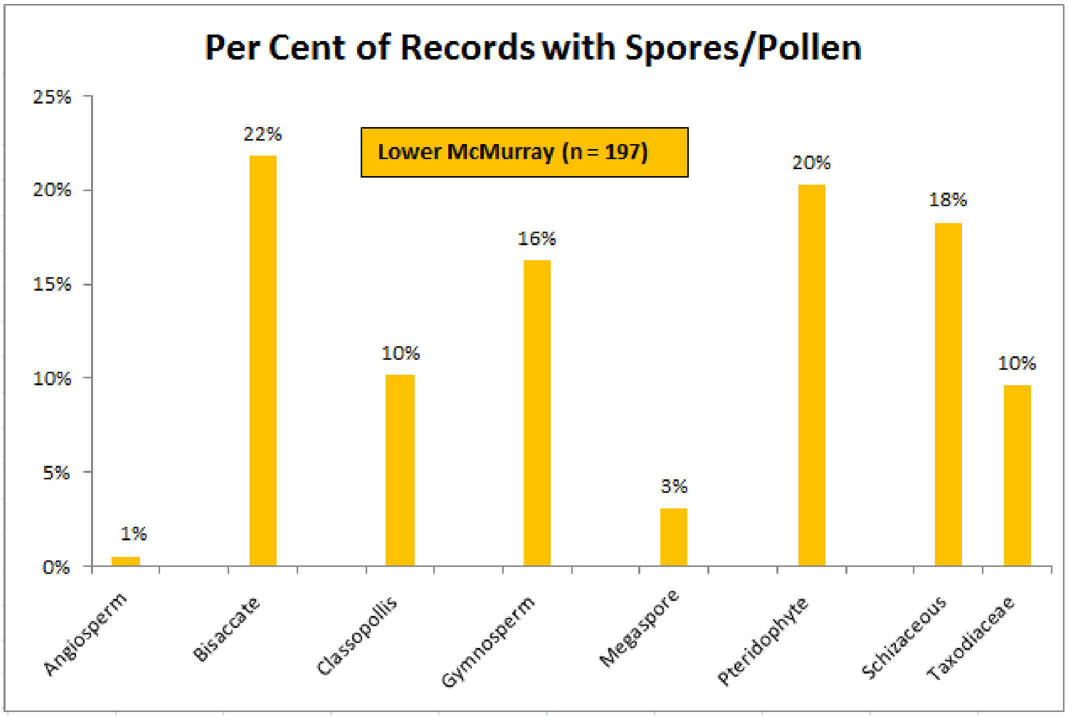


Figure 31. Histogram of the frequency of different spore and pollen types in the lower McMurray succession; n is the number of records (see caption for Figure 30).

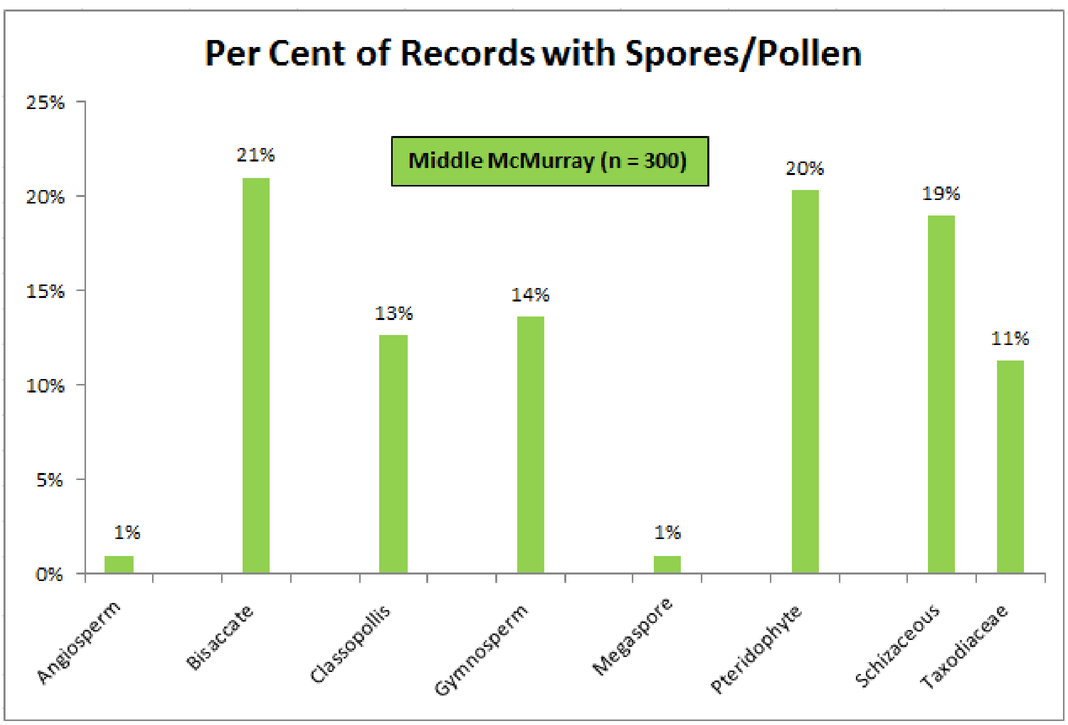


Figure 32. Histogram of the frequency of different spore and pollen types in the middle McMurray succession; n is the number of records (see caption for Figure 30).

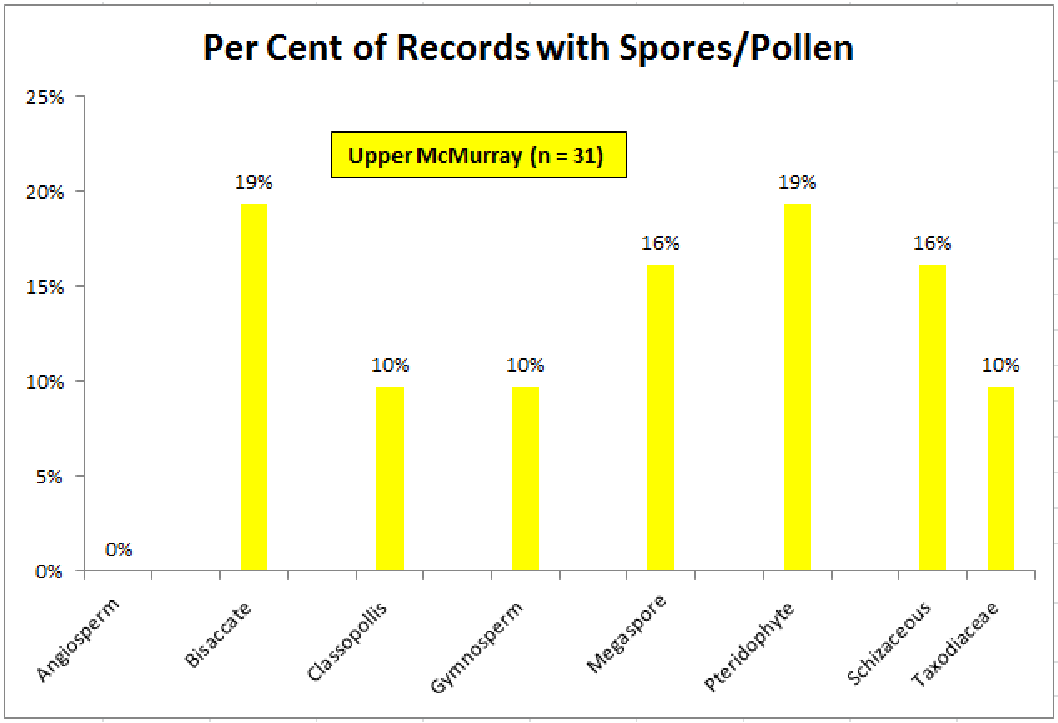


Figure 33. Histogram of the frequency of different spore and pollen types in the upper McMurray succession; n is the number of records (see caption for Figure 30).

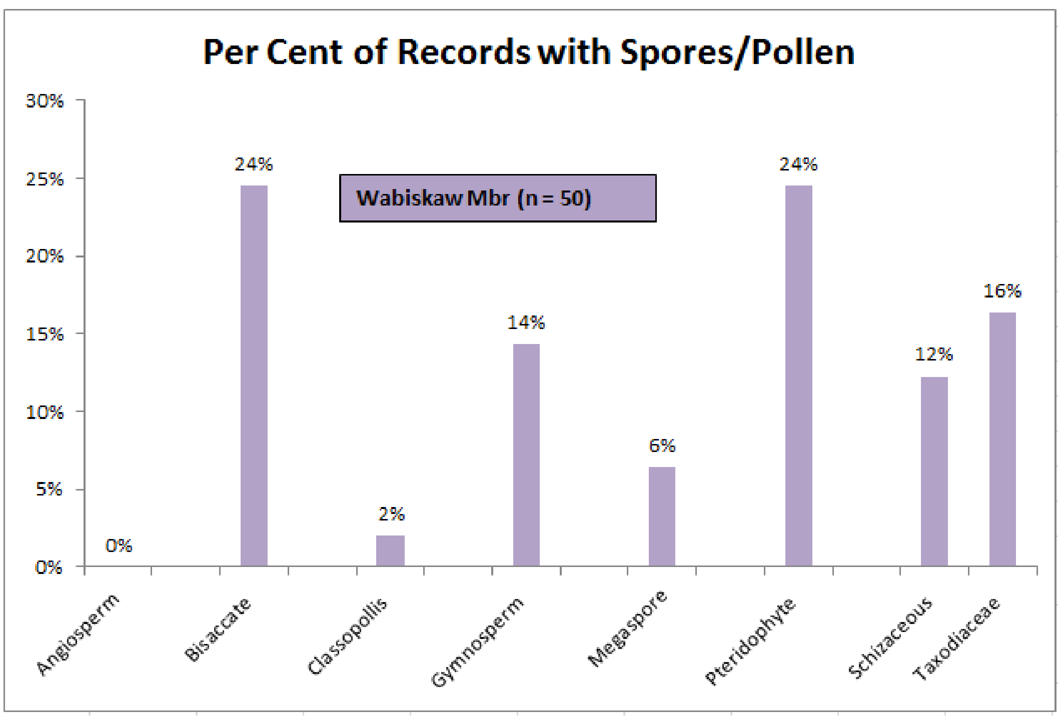


Figure 34. Histogram of the frequency of different spore and pollen types in the Wabiskaw Member succession; n is the number of records (see caption for Figure 30).

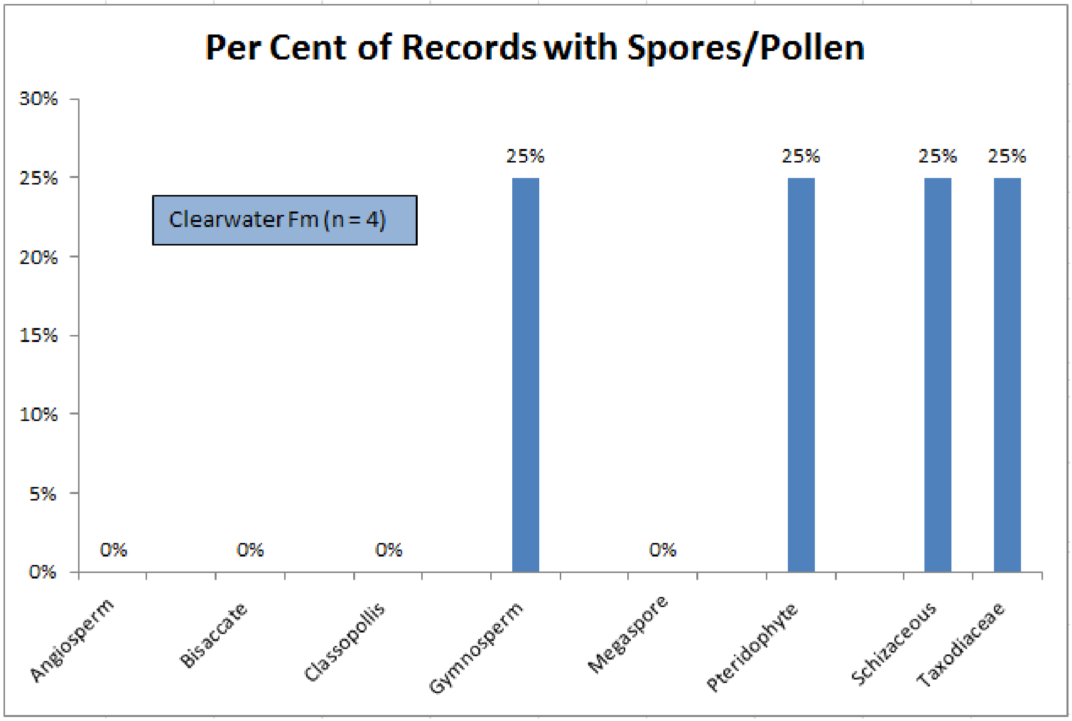


Figure 35. Histogram of the frequency of different spore and pollen types in the Clearwater Formation succession; n is the number of records (see caption for Figure 30).

6.5.1 Spores, Megaspores, and Pollen Discussion

Angiosperm and megaspore fossils were not recorded in the pre-McMurray succession (Figure 30). The bisaccate pollen are the most common type in the pre-McMurray unit, occurring as dominant to predominant types in the samples in which they are recorded. In other samples bisaccate pollen are common to very abundant. The remainder of the other types of spores and pollen are about equally represented, with the exception of *Classopollis* spp., which accounts for <10% of the spore and pollen occurrences. Pteridophyte spores are common to predominant; schizaceous ones very rare to extremely abundant or dominant; and taxodiaceae pollen types are very rare to rare, or recorded as "present in sample." Megaspores have a low level of occurrence (<10%), with the exception of flood samples within the lower McMurray, where frequencies attain 60% of individual samples.

By comparison, the lower and middle McMurray successions have increased numbers of megaspores (1–3%) (Figures 31 and 32), with a presence of angiosperms. Bisaccate pollen is the most common type (21–22%), with less common occurrences of pteridophyte (20%), schizaceous (18–19%), and gymnosperm (14–16%) types. *Classopollis* spp. comprise 10–13% and the taxodiaceeous pollen 10–11%. Most of the different pollen and spore types in the lower and middle McMurray successions have a wide range of frequencies between different samples, from "present in a sample" to predominant or dominant in other samples. Exceptions are the angiosperms, which are rare to very rare; and the megaspores, which range from very rare/rare to common.

Angiosperm pollen were not recorded in the upper McMurray samples (Figure 33). Bisaccate pollen decreases to <20% and gymnosperms to ~10% in the upper McMurray units, with a corresponding increase in megaspores (16%). The pteridophyte spores (19%), *Classopollis* spp. (10%) and Taxodiaceae group (10%) remain about the same as in the lower and middle McMurray successions. Compared to the upper McMurray, the Wabiskaw Member has more bisaccate pollen (24%), gymnosperm (14%), pteridophyte (24%), and taxodiaceous (16%) types (Figure 34). These increases correspond to a drop-off in *Classopollis* spp. (2%) and schizaceous (12%) spores. Only one Clearwater Formation sample was analyzed in the present study and contains equal proportions of gymnosperm, pteridophyte, schizaceous, and taxodiaceae types (Figure 35), most of which were rare to very rare. The exception is the pteridophyte spores which were abundant in the Clearwater sample.

When one considers the shape of the spore and pollen frequency histograms for the McMurray Formation (not taking into account absolute numbers or abundances), many of the spores and pollen show a similar distribution for the different stratigraphic subdivisions of the McMurray Formation (lower, middle, upper) (Figures 31 to 33). This contrasts with the frequency distribution of dinocysts and algae (Figure 27), which tend to show slightly more differentiation between the stratigraphic units.

This lack of specific histogram shapes of spore or pollen distributions for the individual stratigraphic units in the McMurray Formation is likely a result of the strong hinterland contribution of spores and pollen to the entire McMurray succession. As shown by modern studies, pollen and spores derived from terrestrial land masses are the most common microfossils in both continental and marine sediments; and, many have been transported over very long distances (Mudie, 1982). The dominance of the bisaccate pollen along with abundant pteridophyte spores tends to overwhelm the other types and does not take into account individual genus or species which may be important from both a biostratigraphic as well as paleoenvironmental perspective. Furthermore, from a sedimentological and paleontological perspective, proximal to distal variations from the lower to middle to upper McMurray successions may be cryptic, and brackish-water influences may be difficult to differentiate from marine-water systems from the sedimentological and spore/pollen record. A different approach uses both the abundances and types of the main microfossils, as well as 'indicator' species and genera, through the identification of palynofacies and their stratigraphic distributions through time (Demchuk et al., 2005, 2008; Dolby et al., 2013). Other techniques, such as the use of strontium isotopes can be used to determine the paleosalinities of ancient successions (Holmden et al., 1997); but this was beyond the scope of the more conventional sedimentological and paleontological analyses that were done in the present work.

7 Palynofacies and Palynostratigraphy

7.1 Definition of Palynofacies

The term 'palynofacies' was originally defined by Combaz (1964) to refer to the total organic content of a palynological assemblage (organic, non-mineralized microfossils from the acritarchs, algae, dinoflagellate cysts, fungi, spores and pollen). Palynofacies data can be used to determine the paleodepositional environments and paleoclimate (Highton et al., 1991; Lorente, 1990; Whittaker, 1984); to assess source-rock potential (Batten, 1982); and, along with other sedimentological and ichnological features, can be used to help define biostratigraphic zones. From the perspective of sedimentary environments and facies analysis, the palynofacies scheme relies on a combination of the overall morphology of the organic material and microfossil remains (applying the taxonomic scheme, using the Linnaean classification system of genus and species, discussed above) and inferred associations of the preserved organic material(s) to the life cycle of the organism(s) and their depositional environment. In the present discussion, we are more concerned with using the palynology to solve sedimentological (i.e., paleoenvironmental interpretation) and stratigraphic (i.e., chrono- or sequence-stratigraphic delineation) problems. Despite this emphasis in the present work, the organic material and microfossils that are preserved are paleontological remains; the systematic description, paleontological classification and interpretation of the different genera and species are given elsewhere (Dolby, 2014; Dolby et al., 2013; also see Section 2).

Dolby et al. (2013) defined palynofacies for the Wabiskaw–McMurray succession in the Surmont Lease and other subsurface lease areas of the Athabasca Oil Sands Area, west and south of Fort McMurray, AB (from Township 70 to 90; Ranges 3 to 17, west of the 4th Meridian). A variety of palynofacies occur on a continuum from fresh-water to brackish-water to normal marine salinity, interpreted as representing backwater and hinterland areas to fully marine conditions in the open Western Interior Seaway (Figure 4, Plate 1). Using this scheme, the following palynofacies are recognized (Figure 36).

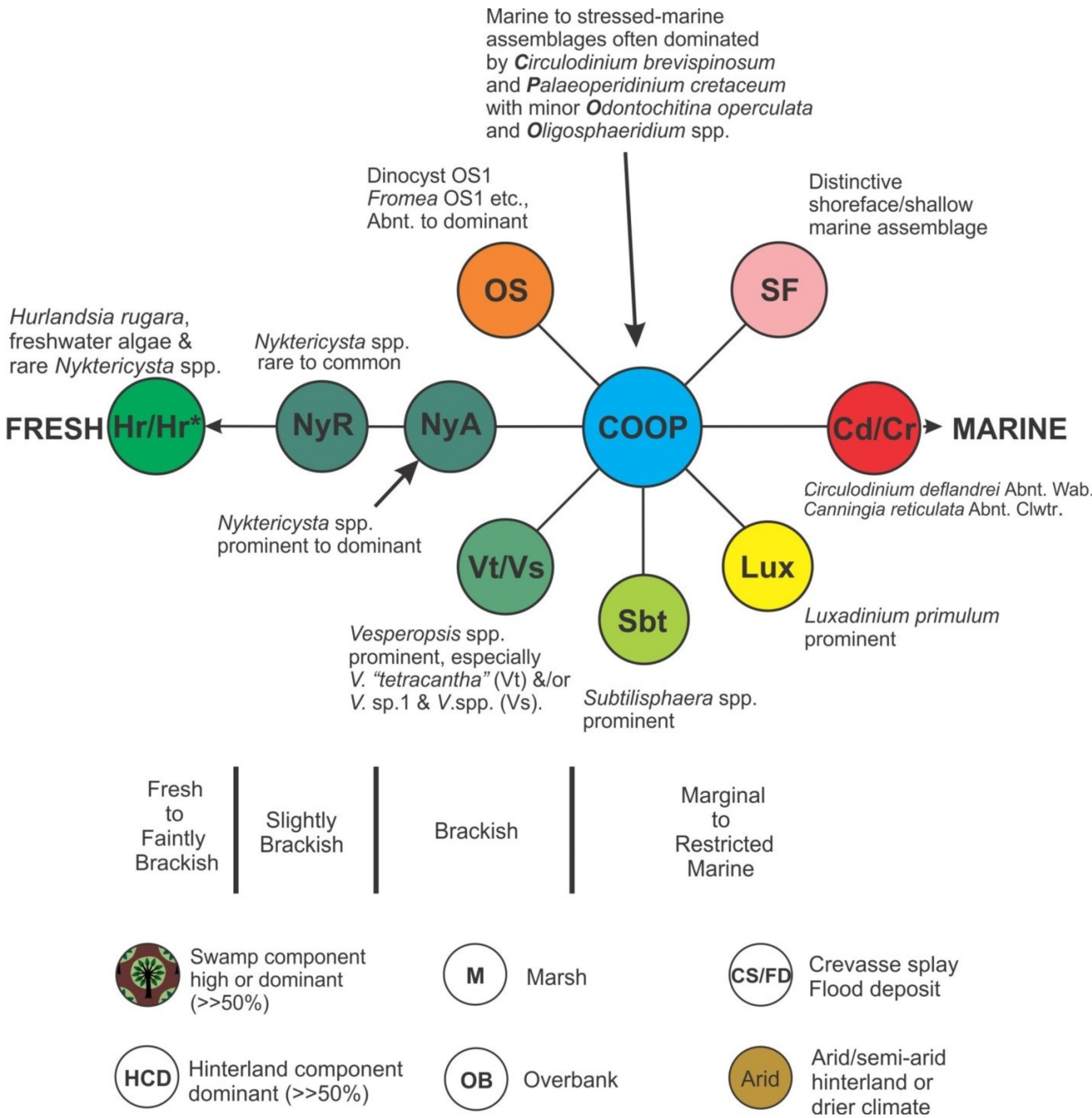


Figure 36. Palynofacies scheme (also called COOP diagram) for the Wabiskaw–McMurray succession, Athabasca Oil Sands Area (see text).

7.1.1 Hr /Hr*Palynofacies

The Hr palynofacies is characterized by the freshwater dinocyst *Hurlandsia rugara,* along with rare *Holmewoodinium spp.* Other freshwater algal remains are present, including: *Lecaniella foveata*, *Schizophacus parvus, Schizophacus reticulatus, Schizoporis* sp., *Tetranguladinium* sp., and *Zygnemataceous* spores (Appendix 5). In some wells, *Botryococcus* is present. Hyaline and simple, indeterminate, thin-walled dinocysts are also present in the Hr palynofacies. *Nyktericysta* spp. is a rare constituent, and, when it occurs, tends to have very simple or general forms. The Hr palynofacies is interpreted as a continental, freshwater deposit. The difference between the Hr and Hr* palynofacies is that the Hr* palynofacies contains no specimens of *Hurlandsia rugara* or any other dinocysts, but may contain freshwater algae, fungi, spores and pollen. Hr* is interpreted as freshwater and therefore Hr equivalent, from a paleoecological perspective.

7.1.2 NyR Palynofacies

The NyR palynofacies has a small number of *Nyktericysta* spp. commonly present, with a smaller number of freshwater dinocyst *Hurlandsia rugara* and other freshwater algal remains, more typical of the Hr palynofacies. In general, although small numbers of *Nyktericysta* specimens are present, the palynomorph assemblage is dominated by terrestrial pollen and spores. The NyR palynofacies is interpreted as representing the upper reaches of estuaries, with slightly brackish salinities. Based upon bimodal sorting of kerogen, there is interpreted to be some current activity, likely associated with tidal influences in the upper estuarine settings (see also Hein, 2015). Rare to small numbers of marine dinocysts, which belong to the COOP-palynofacies described later, may be present. These are interpreted to have been emplaced during flooding events.

7.1.3 NyA Palynofacies

The NyA palynofacies has very high (very abundant to predominant) numbers of *Nyktericysta* spp. Identified species include: *Nyktericysta arachnion, N. davisii,* and *N. tripenta (*formerly *Balmula tripenta)* (Appendix 5). Biodegradation is commonly observed on the dinocysts and the kerogen. As with the NyR palynofacies, rare or small numbers of marine dinocysts (typical of the COOP palynofacies) may be present within the NyA palynofacies. The NyA is interpreted to be indicative of brackish lakes and bays or upper lagoonal settings, which had, at times, some connection to (or influx from) more saline marine waters.

7.1.4 OS Palynofacies

The OS palynofacies is characterized by a very high number (abundant to predominant) assemblage of largely undefined (undescribed) dinocysts (Dinocyst OS1 and *Fromea* OS1), along with variable numbers of marine dinocysts specimens from the COOP palynofacies. The salinity is interpreted to be higher than that favoured by the NyA and NyR assemblages. The palynofacies is interpreted to be indicative of a brackish, restricted, marginal marine setting.

7.1.5 V Palynofacies

The V palynofacies has numerous (very common to abundant) numbers of *Vesperopsis* spp. Identified species include: *Vesperopsis longicornis* and *Vesperopsis mayi*, along with undefined forms (V. sp. 1) (Appendix 5). The V palynofacies is interpreted to be from brackish-water settings, with salinities in between those interpreted for the OS and NyA palynofacies.

7.1.6 COOP Palynofacies

The COOP palynofacies is characterized by a highly distinct group of palynomorphs, with the dominant forms including: ***C****irculodinium brevispinosum* and ***P****alaeoperidinium cretaceum*, with relatively minor ***O****dontochitina operculata* and ***O****ligosphaeridium* spp. Other identified species include: *Circulodinium deflandrei, Odontochitina costata, Oligosphaeridium albertense, Oligosphaeridium anthophorum, Oligosphaeridium complex, Oligosphaeridium pulcherrimum,* and *Oligosphaeridium totum.* Along with the dominant COOP palynomorphs is a whole array of other marine species, which occur in relatively small numbers (Appendix 5). In general, the COOP palynofacies is interpreted as representing generally marginal-marine to shallow-marine settings. When numbers of *C. brevispinosum* and *P. cretaceum* begin to dominate or predominate an assemblage, then the conditions are interpreted to be more restricted and stressed, with likely reduced salinities (see Harding, 1990). Such marginal-marine settings would include: the lower parts of estuaries, the distal (seaward) ends of marginal-marine lagoons, and the landward part of back-barrier bays.

7.1.7 Sbt Palynofacies

The Sbt palynofacies is essentially a subset of the COOP palynofacies, but has abundant *Subtilisphaera* spp. The Sbt palynofacies is interpreted to be indicative of a stressed and restricted (compared to COOP), marginal- to shallow-marine environment.

7.1.8 Lux Palynofacies

The Lux palynofacies is another subset of the COOP palynofacies (similar to the Sbt palynofacies), but has abundant *Luxadinium primulum*. Like the Sbt palynofacies, the Lux palynofacies is interpreted to be indicative of a stressed and restricted (compared to COOP), marginal- to shallow-marine environment.

7.1.9 SF Palynofacies

The SF palynofacies is represented by a distinctive shoreface to lower shoreface, stressed, higher-energy shallow-marine assemblage, including a number of superabundant to predominant specimens of *Kiokansium* spp., including *K. unituberculatum* (formerly *K. polypes*). This distinct assemblage occupies a very narrow stratigraphic range, particularly at the base of the Wabiskaw C succession; which, depending upon the degree of sampling may be missed in more regional work (Dolby et al., 2013).

7.1.10 Cd Palynofacies

The Cd palynofacies consists of an assemblage with abundant to superabundant specimens of *Circulodinium* spp., mainly identified as *C. deflandrei.* As with the other palynofacies, the Cd palynofacies indicates a stressed environmental setting, but one that seems to have a stronger marine influence. The Cd palynofacies is interpreted to be indicative of a more offshore, shallow-marine (? shelf) setting.

7.2 Definition of Palynostratigraphy

Four biostratigraphic charts are presented in the text to illustrate the dominant features of the proposed palynofacies and palynostratigraphy for the Wabiskaw–McMurray succession (Figures 37 to 40). The complete set of biostratigraphic charts is in Appendix 5.

7.2.1 Hr Palynofacies

The Hr palynofacies is most typical of the lower McMurray Formation, with a presence as well in the pre-McMurray, middle, and upper McMurray successions. The Hr palynofacies has not been recorded in samples from the Wabiskaw Member, or in the overlying deposits of the Clearwater Formation.

7.2.2 NyR Palynofacies

The NyR palynofacies has been found to be common in the upper McMurray Formation at the Surmont Lease in previous work (Dolby et al., 2013). In the present work, it is most common in the middle McMurray succession (recorded in 15 samples), with a scattered presence in the Wabiskaw, upper and lower McMurray successions. The NyR palynofacies was not recorded in samples from the Clearwater Formation overlying the Wabiskaw Member, nor in those from the clastic pre-McMurray succession underlying the McMurray Formation.

7.2.3 NyA Palynofacies

The NyA palynofacies is very abundant in parts of the Gething Formation and Ostracod Beds (Dolby et al., 2013); outside the present Athabasca study area. In the Athabasca Oil Sands Area, the NyA palynofacies is most common in the upper McMurray and in the Grand Rapids Formation, which overlies the Clearwater Formation (Dolby et al., 2013) (Figure 2).

7.2.4 OS Palynofacies

The OS palynofacies typically occurs at the base of the Wabiskaw Member (Wabiskaw D), and is interpreted as representing the earliest indication of the transgression of the Clearwater Sea into the Athabasca Oil Sands Area (Dolby et al., 2013). The OS palynofacies also occurs in the stratigraphically-higher Wabiskaw B and Wabiskaw A successions, which are younger transgressive deposits.

7.2.5 V Palynofacies

The V palynofacies is most common in the upper McMurray Formation; less commonly present in the Clearwater Formation overlying the Wabiskaw Member (Dolby et al., 2013).

7.2.6 COOP Palynofacies (including Sbt and Lux)

The COOP palynofacies characterizes the middle and upper McMurray in the lower (more seaward) estuarine settings of the northern Athabasca Oil Sands Area. To the north, COOP palynofacies is present in the middle and upper McMurray, and in the Wabiskaw Member, including the Wabiskaw D units. Here COOP palynofacies assemblages are most abundant in the middle McMurray succession. Palynofacies become more marine-influenced higher upsection from the upper McMurray to Wabiskaw D and Wabiskaw C units. The most marine character is within the Wabiskaw C succession. By contrast, in the Athabasca Oil Sands Area south of the town site of Fort McMurray (for example, in the Long Lake [Township 85, Ranges 6 and 7, west of the 4th Meridian] and Surmont [Townships 83 and 84, Ranges 6 and 7, west of the 4th Meridian] areas) dinocysts are rare in the McMurray succession.

7.2.7 SF Palynofacies

The SF palynofacies, as reported by Dolby et al. (2013), occurs over a relatively thin interval(s) of the Wabiskaw Member. At Surmont (Township 83, Ranges 6 and 7, west of the 4th Meridian), it is at the base of the Wabiskaw A to Wabiskaw C interval. At Saleski, to the northwest (Township 90, Ranges 16 and 17, west of the 4th Meridian) the SF palynofacies is at the base of the Wabiskaw C succession (Dolby et al., 2013).

7.2.8 Cd Palynofacies

The Cd palynofacies is present in many Wabiskaw Member samples, and in samples from the lower

Clearwater Formation that overlies the Wabiskaw Member (Dolby et al., 2013).

7.2.9 Other Components

In addition to the main palynofacies described above, there are other palynofacies groups in the Wabiskaw and McMurray successions that have important paleoenvironmental and/or paleoclimatic implications, which, within the context of the stratigraphic framework, may help determine sequence boundaries. These include:

Swamp components: characterized by a high, very high, or predominant (~75%–85%) component of pollen from woody plants that are consistent with a swamp setting. Swamps are permanent or semi-permanent wetlands, often near rivers or streams, and dominated by woody shrubs and trees.

Hinterland component dominant (HCD): a predominant (>>50%) component of bisaccate and other more far-travelled pollen. The hinterland refers to the land behind the immediate coastal or marginal-marine area that is recorded in the sediments.

Marsh (M): characterized by a high, very high, or predominant (50%–85%) spores/pollen from herbaceous (non-woody) plants that are consistent with a marsh setting. Marshes are permanent or semi-permanent wetlands, often near lakes, rivers or streams, and dominated by herbaceous plants and shrubs.

Overbank (OB): characterized by a predominant component of spores/pollens of plants that tolerate alternating flooding and drying-out cycles. An overbank is an area on the floodplain of a river or estuary which is periodically inundated by floodwaters.

Crevasse Splays (CS) are the floodplain-deposits of a river, estuary, or distributary channel on a delta, which were inundated by floodwaters that broke through the banks or levees. Crevasse splays develop down flow of the breach in the channel and deposits a coarse-grained, lobate fan-deposit (similar in geomorphology to an alluvial fan) on the floodplain of the river or estuary, or within the interdistributary area of a delta top. **Flood Deposits (FD)** result from deposition of sediment during periodic flood flows, and can be preserved either within the channel settings or in the overbank floodplain areas of rivers and estuaries, or within interdistributary areas of deltas.

The crevasse-splay and flood deposits have similar palynofacies as the other overbank (OB) deposits, with a very high to predominant component of spores/pollens of plants that tolerate alternating flooding and drying-out cycles. Both crevasse splays and flood deposits are types of overbank sediments, and are identified by their primary sedimentary structures. Crevasse splays are distinguished by their coarsening-upward grain size, along with varying physical sedimentary structures, indicating a change from lower to higher flow regimes (Elliott, 1974; Gębica and Sokolowski, 2001; O'Brien and Wells, 1986). Flood deposits are coarsening-to-fining upwards, fining-upwards or massive and ungraded. Flood deposits have a variety of flow-regime structures depending upon whether the flooding occurs as traction current or suspension fall-out flow (Karcz, 1970; McKee et al., 1967; Rust and Nanson, 1989). Crevasse splays and flood deposits may contain reworked, mummified or coalified organic plant detritus, and/or mudstone intraclast breccia. Upon drying out, the tops of the crevasse splays and flood deposits may become vegetated, and in the preserved successions crevasse-splays and flood deposits may grade upwards into rooted or coaly paleosols, or into carbonaceous/coaly horizons.

Arid/semi-arid hinterland or drier climate spores and pollen (Arid): the palynomorphs of this climatic variation include the *Classopollis* spp. and *Exesipollenites* spp. in abundance.

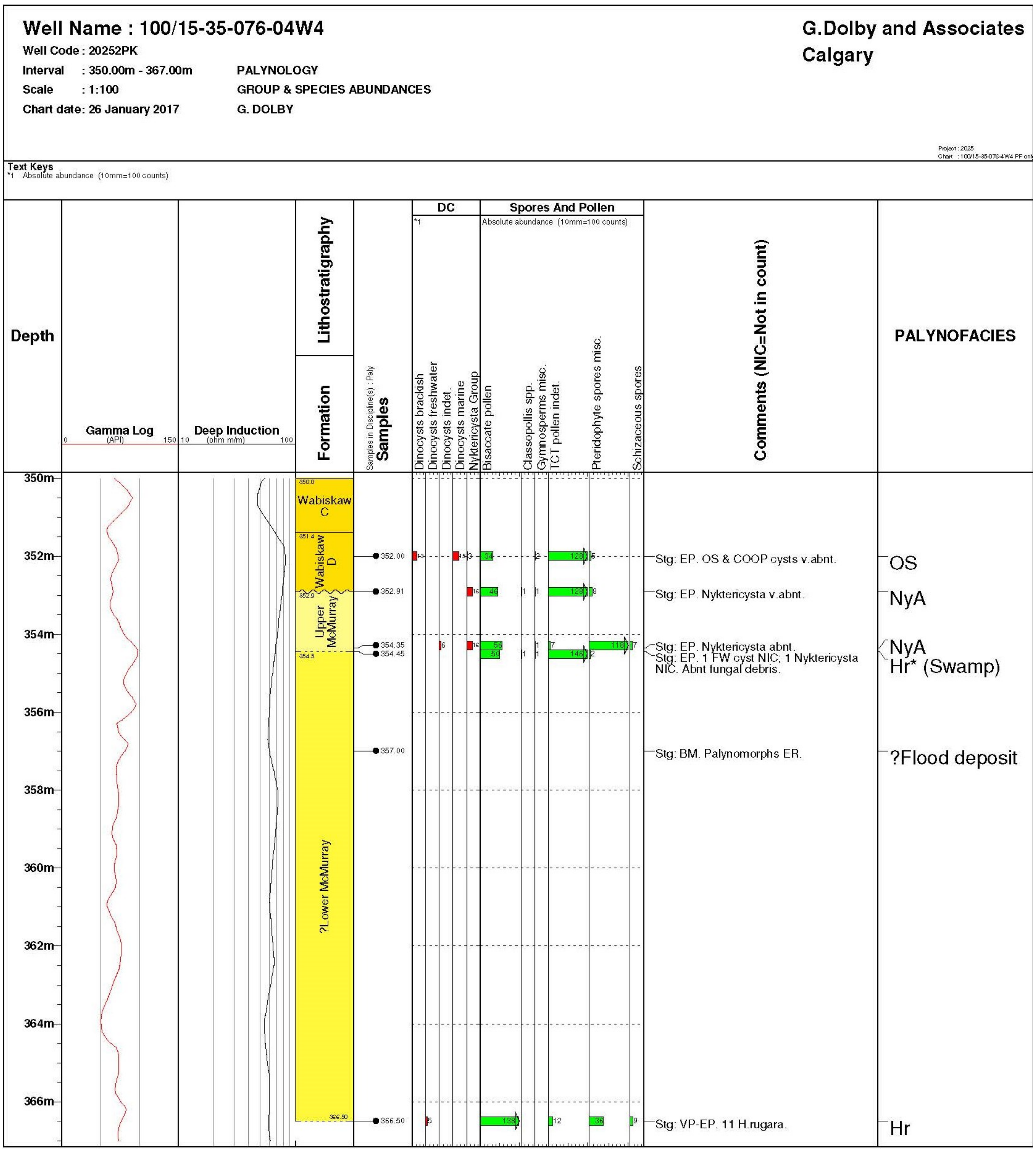


Figure 37. Representative well 100/15-35-076-04W4/00, with typical distribution of stratigraphic units (confirmed in core) from the southern Athabasca Oil Sands Area, illustrating the palynofacies composition for the lower and upper McMurray, Wabiskaw D and C units. The lower McMurray equivalents show fresh to slightly brackish palynofacies, whereas the upper McMurray yields brackish assemblages (DC = dinocyst; NIC = not counted in sample). Gamma-ray and deep-induction wireline logs are shown to the left (for the complete biostratigraphic chart, see Appendix 5).

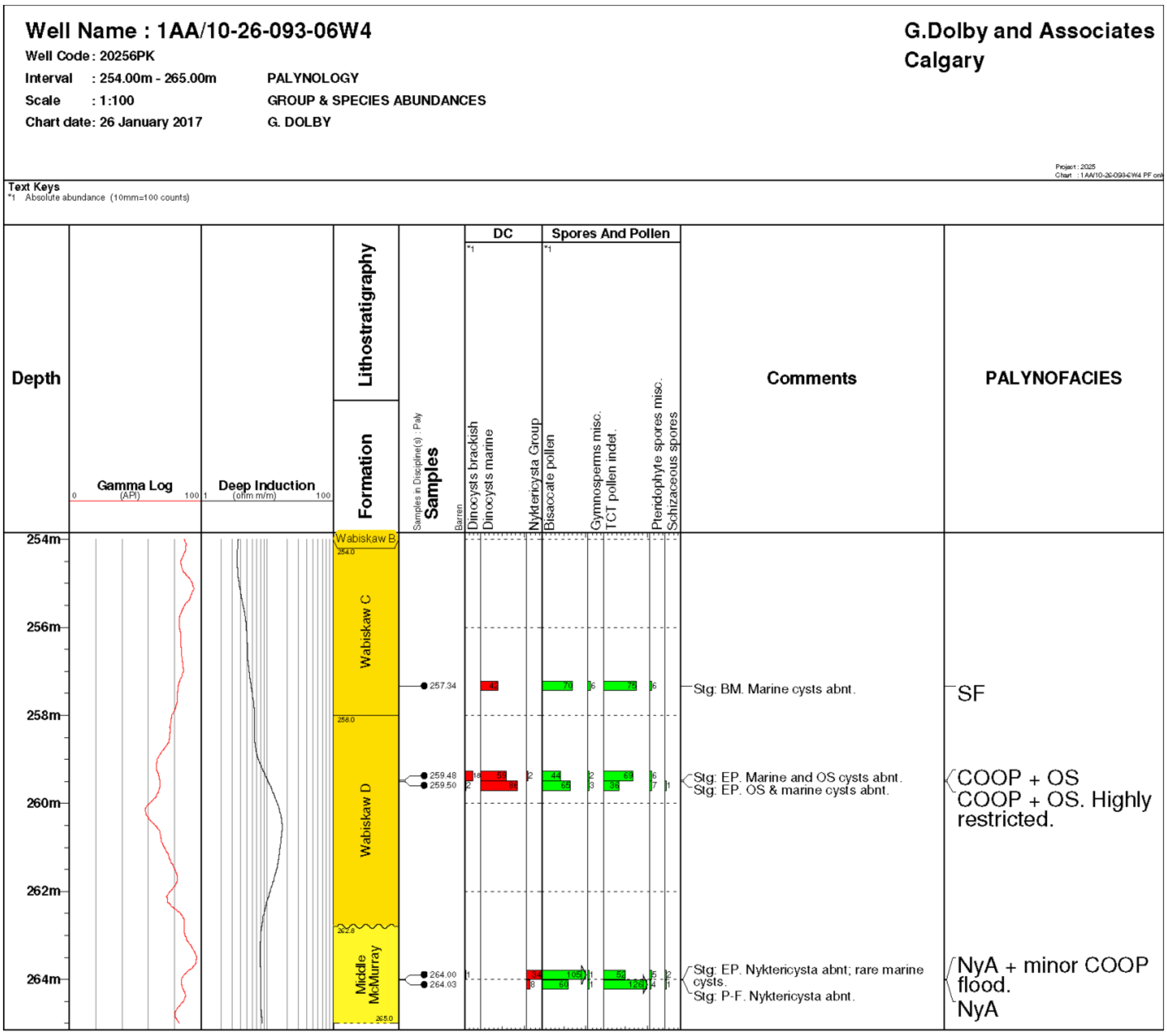


Figure 38. Representative well from the north-central Athabasca Oil Sands Area, illustrating the palynofacies composition for the middle McMurray, Wabiskaw D, C, and B-equivalent units. (DC = dinocyst; NIC = not counted in sample). Note the strong brackish signature in the McMurray with a minor marine flood, and the marine SF palynofacies near the base of the Wabiskaw C. Gamma-ray and deep-induction wireline logs are shown to the left; well 1AA/10-26-093-06W4/0 (for the complete biostratigraphic chart, see Appendix 5).

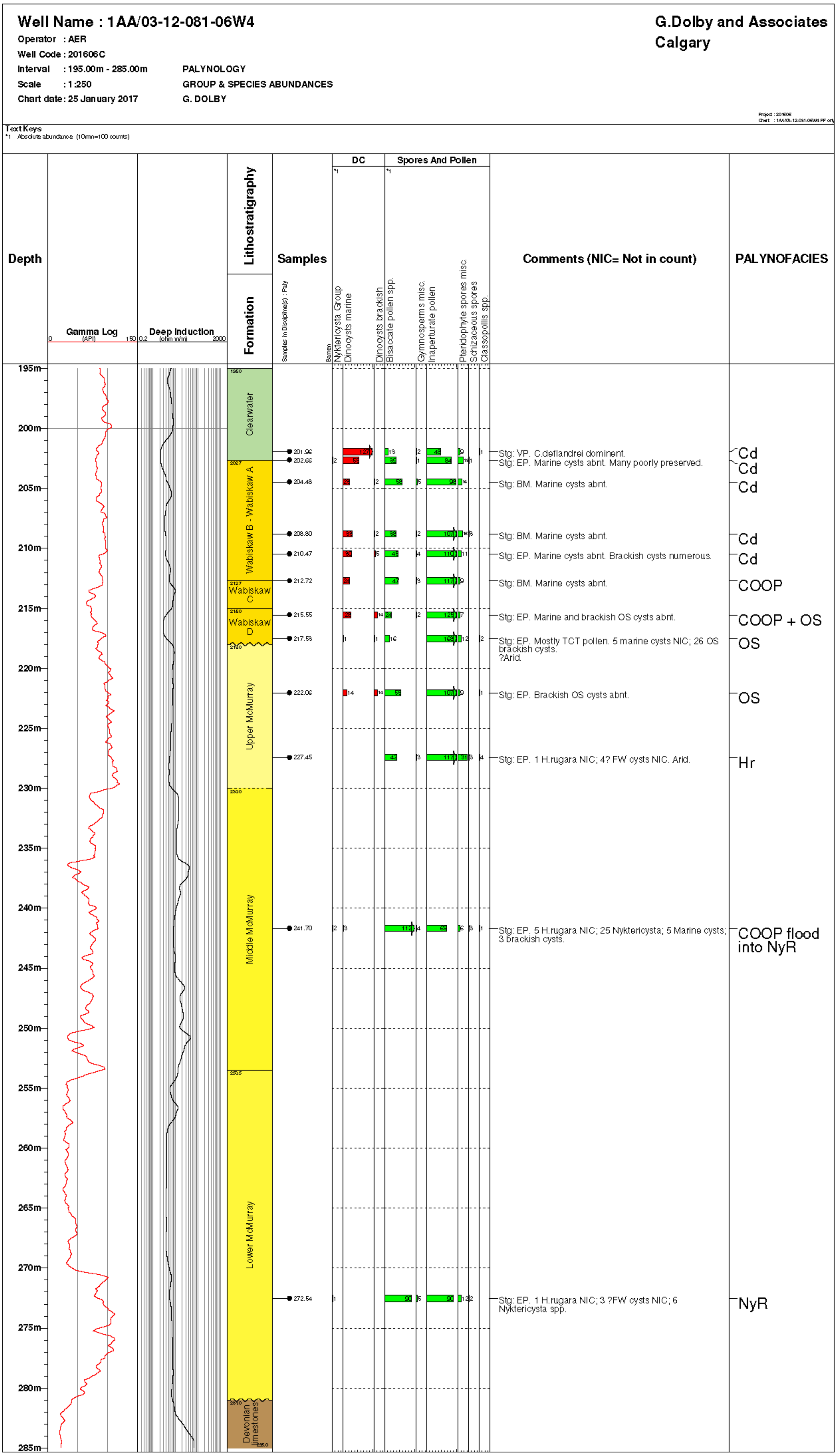


Figure 39. Representative well from the east-central Athabasca Oil Sands Area, illustrating the palynofacies composition for the pre-, lower, middle, and upper McMurray; Wabiskaw D, C, B/A equivalent; and Clearwater units. (DC = dinocyst; NIC = not counted in sample). Note the marine incursion in the middle McMurray and the brackish/stressed marine OS assemblage in the upper McMurray. The Wabiskaw to basal Clearwater succession is increasingly marine. Gamma-ray and deep-induction wireline logs are shown to the left; well 1AA/03-12-081-06W4/0 (for the complete biostratigraphic chart, see Appendix 5).

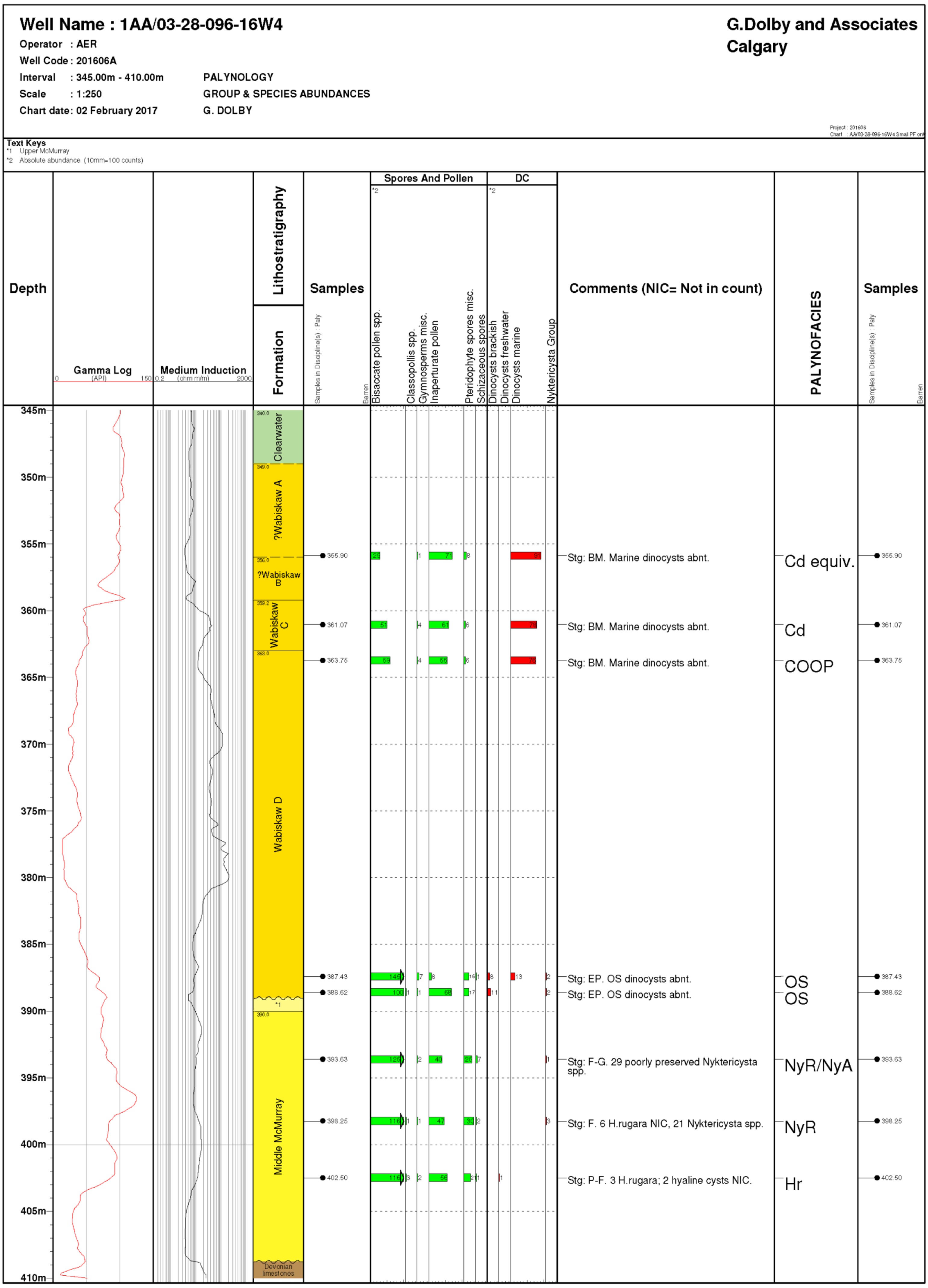


Figure 40. Representative well from the northwestern Athabasca Oil Sands Area, illustrating the palynofacies composition for the middle and upper McMurray, Wabiskaw D, C, B/A-equivalent units. (DC = dinocyst; NIC = not counted in sample). Note OS assemblage at the base of the Wabiskaw D. Gamma-ray and deep-induction wireline logs are shown to the left; well 1AA/03-28-096-16W4/0 (for the complete biostratigraphic chart, see Appendix 5).

8 Discussion

During the previous decades, work by industry, academia, and Alberta government geologists on the Athabasca oil sands has focussed on the definition of lithofacies, palynofacies and other biofacies; the identification different facies associations; and the paleoenvironmental interpretations of the preserved stratigraphic record. The integration of the results of these studies from the various perspectives has been difficult in some cases, with lithofacies interpretations differing from those presented by the palynological, ichnological and/or paleontological record. For example, Dolby et al. (2013) in their examination of palynofloral assemblages of the McMurray Formation from the Surmount and surrounding areas of north-central Alberta found that the depositional setting of the McMurray Formation was best characterized by freshwater to brackish water environments, ranging in a continuum from river to floodplain/overbank and marginal-marine settings. The Wabiskaw Member and overlying Clearwater Formation units were deposited in more marine-influenced, stressed, nearshore to lower shoreface settings, which evolved with the southern transgression of the Clearwater Seaway. Using a largely geomorphic-analog and lithostratigraphic approach, Blum and others (Blum, 2015; Blum and Jennings, 2016) interpreted that the entire Mannville Group of the Alberta Foreland Basin was largely emplaced under freshwater conditions in a continental-scale fluvial system sourced from the eastern Appalachian Mountains. In their view, this interpreted continental-scale fluvial system dominated sedimentation, with little preservation of any marine-saline to brackish influences within the stratigraphic record.

The results from the compilation of the AGS historical records and the present palynological analyses indicate that the lower McMurray depositional environments were essentially fresh; those of the middle McMurray and upper McMurray fresh to brackish, with saline incursions, the latter especially in the upper McMurray; and those of the Wabiskaw brackish/restricted to open marine. Geographical and stratigraphic variations do exist, where some units are freshwater-dominated, and others more saline. Discrepancies between the interpretations based on the palynological record (cf. Dolby et al., 2013) and those interpretations based on the trace-fossil record (ichnofacies) (Gingras et al., 2016) may be a result of differences in the deposition and preservation of geological successions associated with the different data sets. In areas where spring-freshet or large discharges of freshwater flood estuaries and/or marine bays, freshwater signatures (with very low salinities, high turbidity, and very low dinocyst abundances) may overwhelm the microfossil record.

It is not clear whether the increased salinity (above that of freshwater) is due to marine influx associated with transgressive event(s) or the result of saline-spring influx into a continental-marginal marine environment. It is significant that the bulk of the Wabiskaw–McMurray succession is in close proximity to the regional salt-dissolution edge (Figures 5 and 6). Salt dissolution in the area occurred at different times: some dissolution prior to deposition of the McMurray Formation; other dissolution syn-depositional and post-depositional, in fact, continuing up to recent time (Hein et al., 2000, 2001; Broughton, 2013a, b, 2015). Modern saline springs and salinas debouch into the present-day Athabasca River valley and its tributaries (Cowie, 2013; Cowie et al., 2015; Gue, 2012; Jasechko et al., 2012; Lemay, 2002a, b, 2008, Stewart and Lemay, 2011). Similar discharges of saline ground- and formation waters into the paleo-McMurray and -Wabiskaw valley systems may be a process that could account for the increased salinities within the channel-and-bar environments, without having to invoke more regional, marine transgressive events, particularly within the lower and middle parts of the McMurray succession. It is interesting to note that recent analysis of isotopic chemistry of Western Interior Seaway deposits in the U.S.A. found that temperatures and oxygen-isotope values were below values in contemporaneous Gulf of Mexico marine sites (Petersen et al., 2016). Such salinity and temperature variation in the U.S.A. part of the Western Interior Seaway was interpreted to be driven by increasing discharge of continental runoff into the seaway, resulting in the development of salinity-driven water masses within the seaway.

Future geochemical analyses in the Alberta portion of the Western Interior Seaway, tied to palynofacies, may help to elucidate such controls on salinity within the pre- and lower McMurray units (cf. Mao et al., 1999; Yang et al., 2017).

9 Ages

The following is a summary of the age determinations from the microfossil and palynological records compiled and reanalyzed in the current study (Figure 41).

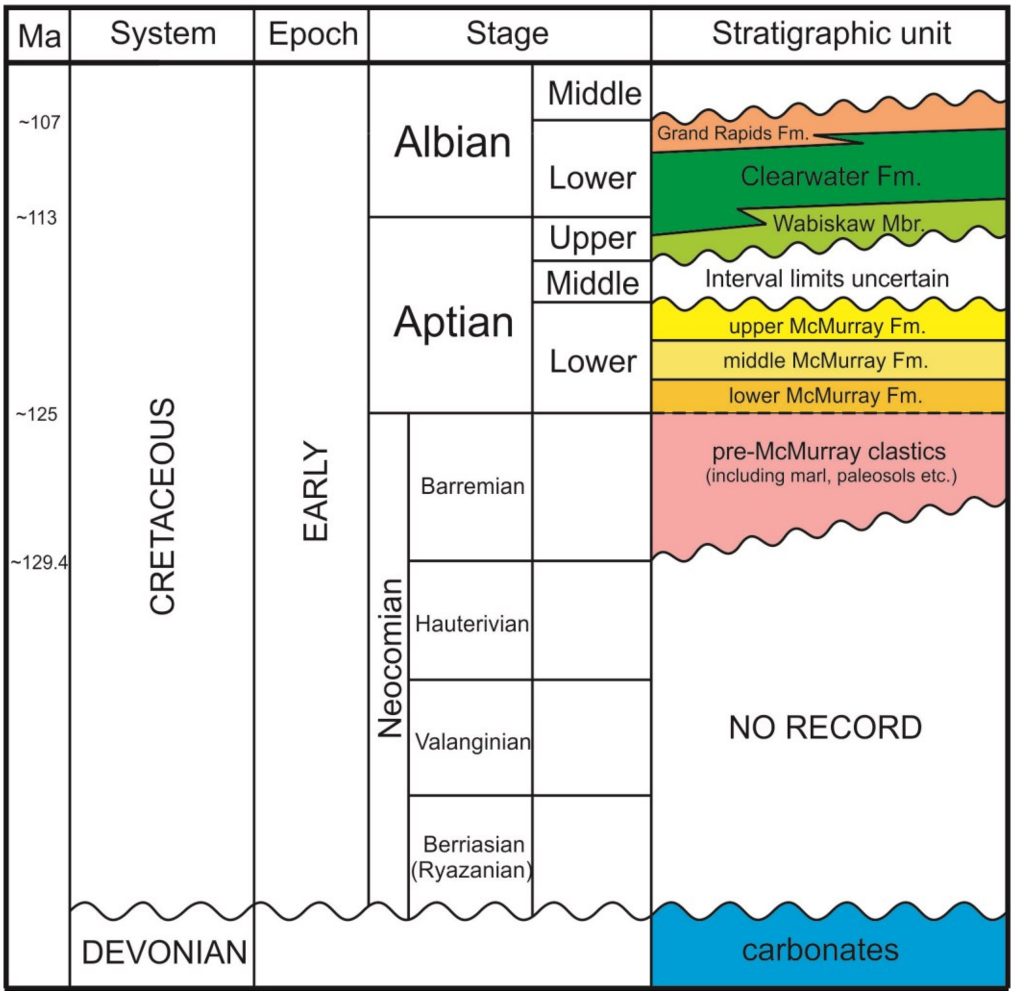


Figure 41. Schematic stratigraphic chart showing the results from the present study of the palynological and microfossil record from the Lower Cretaceous Wabiskaw–McMurray succession (and associated units), Athabasca Oil Sands Area. The age-ranges presented here correspond to other published ages on wood and palynological data by Roy (1972) and Vagvolgyi and Hills (1969), but differs from the palynology of Burden (1984), who had ages extending back to the Valanginian. Based on the sedimentological model for the present study the Wabiskaw, McMurray, and pre-McMurray clastic units are all unconformably (or disconformably) bounded with one another. A gradational and conformable contact is at the top of the Wabiskaw Member (Wabiskaw A) and the overlying mainly marine shale of the Clearwater Formation. Major unconformities/disconformities are illustrated by the wavy contact.

9.1 Pre-McMurray Clastic Succession

Cretaceous pre-McMurray sediments are either weathering products (paleosols or karst-infill) or fluvio-lacustrine sediments (mainly marls) deposited in depressions, including paleo-sinkholes, on the top Devonian unconformity surface. The former usually yield poor assemblages of Cretaceous spores and pollen with Devonian palynomorphs. The latter are described below.

Four sections of pre-McMurray fluvio-lacustrine sediments were sampled for this study:

1AA/06-36-095-11W4/00	(46.3–67.59 m, 2 samples);
1AA/05-01-096-11W4/00	(59.6–75.8 m, 3 samples);
1AB/16-02-096-11W4/00	(76.0–98.2 m, 3 samples); and,
1AA/09-11-096-11W4/00	(101.4–112.0 m, 1 sample).

All nine samples yielded assemblages of undoubted Cretaceous spores such as:

Aequitriradites spinulosus	*Appendicisporites* spp.
Couperisporites tabulatus	*Foraminisporis* spp.
Microreticulatisporites uniformis	*Kuylisporites lunaris*
Concavissimisporites trioreticulosus	*Taurocusporites segmentatus*
Triporoletes reticulatus	*Tigrisporites scurrandus*

An array of Cretaceous species of *Cicatricosisporites* also occur. All have relatively long ranges within the Cretaceous but the first appearance of *C. trioreticulosus* is probably in the Barremian (see Singh, 1971). Spores that have a limited range include a number of *Trilobosporites* species including:

T. canadensis	*T.* cf. *canadensis*	*T.* cf. *aornatus*
T. cf. *bernissartensis*	*T.* cf. *verrucatus*	*T.* cf. *aequiverrucosus*

No specimens of this genus were recorded in the overlying McMurray Formation in any of the samples from wells and outcrops in this study. The genus *Trilobosporites sensu stricto* first appears in the Late Jurassic and evolves into *Concavissimisporites* (*Impardecispora* of some authors) during the Neocomian (Dörhöfer, 1979; Dörhöfer and Norris, 1975; Fensome, 1987). There are no reliable records of *Trilobosporites* above the Neocomian.

The only section where dinocysts were recorded is in the 1AA/05-01-096-11W4/00 well where three samples from the uppermost part of the pre-McMurray yielded abundant specimens. The majority are of as yet undescribed taxa including forms attributable to the genus *Nyktericysta*. The *Nyktericysta* spp. are forms that are found in freshwater to brackish environments as old as the Hauterivian. *Holmwoodinium notatum* occurs in small numbers. This is a freshwater species that almost certainly first appears in the Barremian (Batten, 1985). There are also specimens of a dinocyst that closely resembles *Protoellipsodinium fibratum*, which was first described from the Barremian of S.W. England (Batten and Lister, 1988).

In summary, the pre-McMurray fluvio-lacustrine sediments are Neocomian, most probably Barremian in age.

9.2 McMurray Formation

9.2.1 Lower McMurray Informal Member

The principal dinocysts recorded in this interval are *Hurlandsia rugara*, a freshwater species and

Nyktericysta spp., which characterize freshwater to brackish environments. Both are of little use in defining the age of the unit. *H. rugara* was first described from the late Ryazanian (Berriasian) to Valanginian of Denmark (Piasecki, 1984) and subsequently from the Barremian of England (Lister and Batten, 1988a).

The lack of any Neocomian influence on the spore-pollen assemblages, particularly the absence of *Trilobosporites sensu stricto*, favours an Aptian age for the lower McMurray informal member.

9.2.2 Middle and Upper McMurray Informal Members

There is an increasingly marine influence on the palynomorph assemblages in the middle and upper McMurray that is particularly evident in the northern part of the Athabasca Oil Sands region. Most of the species have relatively long stratigraphic ranges. Those with a more limited distribution include *Circulodinium brevispinosum*, *Leptodinium cancellatum* and *Pseudoceratium eisenackii*. The most reliable data show that these species first appear in the Aptian. Sections where at least one of these species has been recorded from the middle McMurray include 1AA/03-12-081-06W4/00, Daphne Island East #3 and Daphne Island West #3.

The presence of *Pseudoceratium pelliferum* in the middle and upper McMurray is very important. This species has a well-established extinction point near the top of the Early Aptian. It was recorded in the following wells:

100/06-15-076-06W4/00	(? possible middle McMurray)
1AA/10-26-093-06W4/00	(middle McMurray)
1AA/16-17-101-13W4/00	(upper McMurray)

It also occurs rarely and sporadically in the Wabiskaw Member of the Clearwater Formation, however, given the erosional contact with the underlying McMurray and the presence of Late Aptian and younger species; those records are interpreted as the result of reworking.

In summary, the middle and upper informal members of the McMurray Formation are Early Aptian and, consequently, the underlying lower informal member is also interpreted as Early Aptian in age.

9.3 Clearwater Formation

9.3.1 Wabiskaw Member

Dinocyst assemblages from this unit are generally rich and diverse with increasing diversity in its higher parts. However, most of the species are either strongly environmentally controlled (the OS assemblage, for example) or have relatively long stratigraphic ranges. Unfortunately, no taxa that have extinction points in the Late Aptian to Early Albian transition have as yet been recorded in this area.

There are three dinocyst species that have a first stratigraphic appearance in the Late Aptian and therefore have potential in establishing the maximum age of the Wabiskaw Member. These are *Impagidinium verrucosum, Cyclonephelium intonsum,* and *Hapsocysta benteae*.

I. verrucosum was originally described from the Middle Albian (Brideaux and McIntyre, 1975) but it has been recorded in the Late Aptian, upper *martinoides* Ammonite Zone in southern England (Lister and Batten, 1988b). In the present study, *I. verrucosum* has been recorded throughout the Wabiskaw succession, with the lowest example in the Wabiskaw D in the cores from the 100/15-35-076-4W4/00 and 1AA/03-28-096-16W4/00 wells. *C. intonsum* first appears in the Late Aptian *jacobii* Ammonite Zone of southern England (Duxbury, 1983). It is present throughout the Wabiskaw units, including the Wabiskaw

D in the core from 1AA/03-28-096-16W4/00 well. Neither of these species has been widely reported.

H. benteae was considered to be a good marker for the Albian of East Greenland (Nøhr-Hansen, 1993) but there are records from the Late Aptian of Germany (Davey, 1982) and the North Sea (Costa and Davey, 1992). In the present study, *H. benteae* is present in the Wabiskaw D in the core from the 1AA/03-12-081-06W4/00 well.

The Wabiskaw Member of the Clearwater Formation has usually been assigned to the Albian. A precise age cannot be given based on the current data but if the ranges of the above species are valid, it is no older than mid Late Aptian, *jacobii* Zone.

9.3.2 Clearwater Formation Shale (overlying the basal Wabiskaw Member)

Although the dinocyst species that have been logged in the Clearwater Formation during the course of this project (and in a number of confidential studies conducted by Dolby) are typical of the Albian, no species with undoubted Albian first appearances have been recorded.

10 Conclusions

The pre-McMurray clastic succession sits unconformably upon weathered and karstic Devonian carbonate.Where preserved; the contact of the pre-McMurray with the overlying McMurray Formation is disconformable or unconformable. The age of the pre-McMurray clastic succession, based on palynomorphs and microfossils, is Neocomian, and most probably Barremian in age. Sedimentological and palynological data support a fluvial-lacustrine and overbank setting for deposition of these older clastic units.

The lower McMurray informal member sits unconformably/disconformably on older units, including the pre-McMurray clastics or upon weathered and karstic Devonian carbonate. The age of the lower McMurray clastic succession, based on palynomorphs and microfossils, is Aptian, and likely Early Aptian, based upon age of overlying units. Sedimentological and palynological data support a continental, braided channel-and-bar complex with local overbank settings for deposition of the lower McMurray clastic succession.

The middle and upper McMurray informal members sit unconformably/disconformably on older units, including the lower McMurray or upon weathered and karstic Devonian carbonate. The age of the middle and upper McMurray clastic successions, based on palynomorphs and microfossils, is Early Aptian. Sedimentological and palynological data support a mix of continental and marginal-marine complexes, with incised-valley complexes, consisting of fluvial-estuarine channels and point bars, tidally-influenced channels and tidal flats, with local overbank settings, including tidal flats, bay fills, lagoons, marshes, coastal swamps, and bogs, for deposition of the middle and upper McMurray clastic successions.

The Wabiskaw Member sits unconformably/disconformably on older units, including all of the McMurray informal members or upon weathered and karstic Devonian carbonate. The age of the Wabiskaw D and C clastic successions, based on palynomorphs and microfossils, is no older than mid Late Aptian. Sedimentological and palynological data support a mix of marginal-marine complexes, with incised-valley fills, consisting of fluvial-estuarine channels and point bars, tidally-influenced channels and tidal flats, with local overbank settings, including tidal flats, bay fills, lagoons, marshes, coastal swamps, and bogs (Wabiskaw D); and lower shoreface to offshore marine (Wabiskaw D and C) areas for deposition of Wabiskaw clastic successions.

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Appendix 1 – Stratigraphy of Sampled Cores and Outcrops

Table 10. Stratigraphy of cores sampled for palynological analysis. Stratigraphic nomenclature for the Wabiskaw Member and upper McMurray Formation is according to Alberta Energy and Utilities Board (2003). Number of samples is given parenthesis. Abbreviations: RMS = regional marine shale; VF = valley fill; Wbsk Mrk = Wabiskaw marker. For a digital spreadsheet version of this table, see file 'Table 10.xlsx' in the 'Appendix 1' folder of the report ZIP file.

Unique Well Identifier	Clearwater Formation	Wabiskaw Member	McMurray Formation Undefined	Upper McMurray	Middle McMurray	Lower McMurray	Pre-McMurray	Devonian	Appendix	Data Source
100/08-29-067-07W4/00				A1 (1)					3	AGS Records
100/07-18-069-12W4/00		C (1)							3	AGS Records
100/06-20-071-05W4/00	(6)	C (1)		A1 (1), A2 (1), B1 (1)					3	AGS Records
100/10-23-072-07W4/00		B VF (1)		(2)	(3)				3 & 6	AGS Records
100/11-22-073-06W4/00		(5)		(1)	(2)				3 & 6	AGS Records
100/05-21-074-04W4/00				(2)	(3)				3	AGS Records
100/10-02-074-05W4/00				A2 (1)		(2)			3	AGS Records
100/07-26-074-05W4/00				A2 (1), B2 (1)					3	AGS Records
100/10-14-074-09W4/00		D Shale (1)							3	AGS Records
100/05-22-074-15W4/00		D Shale (1)		(1)					3	AGS Records
100/11-08-075-08W4/00		A RMS (3), C (1)		(1)	(4)				4 & 6	Dolby, 2001, 2017
100/12-14-075-08W4/00				(2)	(2)				3 & 6	AGS Records
100/10-29-075-08W4/00		D VF (1)							3	AGS Records
100/10-34-075-09W4/00				B2 (4)					3	AGS Records
100/10-30-076-04W4/00		A RMS (1), D (1)			(2)				3	AGS Records
100/10-30-076-04W4/00		D (2)			(1)	(3)			4, 5 & 6	Dolby, 2001
100/15-35-076-04W4/00		D (3)		A1 (1)		(3)			4, 5 & 6	Dolby, 2001, 2017
100/06-15-076-06W4/00					(1)	(2)			4 & 5	Dolby, 2001, 2017
1AA/08-14-076-07W4/00					(2)				4 & 5	Dolby, 2001
102/10-01-077-07W4/00					(4)				4, 5 & 6	Dolby, 2001
100/11-15-077-07W4/00					(2)	(3)			4, 5 & 6	Dolby, 2001, 2017
100/11-01-077-08W4/00					(1)	(1)			4 & 6	Dolby, 2001
100/06-23-077-15W4/00		D (1)		(4)		(1)			3	AGS Records
100/11-09-079-15W4/00		(1)		(2)		(2)			3	AGS Records
100/07-26-080-11W4/00	(1)	A (1), D (1)		(1)	(1)	(1)			3	AGS Records
1AA/03-12-081-06W4/00	(1)	A–B (4), C (1), D (2)		(1)	(3)	(1)	(1)		4 & 5	Dolby, 2017
1AA/05-17-083-06W4/00	(1)	A (1), B (1), C (1), D (1)			(5)		(1)	(1)	4, 5 & 6	Dolby, 2017
100/10-26-083-07W4/00					(1)	(3)			4, 5 & 6	Dolby, 2001, 2017
1AA/10-11-083-11W4/00	(1)			A1 (1), A2 (1)	(4)	(2)			3 & 6	AGS Records
100/10-29-084-06W4/00		(1)			(1)	(1)			3	AGS Records
100/13-27-084-11W4/00		Wbsk Mkr (1), D Shale (1)		(1)					3 & 6	AGS Records
100/11-26-087-09W4/00						(2)			3	AGS Records
1AA/10-11-087-16W4/00						(6)		(1)	3 & 6	AGS Records
1AA/09-17-088-06W4/00					(1)				4, 5 & 6	Dolby, 2001
1AA/04-08-089-07W4/00		A RMS (1)		A2 (1)	(2)				3	AGS Records
1AA/02-04-090-09W4/00					(6)	(1)			5 & 6	Dolby, 2017
1AA/10-08-090-07W4/00					(3)				4, 5 & 6	Dolby, 2001
1AA/02-04-090-09W4/00					(6)	(1)			4 & 6	Dolby, 2000
1AB/06-09-090-14W4/00		C (1), D (2)		(1)	(1)	(1)			4, 5 & 6	Dolby, 2017
1AE/01-29-092-09W4/00					(3)	(5)	(2)		4, 5 & 6	Dolby, 1999
1AB/10-29-092-09W4/00		C (2), D (2)		(1)	(9)	(4)	(2)		4, 5 & 6	Dolby, 1999
100/05-17-092-17W4/00		(1)	(6)					(2)	4, 5 & 6	Dolby, 2017
1AA/10-26-093-06W4/00		A (1), B (1), C (1)			(2)				4, 5 & 6	Dolby, 2001, 2017
1AA/10-05-095-05W4/00					(1)				4, 5 & 6	Dolby, 2001
1AA/04-14-095-11W4/00					(1)	(1)			5	Dolby, 2001
1AA/06-36-095-11W4/00				(2)	(3)	(2)		(1)	4, 5 & 6	Dolby, 2000
100/16-11-096-10W4/00					(1)	(1)			4 & 5	Dolby, 2000
1AA/05-01-096-11W4/00					(7)	(4)	(2)		4, 5 & 6	Dolby, 2000, 2017
1AB/16-02-096-11W4/00		D (1)		(1)	(4)	(4)	(1)	(1)	4 , 5 & 6	Dolby, 2000, 2017
1AA/09-11-096-11W4/00					(1)	(4)	(1)		4, 5 & 6	Dolby, 2000
1AD/09-12-096-11W4/00					(3)	(5)			4, 5 & 6	Dolby, 2000
1AA/09-02-096-12W4/00					(1)	(2)			4, 5 & 6	Dolby, 2001
1AA/03-28-096-16W4/00	(1)	A (1), C (1), D (3)		(1)	(3)	(1)			4, 5 & 6	Dolby, 2017
1AA/11-09-099-15W4/00		(5)	(1)		(1)	(1)			4, 5 & 6	Dolby, 2001, 2017
1AA/16-17-101-13W4/00		D (2)		(4)	(5)	(3)			4, 5 & 6	Dolby, 2001, 2017
No. of Samples ( )	**(11)**	**(67)**	**(7)**	**(43)**	**(107)**	**(76)**	**(10)**	**(6)**		

Table 11. Location and stratigraphy of outcrops sampled for palynological analysis. Geographic coordinates are based on North American Datum of 1983 (NAD 83). For a digital spreadsheet version of this table, see file 'Table 11.xlsx' in the 'Appendix 1' folder of the report ZIP file.

Outcrop Name	UTM Zone 12 Coordinates (m)		Geographic Coordinates (decimal degrees)		Number of Samples			Appendix
	Easting	Northing	Longitude	Latitude	Upper McMurray	Middle McMurray	pre-McMurray	
Athabasca Sinkhole North	463100	6342230	-111.611072	57.221696		1		4 (Dolby, 2001)
Stony Rapids, Athabasca River	395908	6195773	-112.664628	55.896144				4 (Dolby, 2001)
Athabasca River Section 2	476157	6291350	-111.390042	56.765492		1		4 (Dolby, 2001)
Christina River	498075	6278050	-111.031391	56.646612		1		4 (Dolby, 2001) & 5
Daphne Island East #1	460230	6350120	-111.659862	57.292328		6		4 (Dolby, 2000) & 5
Daphne Island East #2	460220	6350200	-111.660040	57.293046		2		4 (Dolby, 2000) & 5
Daphne Island East #3	460250	6350300	-111.659559	57.293947		3		4 (Dolby, 2000) & 5
Daphne Island West (organic)	459679	6348730	-111.668777	57.279794		14		4 (Dolby, 2001, 2006) & 5
Daphne Island West #1	459630	6349200	-111.669666	57.284012		3		4 (Dolby, 2000) & 5
Daphne Island West #2	459640	6349110	-111.669485	57.283204		7		4 (Dolby, 2000) & 5
Daphne Island West #3	459650	6349002	-111.669302	57.282235		4		4 (Dolby, 2000)
Eymundson Creek Mouth	465500	6371500	-111.575428	57.484802		1		4 (Dolby, 2001)
Fluvial Marl	474746	6305712	-111.414547	56.894439			1	4 (Dolby, 2001) & 5
Horse River #3 (Above Oxbow Lak	475550	6283820	-111.399254	56.697814	4			4 (Dolby, 2000) & 5
Pierre River Mouth (Lower)	462150	6367150	-111.630626	57.445462		1		4 (Dolby, 2001)
Pierre River Mouth (Upper Bench)	462230	6367250	-111.629309	57.446367		1		4 (Dolby, 2001) & 5
Steepbank River	473675	6319100	-111.433521	57.014648		1		4 (Dolby, 1999)
Syncrude North Mine	458273	6321691	-111.687570	57.036788		1		4 (Dolby, 2001)

Appendix 2 – Well Information for Sampled Cores

Table 12. Further identification information for wells with core sampled for palynological analysis. Geographic coordinates are based on North American Datum of 1983 (NAD 83). For a digital spreadsheet version of this table, see file ‘Table 12.xlsx’ in the ‘Appendix 2’ folder of the report ZIP file.

UWI Sort	UWI Label	Well Licence Number	Well Name	Latitude (degrees N)	Longitude (degrees W)	Kelly Bushing Elevation (m)	Ground Elevation (m)
0674072908000	00/08-29-067-07W4/0	0112997	ESSO AEC 85 FISHCK 8-29-67-7	54.826737	-111.026176	690.1	686.5
0694121807000	00/07-18-069-12W4/0	0074008	RAX TWEEDIE 7-18-69-12	54.970208	-111.822132	598.6	595.6
0714052006000	00/06-20-071-05W4/0	0095026	CVE KIRBY 6-20-71-5	55.162577	-110.73759	681.3	677.8
0714073110000	00/10-31-071-07W4/0	0088431	CVE KIRBY 10-31-71-7	55.195173	-111.065876	663.2	660.2
0724072310000	00/10-23-072-07W4/0	0080129	CVE ET AL KIRBY 10-23-72-7	55.252286	-110.963913	694.3	691.2
0734062211000	00/11-22-073-06W4/0	0088375	DEVON KIRBY 11-22-73-6	55.339648	-110.843157	672.3	669.0
0744042105000	00/05-21-074-04W4/0	0087399	DOME ET AL KIRBY 5-21-74-4	55.422611	-110.565074	601.3	598
0744050210000	00/10-02-074-05W4/0	0119243	DEVON KIRBY 10-2-74-5	55.382826	-110.658236	634.3	630.5
0744052607000	00/07-26-074-05W4/0	0087759	DEVON KIRBY 7-26-74-5	55.438024	-110.656946	663.6	659.1
0744091410000	00/10-14-074-09W4/0	0094623	RAX NCR MARGIE 10-14-74-9	55.412607	-111.270843	659	654.7
0744152205000	00/05-22-074-15W4/0	0196151	TALISMAN ET AL DUNCAN 5-22-74-15	55.423683	-112.233498	693.3	689.3
0754080811000	00/11-08-075-08W4/0	0088717	ISH ET AL DEVENISH 11-8-75-8	55.483763	-111.214959	669.3	665.6
0754081412000	00/12-14-075-08W4/0	0088716	ISH ET AL DEVENISH 12-14-75-8	55.500210	-111.139213	671.9	668.2
0754082910000	00/10-29-075-08W4/0	0057455	HOME HB DEVENISH 10-29-75-8	55.529236	-111.204166	664.8	662.3
0754093410000	00/10-34-075-09W4/0	0088948	ISH ET AL GLOVER 10-34-75-9	55.542268	-111.307122	677.2	673.5
0764043010000	00/10-30-076-04W4/0	0074842	PEX PHILLIPS HARDY 10-30-76-4	55.616324	-110.608872	589.2	586.0
0764043515000	00/15-35-076-04W4/0	0120030	TRANSWEST HARDY 15-35-76-4	55.634695	-110.505780	581.0	577.0
0764061506000	00/06-15-076-06W4/0	0210119	CVE FCCL LEISMER 6-15-76-6	55.584472	-110.850846	573.8	568.9
0764071408AA0	AA/08-14-076-07W4/0	0088561	HOME LEISMER OV 8-14-76-7	55.583305	-110.966907	597.6	593.8
0774070110020	02/10-01-077-07W4/0	0052602	HOME LEISMER A10-1-77-7	55.644541	-110.945359	563.3	559.9
0774071511000	00/11-15-077-07W4/0	0049193	HOME LEISMER 11-15-77-7	55.674436	-111.006433	571.2	567.8
0774080111000	00/11-01-077-08W4/0	0067618	HOME HB LEISMER 11-1-77-8	55.644894	-111.109876	570.0	566.9
0774152306000	00/06-23-077-15W4/0	0081730	LOGAN TRUCENA DUNCAN 6-23-77-15	55.685865	-112.223317	675.4	673
0794150911000	00/11-09-079-15W4/0	0080262	TOURNEX PORTAGE 11-9-79-15	55.831792	-112.291999	630.7	627.7
0804112607AA0	AA/07-26-080-11W4/0	0056227	ARCO ACI MCMURRAY OV 7-26-80-11	55.960831	-111.607541	688.8	685.8
0814061203AA0	AA/03-12-081-06W4/0	0430765	COPRC ET AL CHARD 3-12-81-6	56.000076	-110.805417	479.5	475.2
0834061705AA0	AA/05-17-083-06W4/0	0199853	GULF RESDELN 5-17-83-6	56.195234	-110.923785	591.4	587.9
0834072610000	00/10-26-083-07W4/0	0073560	COPRC RESDELN 10-26-83-7	56.225659	-110.991629	633.5	630.0
0834111110AA0	AA/10-11-083-11W4/0	0048482	ARCO ACI MCMURRAY OV 10-11-83-11	56.182272	-111.623596	732.1	729.1
0844062910000	00/10-29-084-06W4/0	0088308	NEXEN NEWBY 10-29-84-6	56.313513	-110.910707	494.9	491.2
0844112713000	00/13-27-084-11W4/0	0106517	PCI PCEJ HANGST EX 13-27-84-11	56.317469	-111.658717	563.2	559.7
0874092611AA0	AA/11-26-087-09W4/0	0087682	PEX PCEJ HANGST OV 11-26-87-9	56.575702	-111.322051	412.9	407.8
0874161110AA0	AA/10-11-087-16W4/0	0074354	PEX PCEJ MCMURRAY OV 10-11-87-16	56.531575	-112.434211	503.3	499.7
0884061709AA0	AA/09-17-088-06W4/0	0198105	WLSC CLEARWATER 9-17-88-6	56.633406	-110.912514	418.6	415.6
0894070804AA0	AA/04-08-089-07W4/0	0052723B	HUSKY 23 MCMURRAY OV 4-8-89-7	56.699702	-111.090955	423.7	422.5
0904070810AA0	AA/10-08-090-07W4/0	0138379	MOBIL 1-89 CLARKECK OV 10-8-90-7	56.793365	-111.078709	456.1	456.1
0904090402AA0	AA/02-04-090-09W4/0	0049129B	SOBC 6-1 FEE LOT OV 2-4-90-9	56.771700	-111.370971	352.7	351.1
0904140906AB0	AB/06-09-090-14W4/0	0472807	MACOP ELLS 6-9-90-14	56.788495	-112.177012	487.2	483.2
0924092901AE0	AE/01-29-092-09W4/0	0048754K	FINA 74-10 STEEPBANK OV 1-29-92-9	57.004420	-111.405213	334.1	334.1
0924092910AB0	AB/10-29-092-09W4/0	0199335	SUNCOR FL1 B STEEPBANK 10-29-92-9	57.010194	-111.411771	334.0	331.6
0924171705000	00/05-17-092-17W4/0	0112226	PCI PCEJ LIEGE 5-17-92-17	56.977560	-112.709415	519.4	515.8
0934062610AA0	AA/10-26-093-06W4/0	0212404	SUNCOR FIREBAG 10-26-93-6	57.099009	-110.847088	594.6	592.4
0954050510AA0	AA/10-05-095-05W4/0	0212413	SUNCOR FIREBAG 10-5-95-5	57.215097	-110.774940	590.0	581.8
0954111404AA0	AA/04-14-095-11W4/0	221157	AMOCO INGS 4-14-95-11	57.235733	-111.684980	297.9	302.0
0954113606AA0	AA/06-36-095-11W4/0	0111382	PCI BITU #13-85-001 OV 6-36-95-11	57.284703	-111.649639	267.0	267.0
0964101116AA0	AA/16-11-096-10W4/0	0080701H	SHELL ALS 5019 MUSKEG OV 16-11-96-10	57.319303	-111.502739	299.0	299.0
0964110105AA0	AA/05-01-096-11W4/0	0106322	PCI DAPHNE 1-84 OV 5-1-96-11	57.297211	-111.653879	271.9	271.9
0964110216AA0	AA/16-02-096-11W4/0	0111251	PCI BITU #96-85-013 OV 16-2-96-11	57.307692	-111.664182	261.9	261.9
0964111109AA0	AA/09-11-096-11W4/0	0106320	PCI DAPHNE 1-84 OV 9-11-96-11	57.318530	-111.660515	276.3	276.3
0964111209AD0	AD/09-12-096-11W4/0	0173525	SYNCRUDE 95-03 AURORA 9-12-96-11	57.318709	-111.63827	286.3	286.3
0964120209AA0	AA/09-02-096-12W4/0	0044681J	SUPTST 1-73-2C ATHA OV 9-2-96-12	57.302551	-111.822306	322.5	321
0964162803AA0	AA/03-28-096-16W4/0	0088018I	TEXACO NAMUR 3-81 OV 3-28-96-16	57.354368	-112.541576	658.8	655.4
0994150911AA0	AA/11-09-099-15W4/0	0088016E	TEXACO NAMUR 2-81 OV 11-9-99-15	57.578906	-112.398343	727.3	723.9
1014131716AA0	AA/16-17-101-13W4/0	0056315E	TEXEX EAGLESNEST 4-75OV 16-17-101-13	57.769810	-112.087288	759.3	755.9

Appendix 3 – AGS Historical Palynological Records (pre-1999, no samples available, records only)

Table 13. Compilation of historical palynological sample analyses results from AGS records. Abbreviations: glauc = glauconitic, I.H.S. = inclined heterolithic stratification, RMS = regional marine shale. For a digital spreadsheet version of this table, see file 'Table 13.xlsx' in the 'Appendix 3' folder of the report ZIP file.

Unique Well Identifier	Sample Top Core Depth [ft]	Sample Top Core Depth [m]	Sample Base Core Depth [ft]	Sample Base Core Depth [m]	Stratigraphic Unit	Notes	Sample Name	Preservation	Spore Frequency [%]	Microplankton Frequency [%]	Megaspore Count [#]	Acritarchs Undifferentiated Frequency	Acritarchs Undifferentiated Diversity	Dinocysts Ceratioid Frequency	Dinocysts Ceratioid Diversity	Dinocysts Peridinioid Frequency	Dinocysts Peridinioid Diversity	Dinocysts Gonyaulacoid Proximate Frequency	Dinocysts Gonyaulacoid Proximate Diversity	Dinocysts Simple Indeterminate Frequency	Dinocysts Simple Indeterminate Diversity	Paleoenvironmental Interpretation Code (Dinocyst Zones)	Paleoenvironmental Interpretation	Data Source
100/08-29-067-07W4/00		539.25		539.75	Upper McMurray A1		DK-89-15-1	Poor						Common	Low							2	Slightly Brackish	AGS Records
100/07-18-069-12W4/00		451.10		451.10	Wabiskaw C shale	Dark grey shale ~ 0.75 m above Wabiskaw C glauc sand	DK-89-19-1	Moderate				Common	Low	Rare	Low	Common	Low	Common	Low	Abundant	High	4	Nearshore Marine	AGS Records
100/06-20-071-05W4/00		447.25		447.25	Clearwater	Upper shale in Clearwater "F" interval	TB-88-1-1	Moderate						Rare	Low	Rare	Low	Rare	Low	Common	Moderate	3	Brackish	AGS Records
100/06-20-071-05W4/00		454.65		454.65	Clearwater	Top of Clearwater "F" shale	TB-88-1-3	Moderate				Rare	Low	Rare	Low	Common	Low	Common	Low	Flood	High	4	Nearshore Marine	AGS Records
100/06-20-071-05W4/00		456.15		456.15	Clearwater	Base of Clearwater "F" shale	TB-88-1-4	Moderate				Rare	Low	Rare	Low	Rare	Low	Rare	Low	Abundant	Moderate	3	Brackish	AGS Records
100/06-20-071-05W4/00		461.60		461.60	Clearwater	Base of Clearwater "E" interval	TB-88-1-7	Poor to Moderate				Rare	Low	Rare	Low					Abundant	Low	3	Brackish	AGS Records
100/06-20-071-05W4/00		467.20		467.20	Clearwater	First shale in Clearwater "D" interval	TB-88-1-10	Moderate						Rare	Low	Rare	Low	Rare	Low	Flood	Moderate	4	Nearshore Marine	AGS Records
100/06-20-071-05W4/00		470.00		470.00	Clearwater	Second shale in Clearwater "D" interval	TB-88-1-11	Moderate				Rare	Low	Rare	Low	Common	Low	Common	Low	Flood	Moderate	4	Nearshore Marine	AGS Records
100/06-20-071-05W4/00		476.50		476.50	Wabiskaw C shale	Above Wabiskaw/McMurray contact	TB-88-1-13	Poor				Rare	Low	Rare	Low	Rare	Low	Rare	Low	Flood	Moderate	4	Nearshore Marine	AGS Records
100/06-20-071-05W4/00		477.75		477.75	Upper McMurray A1	Below Wabiskaw/McMurray contact	TB-88-1-15	Poor to Moderate			1			Rare	Low					Rare	Low	2	Slightly Brackish	AGS Records
100/06-20-071-05W4/00		480.60		480.60	Upper McMurray A2	Light grey shale	TB-88-1-17	Poor				Rare	Low	Rare	Low							2	Slightly Brackish	AGS Records
100/06-20-071-05W4/00		488.00		488.00	Upper McMurray B1	Light grey shale	TB-88-1-18	Poor to Moderate				Rare	Low	Rare	Low							2	Slightly Brackish	AGS Records
100/10-23-072-07W4/00		485.20		485.20	Wabiskaw B valley fill	Dark shale (? Wabiskaw B) overlying top of McMurray	DK-89-12-1	Moderate						Rare	Low	Common	Low	Common	Low	Common	Low	3	Brackish	AGS Records
100/10-23-072-07W4/00		488.30		488.30	Upper McMurray		DK-89-12-2	Poor														1	Continental	AGS Records
100/10-23-072-07W4/00		494.80		494.80	Upper McMurray		DK-89-12-3	Poor						Rare	Low							2	Slightly Brackish	AGS Records
100/10-23-072-07W4/00		494.95		494.95	Middle McMurray		DK-89-12-4	Poor														1	Continental	AGS Records
100/10-23-072-07W4/00		502.50		502.50	Middle McMurray		DK-89-12-5	Moderate			1									Rare	Low	2	Slightly Brackish	AGS Records
100/10-23-072-07W4/00		513.75		513.75	Middle McMurray		DK-89-12-6	Moderate						Rare	Low							2	Slightly Brackish	AGS Records
100/11-22-073-06W4/00		424.10		424.10	Wabiskaw	Top of Wabiskaw Member	TB-88-2-22	Moderate						Rare	Low	Common	Low	Common	Low	Flood	Moderate	4	Nearshore	AGS Records
100/11-22-073-06W4/00		429.60		429.60	Wabiskaw	Below top of Wabiskaw Member	TB-88-2-24	Poor				Rare	Low	Rare	Low	Rare	Low	Rare	Low	Flood	Moderate	4	Nearshore	AGS Records
100/11-22-073-06W4/00		432.75		432.75	Wabiskaw	Middle of Wabiskaw Member	TB-88-2-25	Moderate				Rare	Low	Rare	Low	Common	Low	Common	Low	Flood	Moderate	4	Nearshore	AGS Records
100/11-22-073-06W4/00		444.90		444.90	Wabiskaw	Questionable top of McMurray Formation	TB-88-2-28	Moderate			1			Rare	Low	Rare	Low	Rare	Low	Flood	Moderate	4	Nearshore	AGS Records
100/11-22-073-06W4/00		450.75		450.75	Wabiskaw	Top of McMurray Formation; evidence of erosion between this and next sample above	TB-88-2-30	Poor						Rare	Low							2	Slightly Brackish	AGS Records
100/11-22-073-06W4/00		453.90		453.90	Upper McMurray	True top of typical McMurray Formation	TB-88-2-32	Moderate														1	Continental	AGS Records
100/11-22-073-06W4/00		472.25		472.25	Middle McMurray	Upper to middle (?) McMurray Formation	TB-88-2-36	Moderate				Rare	Low	Rare	Low							2	Slightly Brackish	AGS Records
100/11-22-073-06W4/00		479.00		479.00	Middle McMurray	Top of middle McMurray	TB-88-2-38	Moderate				Rare	Low	Rare	Low							2	Slightly Brackish	AGS Records
100/05-21-074-04W4/00		370.75		370.75	Upper McMurray	Dark grey carbonaceous shale	DK-89-18-1	Moderate				Rare	Low			Common	Low	Common	Low	Common	Moderate	3	Brackish Shoreline	AGS Records
100/05-21-074-04W4/00		392.45		392.45	Upper McMurray	Dark shale above a coarsening-up sequence	DK-89-18-2	Poor to Moderate			2			Common	Low							2	Slightly Brackish Coastal Plain	AGS Records
100/05-21-074-04W4/00		392.65		392.65	Middle McMurray	Light grey mudstone capping "C" Channel	DK-89-18-3	Poor to Moderate														1	Continental	AGS Records
100/05-21-074-04W4/00		397.50		397.75	Middle McMurray	Mudstone at base of "C" Channel sequence	DK-89-18-4	Moderate				Rare	Low	Rare	Low					Rare	Low	2	Slightly Brackish Coastal Plain	AGS Records
100/05-21-074-04W4/00		403.50		403.50	Middle McMurray	Mudstone interbedded within "B" Channel sequence	DK-89-18-5	Poor to Moderate						Rare	Low					Rare	Low	2	Slightly Brackish Coastal Plain	AGS Records
100/10-02-074-05W4/00		415.50		415.50	Upper McMurray A2		DK-89-11-7	Poor						Common	Low							2	Slightly Brackish Coastal Plain	AGS Records
100/10-02-074-05W4/00		429.35		429.70	Lower McMurray		DK-89-11-5	Moderate														1	Continental	AGS Records
100/10-02-074-05W4/00		439.30		439.50	Lower McMurray		DK-89-11-6	Moderate to Good														1	Continental	AGS Records
100/07-26-074-05W4/00		416.25		416.25	Upper McMurray A2		DK-89-5-5	Poor to Moderate				Rare	Low	Rare	Low	Common	Low	Common	Low	Rare	Low	3	Brackish	AGS Records
100/07-26-074-05W4/00		433.00		433.00	Upper McMurray B2		DK-89-5-2	Poor to Moderate						Rare	Low							2	Slightly Brackish	AGS Records
100/10-14-074-09W4/00		438.30		438.30	Wabiskaw D shale	Shale above Wabiskaw/McMurray contact	DK-89-4-1	Moderate				Rare	Low	Abundant	Low	Abundant	Low	Abundant	Low	Abundant	Moderate	4	Nearshore Marine	AGS Records
100/05-22-074-15W4/00		417.10		417.10	Wabiskaw D shale	Shale above Wabiskaw/McMurray contact	DK-89-10-1	Moderate						Flood	Low							2	Slightly Brackish	AGS Records
100/05-22-074-15W4/00		418.50		418.50	Upper McMurray		DK-89-10-2	Poor						Common	Low							2	Slightly Brackish	AGS Records
100/12-14-075-08W4/00		448.00		448.00	Upper McMurray			Moderate				Common	Low	Abundant	Low	Abundant	Low	Abundant	Low	Abundant	Moderate	4	Nearshore Marine	AGS Records
100/12-14-075-08W4/00		450.80		450.80	Upper McMurray			Moderate				Rare	Low							Rare	Low	3	Brackish	AGS Records
100/12-14-075-08W4/00		459.70		459.70	Middle McMurray			Moderate				Rare	Low							Rare	Low	3	Brackish	AGS Records
100/12-14-075-08W4/00		482.00		482.00	Middle McMurray			Poor to Moderate				Rare	Low	Rare	Low							2	Slightly Brackish Coastal Plain	AGS Records
100/10-29-075-08W4/00	1465.00		1465.00		Wabiskaw D valley fill	Shale above Wabiskaw/McMurray contact; Wabiskaw D shale		Poor to Moderate				Rare	Low	Abundant	Low	Abundant	Low	Abundant	Low	Abundant	Moderate	4	Nearshore Brackish-Marine	AGS Records
100/10-34-075-09W4/00		470.15		470.15	Upper McMurray B2		DK-89-1-1	Poor to Moderate						Rare	Low					Rare	Low	2	Coastal Plain	AGS Records
100/10-34-075-09W4/00		471.85		471.85	Upper McMurray B2		DK-89-1-2	Moderate														1	Continental	AGS Records
100/10-34-075-09W4/00		476.90		476.90	Upper McMurray B2		DK-89-1-3	Poor to Moderate				Rare	Low							Rare	Low	2	Coastal Plain	AGS Records
100/10-34-075-09W4/00		477.55		477.55	Upper McMurray B2		DK-89-1-4	Poor to Moderate								Rare	Low	Rare	Low			2	Coastal Plain	AGS Records

Continued on next page

Table 13 continued.

Unique Well Identifier	Sample Top Core Depth [ft]	Sample Top Core Depth [m]	Sample Base Core Depth [ft]	Sample Base Core Depth [m]	Stratigraphic Unit	Notes	Sample Name	Preservation	Spore Frequency [%]	Microplankton Frequency [%]	Megaspore Count [#]	Acritarchs Undifferentiated Frequency	Acritarchs Undifferentiated Diversity	Dinocysts: Ceratioid Frequency	Ceratioid Diversity	Peridinioid Frequency	Peridinioid Diversity	Gonyaulacoid Proximate Frequency	Gonyaulacoid Proximate Diversity	Simple Indeterminate Frequency	Simple Indeterminate Diversity	Paleoenvironmental Interpretation Code (Dinocyst Zones)	Paleoenvironmental Interpretation	Data Source
100/10-30-076-04W4/00		341.50		341.50	Wabiskaw A shale (RMS)	Wavy muds - datum shale	DK-89-17-5	Poor to Moderate				Rare	Low			Common	Low	Common	Low	Abundant	Moderate	4	Nearshore marine	AGS Records
100/10-30-076-04W4/00		347.25		347.25	Wabiskaw D shale	Black carbonaceous shale immediately below channel sand	DK-89-17-4	Poor to Moderate				Rare	Low	Rare	Low	Common	Low	Common	Low	Common	Moderate	3	Brackish Shoreline	AGS Records
100/10-30-076-04W4/00		361.50		361.50	Middle McMurray	Mudstone above highest I.H.S. bedsets	DK-89-17-3	Moderate						Common	Low							2	Slightly Brackish Coaslal Plain	AGS Records
100/10-30-076-04W4/00		364.00		364.00	Middle McMurray	Silty mudstone near top of I.H.S. bedsets	DK-89-17-2	Poor						Common	Low							2	Slightly Brackish Coaslal Plain	AGS Records
100/06-23-077-15W4/00		468.25		468.25	Wabiskaw D	Nearshore marine shale above top of McMurray Formation	DK-89-14-7	Moderate						Rare	Low	Abundant	Low	Abundant	Low	Abundant	Moderate	4	Nearshore Marine	AGS Records
100/06-23-077-15W4/00		471.25		471.25	Middle McMurray	Shell fragments present in top marker	DK-89-14-6															2	Slightly Brackish	AGS Records
100/06-23-077-15W4/00		471.30		471.30	Middle McMurray	Shell fragments present	DK-89-14-1	Poor						Abundant	Low							2	Slightly Brackish	AGS Records
100/06-23-077-15W4/00		477.50		477.50	Middle McMurray		DK-89-14-2	Poor to Moderate						Common	Low							2	Slightly Brackish	AGS Records
100/06-23-077-15W4/00		478.25		478.25	Middle McMurray		DK-89-14-3	Poor to Moderate			2	Rare	Low	Rare	Low					Rare	Low	3	Brackish	AGS Records
100/06-23-077-15W4/00		499.00		499.00	Lower McMurray		DK-89-14-5	Moderate to Good														1	Continental	AGS Records
100/11-09-079-15W4/00		402.50		402.50	Wabiskaw/McMurray contact	Wabiskaw	DK-89-13-1	Moderate	>80	<20				Flood	Low							2	Slightly Brackish	AGS Records
100/11-09-079-15W4/00		402.80		402.80	Wabiskaw/McMurray contact	Shell fragments present, upper McMurray	DK-89-16-4															2	Slightly Brackish	AGS Records
100/11-09-079-15W4/00		412.60		414.00	Upper McMurray	Mudstone between two coarsening-up sequences	DK-89-16-3	Poor to Moderate														1	Continental	AGS Records
100/11-09-079-15W4/00		423.70		423.70	Lower McMurray	Mud at top of "B" Channel sandstone	DK-89-16-2	Moderate			1											1	Continental	AGS Records
100/11-09-079-15W4/00		445.25		445.25	Lower McMurray	Mud at base of "B" Channel sandstone	DK-89-16-1	Moderate														1	Continental	AGS Records
100/07-26-080-11W4/00	1362.00		1364.00		Clearwater	Mudstone above Wabiskaw Member	DK-88-2-6	Moderate	>80	<20		Rare	Low			Rare	Low	Rare	Low	Flood	High	5	Offshore Open Marine	AGS Records
100/07-26-080-11W4/00	1387.00		1388.00		Wabiskaw top	Wabiskaw marker - shale datum	DK-88-2-5	Moderate	>95	<5				Rare	Low							4	Nearshore Marine	AGS Records
100/07-26-080-11W4/00	1411.00		1411.00		? Base Wabiskaw D	Dark mudstone just below Wabiskaw D sand	DK-88-2-4	Poor to Moderate	100													1	Continental	AGS Records
100/07-26-080-11W4/00	1469.00		1469.00		Upper McMurray	Silty mudstone upper McMurray	DK-88-2-3	Moderate	>99	<1		Rare	Low	Rare	Low							2	Slightly Brackish	AGS Records
100/07-26-080-11W4/00	1523.50		1523.50		Middle McMurray	Silty tidal flat mudstone mid-middle McMurray	DK-88-2-2	Moderate	>99	<1		Rare	Low	Rare	Low							2	Slightly Brackish	AGS Records
100/07-26-080-11W4/00	1574.50		1574.50		Lower McMurray	Carbonaceous silty shale above unconformity	DK-88-2-1	Moderate	>98	<2	6	Rare	Low	Rare	Low							2	Slightly Brackish	AGS Records
1AA/10-11-083-11W4/00	1464.00		1465.00		Clearwater	Mudstone above Wabiskaw Member	DK-88-3-9	Moderate	>95	<5		Rare	Low	Rare	Low	Rare	Low	Rare	Low	Flood	Moderate	4	Nearshore Marine	AGS Records
1AA/10-11-083-11W4/0	1481.00		1481.00		Upper McMurray A1	Grey mudstone below datum shale (Wabiskaw marker)	DK-88-3-8	Poor	>99	<1				Common	Low							2	Slightly Brackish	AGS Records
1AA/10-11-083-11W4/00	1488.00		1488.00		Upper McMurray A2	Mudstone above uppermost McM bitumen sand	DK-88-3-7	Moderate	>98	<2				Abundant	Low							2	Slightly Brackish	AGS Records
1AA/10-11-083-11W4/00	1508.00		1508.00		Middle McMurray	Paleosol	DK-88-3-6	Moderate	100	0												1	Continental	AGS Records
1AA/10-11-083-11W4/00	1530.00		1530.00		Middle McMurray	Light grey silty mudstone	DK-88-3-5	Poor	>98	<2				Abundant	Low							2	Slightly Brackish	AGS Records
1AA/10-11-083-11W4/00	1573.00		1573.00		Middle McMurray	Shaley mudstone	DK-88-3-4	Moderate	>99	<1		Rare	Low	Rare	Low					Rare	Low	2	Slightly Brackish	AGS Records
1AA/10-11-083-11W4/00	1591.00		1592.00		Middle McMurray	Shaley mudstone	DK-88-3-3	Moderate	>99	<1		Rare	Low	Rare	Low							2	Slightly Brackish	AGS Records
1AA/10-11-083-11W4/00	1602.00		1602.00		Lower McMurray	Shaley mudstone	DK-88-3-2	Poor to Moderate	100	0	8											1	Continental	AGS Records
1AA/10-11-083-11W4/00	1609.00		1610.00		Lower McMurray	Shaley mudstone	DK-88-3-1	Poor to Moderate	100	0												1	Continental	AGS Records
100/10-29-084-06W4/00		209.25		209.25	Wabiskaw	Preservation poor, slightly coaly; plankton diversity low	DK-87-1-1	Poor	>99	<1	2	Rare	Low	Abundant	Low					Rare	Low	3	Brackish Shoreline	AGS Records
100/10-29-084-06W4/00		247.45		247.45	Middle McMurray	Preservation moderate, coaly; plankton diversity low	DK-87-1-5	Moderate	>99	<1		Rare	Low	Common	Low	Rare	Low	Rare	Low			2	Slightly Brackish	AGS Records
100/10-29-084-06W4/00		261.55		261.55	Lower McMurray	Preservation moderate, coaly, no plankton	DK-87-1-7	Moderate	100	0	1											1	Continental	AGS Records
100/13-27-084-11W4/00		260.80		260.80	Wabiskaw marker	Datum shale	DK-87-4-29	Poor	>99	<1		Rare	Low	Rare	Low	Common	Low	Common	Low	Flood	High	4	Nearshore	AGS Records
100/13-27-084-11W4/00		265.50		265.50	Wabiskaw D base	At base Wabiskaw/top McMurray contact	DK-87-4-31	Poor	>95	<5						Rare	Low	Rare	Low	Flood	Moderate	4	Nearshore	AGS Records
100/13-27-084-11W4/00		267.70		267.70	Upper McMurray		DJ-87-4-32	Moderate	>99	<1				Rare	Low	Rare	Low	Rare	Low	Rare	Low	3	Brackish	AGS Records
100/11-26-087-09W4/00		116.55		116.55	Lower McMurray		DK-87-3-20	Moderate	100	0												1	Continental	AGS Records
100/11-26-087-09W4/00		152.75		152.75	Lower McMurray		DK-87-3-25	Poor to Moderate	>99	<1	6									Rare	Low	3	Brackish	AGS Records
1AA/10-11-087-16W4/00		246.00		246.00	Lower McMurray	Silty mudstone in McMurray	DK-88-1-9	Poor	100	0	6											1	Continental	AGS Records
1AA/10-11-087-16W4/00		246.450		246.450	Lower McMurray	Transgressive mudstone regime	DK-88-1-8	Moderate	100	0												1	Continental	AGS Records
1AA/10-11-087-16W4/00		246.800		246.800	Lower McMurray	Paleosol in 1st McMurray Channel	DK-88-1-7	Poor	100	0												1	Continental	AGS Records
1AA/10-11-087-16W4/00		247.25		247.25	Lower McMurray	Mudstone near top lowest McMurray Channel sand	DK-88-1-6	Poor	100	0												1	Continental	AGS Records
1AA/10-11-087-16W4/00		248.30		248.30	Lower McMurray	Mudstone near top lowest McMurray Channel sand	DK-88-1-5	Poor	100	0												1	Continental	AGS Records
1AA/10-11-087-16W4/00		251.25		251.25	Lower McMurray	Silty mudstone below McMurray Channel sand	DK-88-1-2	Poor	>99	<1		Rare	Low									2	Slightly Brackish	AGS Records
1AA/10-11-087-16W4/00		252.00		252.00	Paleozoic carbonate top	Just below sub-Cretaceous unconformity	DK-88-1-1	Moderate	20	80		Flood	High									0	Paleozoic Sample	AGS Records
1AA/04-08-089-07W4/00	348.00		348.00		Wabiskaw marker	Datum shale	DK-87-2-9	Moderate	>98	<2		Rare	Low	Rare	Low	Rare	Low	Rare	Low	Flood	Moderate	4	Nearshore	AGS Records
1AA/04-08-089-07W4/00	381.00		381.00		Upper McMurray A2		DK-87-2-11	Poor to Moderate	>98	<2		Rare	Low	Flood	Low					Common	Moderate	3	Brackish	AGS Records
1AA/04-08-089-07W4/00	443.00		443.00		Middle McMurray		DK-87-2-12	Moderate	>99	<1	2	Rare	Low	Common	Low					Rare	Low	3.00	Brackish	AGS Records
1AA/04-08-089-07W4/00	496.00		496.00		Middle McMurray		DK-87-2-13	Moderate	>99	<1		Rare	Low	Common	Low							2	Slightly Brackish	AGS Records

Appendix 4 – Dolby Palynological Reports to AGS (1999–2017)

Please refer to the digital copies of the palynological reports produced by G. Dolby included in the 'Appendix 4' folder in the report ZIP file. See Appendix 5 for biostratigraphic charts and count tables. See Appendix 8 for glossary of abbreviations.

Dolby, G. (1999): Palynological analysis of the Steepbank 1-29-92-9W4 & 10-29-92-9W4 wells, northeast Alberta; report to the Alberta Geological Survey [AGS Tarsands Report #1], Project 98.28, 21 p. (includes biostratigraphic charts updated on 16 January 2017).

Dolby, G. (2000): Palynological analysis of core and outcrop samples from the McMurray Formation; report to the Alberta Geological Survey [AGS Tarsands Report #2], Project 9933, 60 p. (includes biostratigraphic charts updated on 21 April 2009).

Dolby, G. (2001): Palynological analysis of core and outcrop samples from the McMurray Formation; report to the Alberta Geological Survey [AGS Tarsands Report #3], Project 2025, 73 p. (includes biostratigraphic charts updated on 20 April 2009).

Dolby, G. (2006): Palynological analysis of four outcrop samples from the McMurray Formation; report to the Alberta Geological Survey, Project 2005.22, 3 p.

Dolby, G. (2017): Palynological analysis of core and outcrop samples from the McMurray Formation; report to the Alberta Geological Survey, Project 2016.01, 20 p.

Appendix 5 – Biostratigraphy Based on Palynofacies Analysis of All Available Samples in Dolby Palynological Reports to AGS (1999–2017)

Biostratigraphic charts for sampled cores and outcrops are included as PDF files in the 'Biostratigraphic Charts' subfolder of the report ZIP file's 'Appendix 5' folder. Palynological analysis data for all sampled cores is available as digital spreadsheets in the 'Palynology Count Tables' subfolder of the 'Appendix 5' folder. Files with the suffix PFAC contain data used for palynofacies determination; files with the suffix STRAT contain data used for stratigraphic age determination. See Appendix 8 for glossary of abbreviations. List of files:

100-11-08-075-08w4.pdf

100-11-08-075-08W4PFAC.xlsx

100-11-08-075-08W4STRAT.xlsx

100-10-30-076-04w4rec1.pdf

100-10-30-076-04w4rec2.pdf

100-10-30-076-04W4PFAC.xlsx

100-10-30-076-04W4STRAT.xlsx

100-15-35-076-04w4.pdf

100-15-35-076-04W4PFAC.xlsx

100-15-35-076-04W4STRAT.xlsx

100-06-15-076-06w4.pdf

100-06-15-076-06W4PFAC.xlsx

100-06-15-076-06W4STRAT.xlsx

1AA-08-14-076-07w4.pdf

1AA-08-14-076-07W4PFAC.xlsx

1AA-08-14-076-07W4STRAT.xlsx

102-10-01-077-07w4.pdf

102-10-01-077-07W4PFAC.xlsx

102-10-01-077-07W4STRAT.xlsx

100-11-15-077-07w4.pdf

100-11-15-077-07W4PFAC.xlsx

100-11-15-077-07W4STRAT.xlsx

100-11-01-077-08w4.pdf

100-11-01-077-08W4PFAC.xlsx

100-11-01-077-08W4STRAT.xlsx

1AA-03-12-081-06w4.pdf

1AA-03-12-081-06W4PFAC.xlsx

1AA-03-12-081-06W4STRAT.xlsx

1AA-05-17-083-06w4.pdf

1AA-05-17-083-06W4PFAC.xlsx

1AA-05-17-083-06W4STRAT.xlsx

100-10-26-083-07w4.pdf

100-10-26-083-07W4PFAC.xlsx

100-10-26-083-07W4STRAT.xlsx

1AA-09-17-088-06w4.pdf

1AA-09-17-088-06W4PFAC.xlsx

1AA-09-17-088-06W4STRAT.xlsx

1AA-10-08-090-07w4.pdf

1AA-10-08-090-07W4PFAC.xlsx

1AA-10-08-090-07W4STRAT.xlsx

1AA-02-04-090-09w4.pdf

1AA-02-04-090-09W4PFAC.xlsx

1AA-02-04-090-09W4STRAT.xlsx

1AE-01-29-092-09w4.pdf

1AE-01-29-092-09W4PFAC.xlsx

1AE-01-29-092-09W4STRAT.xlsx

1AB-10-29-092-09w4.pdf

1AB-10-29-092-09W4PFAC.xlsx

1AB-10-29-092-09W4STRAT.xlsx

100-05-17-092-17W4STRAT.xlsx [no chart available]

1AA-10-26-093-06w4rec2.pdf

1AA-10-26-093-06W4PFAC.xlsx

1AA-10-26-093-06W4STRAT.xlsx

1AA-10-05-095-05w4.pdf

1AA-10-05-095-05W4PFAC.xlsx

1AA-10-05-095-05W4STRAT.xlsx

1AA-04-14-095-11w4.pdf

1AA-04-14-095-11W4PFAC.xlsx

1AA-04-14-095-11W4STRAT.xlsx

1AA-06-36-095-11w4.pdf

1AA-06-36-095-11W4PFAC.xlsx

1AA-06-36-095-11W4STRAT.xlsx

1AA-16-11-096-10w4.pdf

1AA-16-11-096-10W4PFAC.xlsx

1AA-16-11-096-10W4STRAT.xlsx

1AA-05-01-096-11w4.pdf

1AA-05-01-096-11W4PFAC.xlsx

1AA-05-01-096-11W4STRAT.xlsx

1AB-16-02-096-11w4.pdf

1AB-16-02-096-11W41PFAC.xlsx

AB-16-02-096-11W4STRAT.xlsx

1AA-09-11-096-11w4.pdf

1AA-09-11-096-11W4PFAC.xlsx

1AA-09-11-096-11W4STRAT.xlsx

1AD-09-12-096-11w4.pdf

1AD-09-12-096-11W4PFAC.xlsx

1AD-09-12-096-11W4STRAT.xlsx

1AA-09-02-096-12w4.pdf

1AA-09-02-096-12W4PFAC.xlsx

1AA-09-02-096-12W4STRAT.xlsx

1AA-03-28-096-16w4.pdf

1AA-03-28-096-16W4PFAC.xlsx

1AA-03-28-096-16W4STRAT.xlsx

1AA-11-09-099-15w4.pdf

1AA-11-09-099-15W4PFAC.xlsx

1AA-11-09-099-15W4STRAT.xlsx

1AA-16-17-101-13w4.pdf

1AA-16-17-101-13W4PFAC.xlsx

1AA-16-17-101-13W4STRAT.xlsx

Christina River.pdf [no palynological analysis count tables available]

Daphne Island E #1.pdf [no palynological analysis count tables available]

Daphne Island E #2.pdf [no palynological analysis count tables available]

Daphne Island E #3.pdf [no palynological analysis count tables available]

Daphne Island W #1.pdf [no palynological analysis count tables available]

Daphne Island W #2.pdf [no palynological analysis count tables available]

Daphne Island W #3.pdf [no palynological analysis count tables available]

Daphne Island W (Organic).pdf [no palynological analysis count tables available]

Fluvial Marl.pdf [no palynological analysis count tables available]

Pierre Creek (Upper).pdf [no palynological analysis count tables available]

Appendix 6 – Descriptions of Core and Outcrop Palynology Sample Locations

All descriptions are included as individual PDF files in the 'Appendix 6' folder of the report ZIP file. See Appendix 8 for glossary of abbreviations. List of files:

100_10-23-072-07W4_00.pdf

100_11-22-073-06W4_00rec1.pdf [record #1, 2000]

100_11-22-073-06W4_00rec2.pdf [record #2, 2000]

100_11-22-073-06W4_00rec3.pdf [record #3, 2000]

100_11-08-075-08W4_00.pdf

100_12-14-075-08W4_00.pdf

100_10-30-076-04W4_00rec1.pdf [record #1, upper part of core, 2003]

100_10-30-076-04W4_0rec2.pdf [record #2, 2000]

100_10-30-076-04W4_00rec3pdf [record #3, upper part of core]

100_15-35-076-04W4_00.pdf

102_10-01-077-07W4_00.pdf

100_11-15-077-07W4_00.pdf

100_11-01-077-08W4_00.pdf

1AA_05-17-083-06W4_00.pdf

100_10-26-083-07W4_00.pdf

100_13-27-084-11W4_00.pdf

1AA_10-11-087-16W4_00.pdf

1AA_09-17-088-06W4_00.pdf

1AA_10-08-090-07W4_00.pdf

1AA_02-04-090-09W4_00.pdf

0AB_06-09-090-14W4_00.pdf

1AE_01-29-092-09W4_00.pdf

1AB_10-29-092-09W4_00rec1.pdf [record #1, 1998]

1AB_10-29-092-09W4_00rec2.pdf [record #2, 2000]

100_05-17-092-17W4_00.pdf

1AA_10-26-093-06W4_00.pdf

AA_10-05-095-05W4_0.pdf

1AA_06-36-095-11W4_00.pdf

1AA_05-01-096-11W4_00.pdf

1AB_16-02-096-11W4_00.pdf

1AA_09-11-096-11W4_00.pdf

1AD_09-12-096-11W4_00.pdf

1AA_09-02-096-12W4_00.pdf

1AA_03-28-096-16W4_00rec1.pdf [record #1, 1994]

1AA_03-28-096-16W4_00rec2.pdf [record #2 1997]

1AA_03-28-096-16W4_00rec3.pdf [record #3, 2016]

1AA_11-09-099-15W4_00.pdf

1AA_16-17-101-13W4_00rec1.pdf [record #1, 2001]

1AA_16-17-101-13W4_00rec2.pdf [record #2, 2016]

1AA_16-17-101-13W4_00rec3.pdf [record #3, 2001]

Christina River Upstream #3 14-14-088-07W4.pdf

Daphne Island East #1 16-35-095-11W4.pdf

Daphne Island East #2 16-35-095-11W4.pdf

Daphne Island East #3 01-02-096-11W4.pdf

Daphne Island West #1 07-35-096-11W4.pdf

Daphne Island West #2 07-35-096-11W4.pdf

Daphne Island West #3 02-35-096-11W4.pdf

Fluvial Marl 11-17-091-09W4.pdf

Horse River (Road Cut) #4 16-18-089-09W4.pdf

Pierre River Mouth (Lower) 05-30-097-10W4.pdf

Pierre River Mouth (Upper) 12-30-097-10W4.pdf

Steepbank 3-3_16-30-092-09W4.pdf

Appendix 7 – Stratigraphic Picks for Wells Associated with Cores Sampled for Palynological Analysis

Table 14. Stratigraphic picks for wells associated with cores sampled for palynological analysis. Stratigraphic marker terminology after Wynne et al. (1994) and Alberta Energy and Utilities Board (2003). Picks are given as depth in metres below kelly bushing. For a digital spreadsheet version of this table, see file 'Table 14.xlsx' in the 'Appendix 7' folder of the report ZIP file.

Unique Well Identifier	T31	T21	T15	T11	T10.5	E10	A1	A2	B1	B2	McM Ch	E5	preMcM	Pz (Devonian)	Comments
100/11-08-075-08W4/00		426	431.6	436.7		444		444	450.3		453			492	
100/11-22-073-06W4/00				421.9		453					453				
100/11-08-075-08W4/00		426	431.6	436.7		444		444	450.3		453			492	
100/12-14-075-08W4/00				429.5	448	454.5					454.5				
100/10-30-076-04W4/00		334.6		343	345	347	347				350	397.1	408.5		
100/15-35-076-04W4/00		337.5		345	351.4	352.9	352.9				354.5	390		435	
100/06-15-076-06W4/00		310		319.3	321.2	330					330	353.4	380	385	
1AA/08-14-076-07W4/00		329.5		338.4	339.3	361.7					361.7			395	Wabiskaw D shale just below T10.5 surface
102/10-01-077-07W4/00		296		303.9	306.5	307.5	307.5	316.9			335.28		363.6	364.3	
100/11-15-077-07W4/00		305.3		313	313.9	327.7					327.7	359.7	364.1	365.6	
100/11-01-077-08W4/00		302.7		310		313	313	315.5			316			365.2	from core seems all McM Ch to base
1AA/03-12-081-06W4/00		202.7		212.7	215	218					230	253.5		281	upper McMurray undefined units
1AA/05-17-083-06W4/00		306.8	309.2	313	314.1	315.5					315.5		346.45	347.4	
100/10-26-083-07W4/00						361					361		433.9		
1AA/10-11-083-11W4/00				447.4		448.9	448.9	452	453.6		455				
100/13-27-084-11W4/00				261		265					265			313	
1AA/09-17-088-06W4/00					92.1	104.5					104.5				
1AA/10-08-090-07W4/00		124.5		132.3	136.4	137					137			193	originally Wabiskaw D shale & valley fill misidentified as upper McMurray
1AA/02-04-090-09W4/00		55.5		63	67.6	69.2					69.2	121.3		137	
1AB/06-09-090-14W4/00		171.3		183	184.2	200					200	206.2		212.5	
100/05-17-092-17W4/00		202.5		222.3	234.8	244.9					244.9		259.29	262	
1AE/01-29-092-09W4/00						19					19	88.4	103.5		core starts in McM Chnl; base of Quaternary at 9.8 m
1AB/10-29-092-09W4/00			16	19	22	25		25			27.75	71.5	83	86.5	originally upper McM A2 misidentified as Wabiskaw D on logs
1AA/10-26-093-06W4/00		250.2	252	254	258	262.8					262.8			304.7	
1AA/10-05-095-05W4/00				231.8	233.5	235.5	235.5	237			241.5				
1AA/04-14-095-11W4/00				24		29					48	54		64	upper McMurray undefined units; base of Quaternary at ~ 7.5 m
1AA/06-36-095-11W4/00						5					5	46.3	67.69	68.5	base of Quaternary ~ 2 m
1AA/16-11-096-10W4/00						30					30	90		134.5	
1AA/05-01-096-11W4/00						3.5					3.5	54.7	59.6	75.8	pre-McMurray marl and weathered Devonian at 75.8 m
1AB/16-02-096-11W4/00					2.5	5.4					5.4	59	76	99	pre-McMurray marl and weathered Devonian at 75.8 m
1AA/09-11-096-11W4/00						40.5					40.5	76	101.5	112	
1AD/09-12-096-11W4/00				12		21	21	25	32	36.5	42	92	115.2		questionable A1 (21 m) and A2 (25 m)
1AA/09-02-096-12W4/00		21.9		29		31.2					31.2	92.7	124.1		
1AA/03-28-096-16W4/00		349	356	359.2	363	390					390			409	
1AA/11-09-099-15W4/00				428.35	432	436.5					436.5			456.9	
1AA/16-17-101-13W4/00	397.5	461.2		466.3		475.5		475.5			499.5	531.1		535.2	thick Wabiskaw fill; upper McMurray undifferentiated

T31 = marker in the Clearwater Formation; not usually picked
T21 = top of Wabiskaw Member = top of Wabiskaw A; base of Wabiskaw marker (on logs)
T15 = top of Wabiskaw B; top of Wabiskaw B-equivalent coarsening-upward sequence; top of Wabiskaw B valley fill (in South Athabasca area)
T11 = top of Wabiskaw C; top of Wabiskaw C sand unit
T10.5 = top of Wabiskaw D; if top Wabiskaw D shale and top of Wabiskaw D valley fill are both picked, then the upper (shallower) one is the top of the Wabiskaw D
E10 = top of McMurray Formation; major unconformity, so the stratigraphy is variable beneath this surface
A1, A2, B1, B2, C1, C2 = regional coarsening-upward sequences typical of the upper McMurray Formation; channels from any level may cut into these sequences
McM Ch = top of McMurray channel succession; if overlain by the regional coarsening-upward successions of the upper McMurray Formation, then this is the middle McMurray; commonly undifferentiated unless overlain by regional capping mudstones
E5 = top of lower McMurray channel succession; locally preserved, mainly fluvial and continental overbank deposits
pre-McM = top of pre-McMurray older paleosols, overbank, lacustrine marls, karst-lacustrine marls (cenote deposits), rooted zones along sub-Cretaceous unconformity
Pz = top of Paleozoic, regional sub-Cretaceous unconformity surface

Appendix 8 – Glossary of Abbreviations Used in Appendices

AER	Alberta Energy Regulator
AGS	Alberta Geological Survey
AC	acritarch
AL	algae
ALBO	algae and *Botryoccoccus* colonies
BM	bi-modally sorted kerogen
C	Celsius
CO	core depth, modifier to sample depth, determined from measurement on recovered core section
DC	dinocyst or dinoflagellate cysts
E	Easting (x-coordinate) in UTM coordinate system, refers to the eastward-measured distance from the Greenwich Meridian (0o longitude)
EP	extremely poorly sorted kerogen
Fm./Fm	formation, a fundamental lithostratigraphic designation of a unit of rock, in which the rocks of a formation have similar lithology, facies or other distinguishing properties. Geological formations are distinguishable at a mappable scale.
ft./ft (')	feet
FU	fungi
Ground	ground elevation for a well
I.H.S.	inclined heterolithic stratification
indet.	indeterminate, unassignable, usually fragments or biodegraded
KB	kelly bushing elevation, used as a depth reference point for a well
km	kilometres
Litho.	lithostratigraphy
LOG	log depth, modifier to sample depth, determined from wire-line logs
mm	millimetres
m	metres
misc.	miscellaneous
Ma	million years (Latin abbreviation of “mega-annum”
Mbr./Mbr	member, a subdivision of a geological formation; used for more detailed geologic description, where members have local geological significance.
N	northing (y-coordinate) in UTM coordinate system; refers to the eastward-measured distance from the Equator
OS1	new, previously unidentified species (i.e. Cyst OS1 is a new, previously unidentified species of cyst found in the oil sands)
Paly	palynology
P	poorly sorted kerogen
PFAC	palynofacies (excel tables with biostratigraphic charts, used to determine the type of palynofacies for the sediment in the sampled core)
pH	potential of hydrogen; a numeric scale used to identify the acidity or basicity of an aqueous solution. Solutions < 7 are acidic; solution > 7 are basic
RW	reworked
sand	on outcrop descriptions refers to sand lithologies, with the following modifiers: v (on left side of grain-size scale), very coarse; c, coarse; m, medium; f, fine; v (on right side of grain-size scale), very fine
Sl.win.	slightly winnowed, refers to sorting
sp.	Latin abbreviation for single species

spp.	Latin abbreviation for multiple species
SP	spores and pollen
STRAT	stratigraphy (excel tables with biostratigraphic charts, used to determine the age of sediment for the sampled core)
TD	Total depth of core
UTM	Universal Transverse Mercator coordinate system
UWI	Unique Well Identifier format
VP	very poorly sorted kerogen
V. poor	very poor, refers to sorting
%	per cent sign, used to indicate a percentage, or ratio as a fraction of 100.
#	number (integer count)