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Alberta Energy Regulator

Geological Characterization of the Lower Clearwater Shale in the Athabasca Oil Sands Area, Townships 87–99, Ranges 1–13, West of the Fourth Meridian

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Geological Characterization of the Lower Clearwater Shale in the Athabasca Oil Sands Area, Townships 87–99, Ranges 1–13, West of the Fourth Meridian

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Abstract

This report focuses on regional geological mapping of the Cretaceous strata, specifically the extent and thickness of the lower Clearwater shale unit that overlays the Wabiskaw-McMurray bitumen deposit. The study area (Twp. 87 to 99, Rge. 1 to 13, W 4th Mer.) is located in the Athabasca Oil Sands Area in northeastern Alberta and encompasses most of the surface-mineable area and the northeastern extents of the Wabiskaw-McMurray bitumen deposit. The objective of the study was to characterize the units above and below the bitumen-bearing zones. We mapped the erosional zero edge of the unit in the northern part of the study area highlighting where the lower Clearwater shale unit is thin (<5 m thick) or absent. Over most of its extent in the study area, the lower Clearwater shale was found to be between 20 and 30 m thick. Results from petrographic and mineralogical analyses on shale, silty shale, and siltstone samples showed that the lower Clearwater shale ranged from a quartz-rich shale to a carbonaceous silty shale to argillaceous siltstone. The total clay content of the samples ranged from 13% to 31%. In addition, Light Detection and Ranging (LiDAR) bare earth digital elevation model (DEM) images were used to locate the surface expression of sinkholes.

1 Introduction

This report focuses on the mapping completed on the lower Clearwater shale in northeastern Alberta. Geophysical logs and petrophysical analysis were used to map and characterize this unit. In addition, light detecting and ranging (LiDAR) remote sensing images were used to highlight surficial features found in the study area.

The project study area is located within the Athabasca Oil Sands Area, from Twp. 87 to 99, Rge. 1 to 13, W 4th Mer (Figure 1). This area encompasses most of the Athabasca Oil Sands surface mineable area (SMA) and covers the northeastern extents of the Athabasca Wabiskaw-McMurray bitumen deposit. Figure 2 presents a base map of the study area showing the distribution of wells that contain a lower Clearwater shale stratigraphic pick, the trajectories of cross-sections presented in this report, as well as the locations of provincial parks and conservation areas. Figure 3 shows digital elevation model (DEM) for the study area overlain with physiography (Pettapiece, 1986; Andriashek and Atkinson, 2007) and hydrography. The study area includes the topographic highs of the Birch and Muskeg mountains and lows along the valleys of the Athabasca and Clearwater rivers.

According to *ST98-2014*—the Alberta Energy Regulator's (AER) annual report on Alberta energy reserves (Alberta Energy Regulator, 2014)—initial volume in place of crude bitumen for the entire Athabasca Oil Sands Area Wabiskaw-McMurray deposit is estimated to be 20 823 10^6 m^3 for mineable resources and 131 609 10^6 m^3 for in situ resources (Table 1). The in-place resource values represent the total crude bitumen accumulated throughout the deposit where the cumulative bitumen pay thickness is equal to or greater than 1.5 m. North of Fort McMurray, crude bitumen occurs near the surface and can be recovered economically by open-pit mining in the SMA (Figure 1). The AER-defined SMA encompasses 51½ townships, covering the part of the Athabasca Wabiskaw-McMurray deposit where the total overburden thickness does not exceed 65 m. Outside the SMA, in situ thermal recovery techniques are currently the only economically viable option for bitumen recovery. The most common are steam assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS).

Table 1. Initial in-place volumes of crude bitumen as of December 31, 2013 (Alberta Energy Regulator, 2014).

Oil sands deposit	Initial volume in place (10^6 m^3)	Area (10^3 hectares)	Average pay thickness (m)
Wabiskaw-McMurray (mineable)	20 823	375	25.9
Wabiskaw-McMurray (in situ)	131 609	4 694	13.1

The objective of the study was to characterize the units above and below the bitumen-bearing zones in northeastern Alberta in order to provide insight into geological issues that may affect caprock integrity in the study area. This report focuses on the formation directly above the bitumen and the other reports from the study focuses on units below the resource where halite dissolution has impacted the structure (Mei et al., in press, Schneider et al., in press).

2 Methods

This study involved the mapping of well-known and regionally correlatable stratigraphic units from the Paleozoic up to the base of drift. Stratigraphic tops were picked using geophysical wells logs, in both digital and raster format, supplemented by drill core investigations. Stratigraphic picks were made using

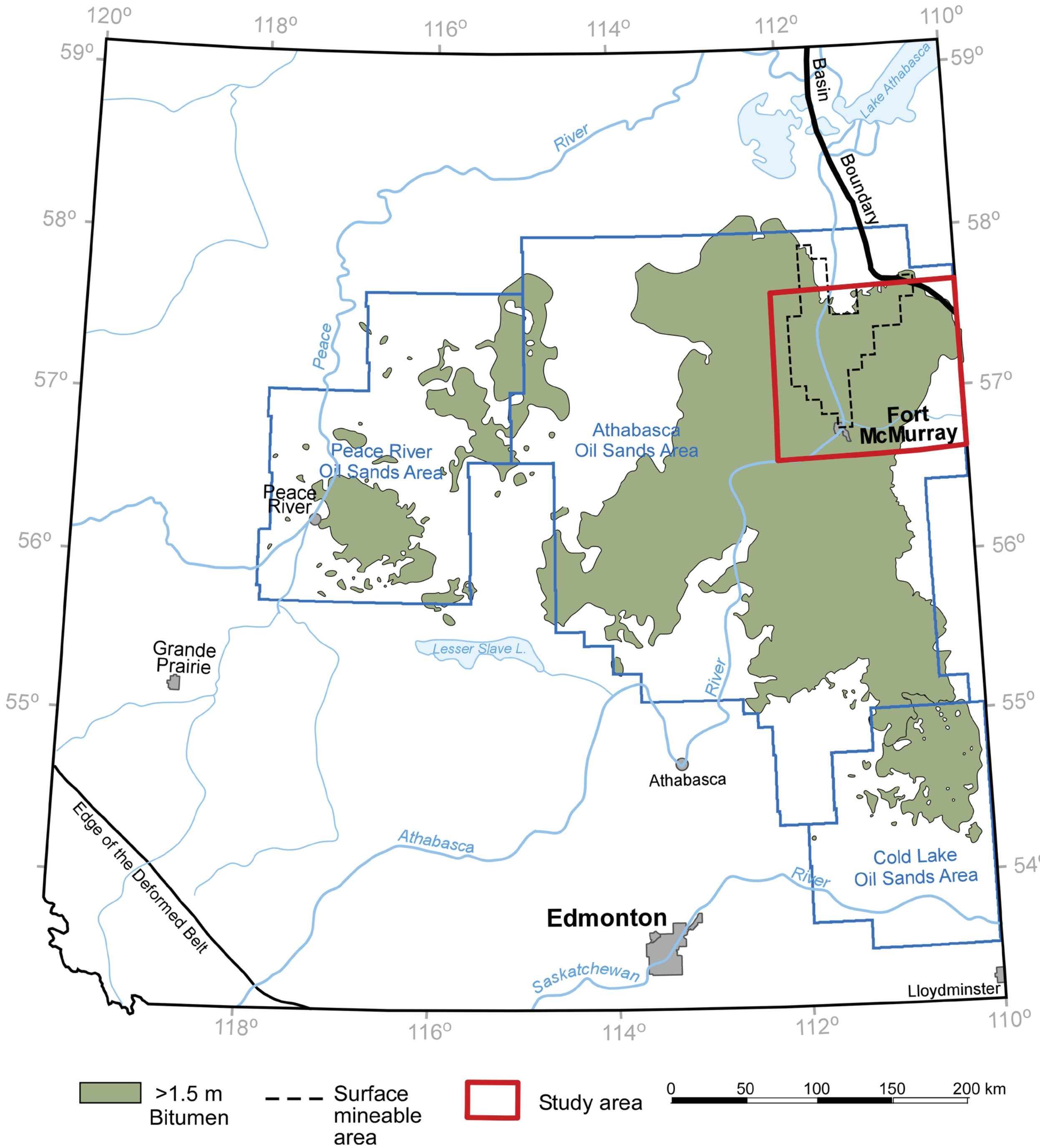


Figure 1. Study area in the Athabasca Oil Sands Area. Bitumen outline from Alberta Energy Regulator (2014).

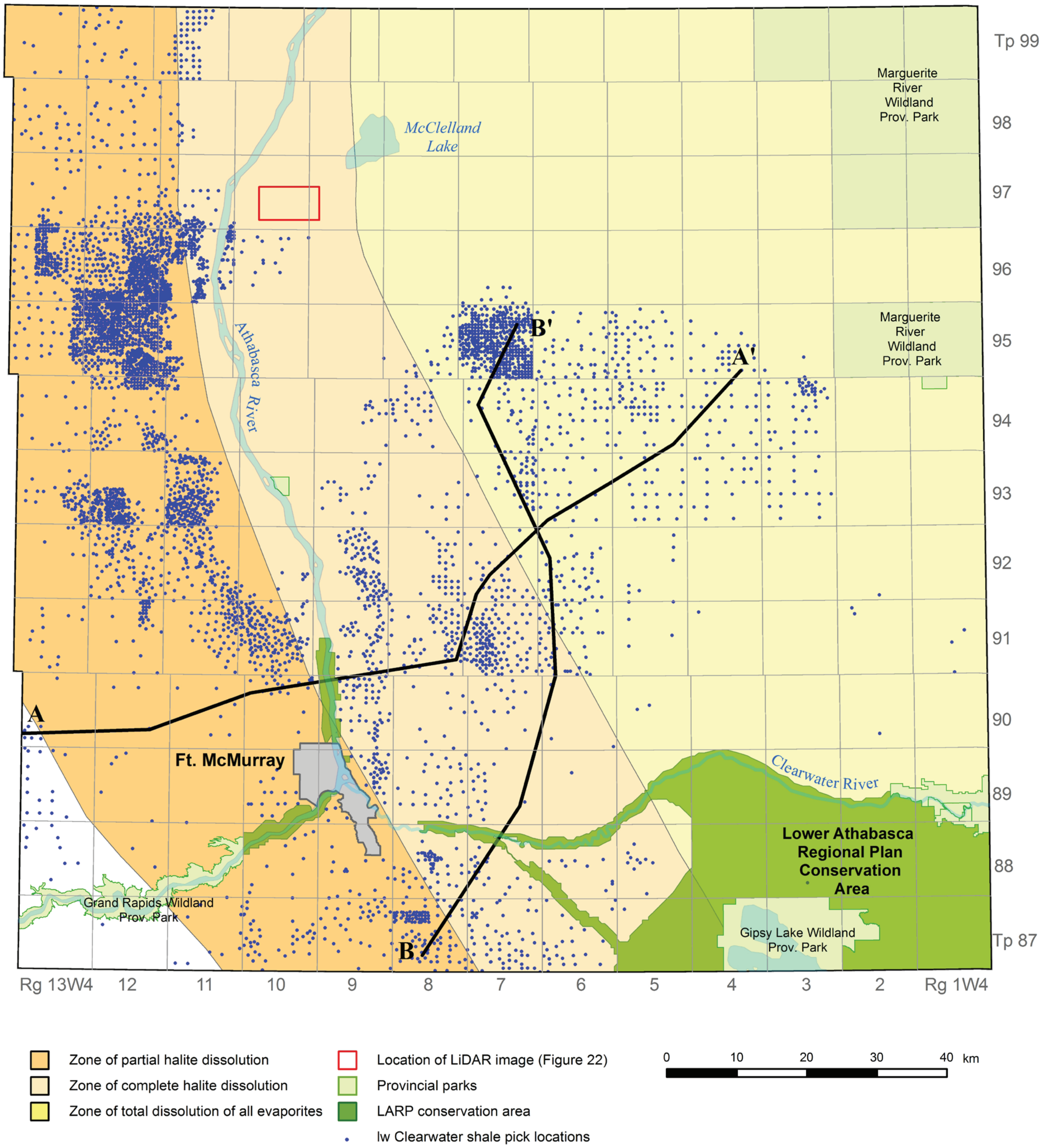


Figure 2. Study area base map showing the distribution of wells with a lower Clearwater shale stratigraphic pick, the trajectories of cross-section A–A′ and B–B′, and the location of provincial parks and conservation areas. Dissolution zone underlay modified from Schneider and Grobe (2013).

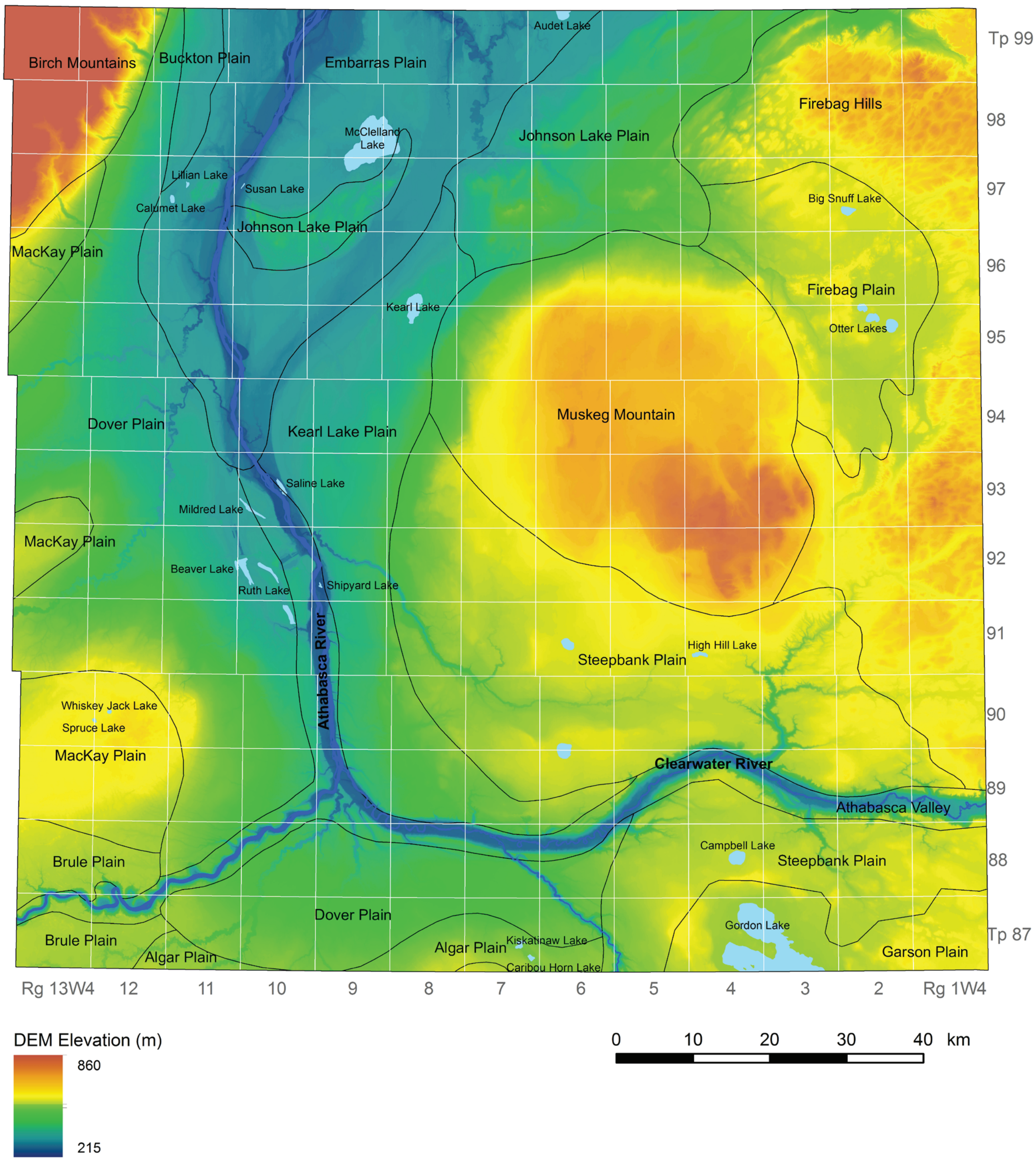


Figure 3. Digital elevation model (DEM) of the study area overlain with physiography (Pettapiece, 1986) and hydrography (modified from Andriakshek and Atkinson, 2007). DEM provided by Environment and Sustainable Resource Development.

IHS Petra and AccuMap software and recorded in an Access database. Cross-sections and contour maps were completed using IHS Petra and ESRI's ArcMap geospatial processing tool, respectively.

For the results presented in this report the well logs were selected according to the following criteria:

1) Only well logs from vertical wells and deviated wells that were corrected to true vertical depth (TVD) were used. Logs from deviated wells without correction to TVD were not used.
2) The majority of well logs used were recorded after 1980. Older logs were used where necessary in areas of low well density.
3) Preference was given to downhole geophysical well-log suites that included the following geophysical logs: gamma ray, neutron, density, and resistivity. In addition, preference was given to high-quality geophysical logs with large vertical section and representative log signature.
4) In areas of extremely high well density (such as in the SMA) a minimum of two delineation wells per section were used.

In the area where the Clearwater Formation is thin, close to its erosional zero edge, wells are sparse and suitable well logs from all wells drilled in this area were used. The study area contains 169 townships, approximately 20 of which had no suitable well logs and therefore no stratigraphic picks. The maximum number of wells with stratigraphic picks per township was 670 in Twp. 97, Rge. 12. Figure 2 shows the distribution of all wells in which stratigraphic picks for the top of the lower Clearwater shale were made. During the mapping process, picks were checked relative to one another on stratigraphic cross-sections. Stratigraphic picks made on logs recorded behind casing were not included on the cross-sections or maps due to decreased confidence in picks. Also, contour maps were created using IHS Petra software to identify and check for outliers, which appear as 'bull's-eyes' on a map.

3 Stratigraphic Framework

Figure 4 illustrates the stratigraphic and hydrostratigraphic succession within the study area. The lowermost units in the succession are the Devonian carbonates, evaporites, shales, and sandstones that sit unconformably above the Precambrian basement. Regionally, the Devonian strata form an eastward-tapering wedge. The Devonian is unconformably overlain by the sandstone and shale succession of the Lower Cretaceous Mannville Group. The uppermost units are unconsolidated Quaternary and Holocene sediments.

In the study area, the Devonian succession directly and unconformably overlies the Precambrian basement. At the base of the Elk Point Group, the La Loche Formation (granite wash) consists of sandstones and thin shales. The La Loche Formation is overlain by the dolomitic, shaly siltstone to silty shale of the Contact Rapids Formation, which is then overlain by the Keg River Formation dolostone. The Prairie Evaporite Formation of the Elk Point Group consists of halite and anhydrite with minor dolostone, limestone, and shale. The Prairie Evaporite Formation (where present) is conformably overlain by the shale, silty shale, and dolostone of the Watt Mountain Formation, which is the uppermost unit of the Elk Point Group.

The Elk Point Group is overlain by the Fort Vermilion (shale and anhydrite), Slave Point (limestone), and Waterways (limestone) formations of the Beaverhill Lake Group. Above this are Woodbend Group strata, consisting of limestones of the Cooking Lake Formation and overlying calcareous shale of the Ireton Formation. These are present only in the southwestern corner of the study area, the rest of the Woodbend Group succession having been removed by erosion (Schneider and Grobe, 2013).

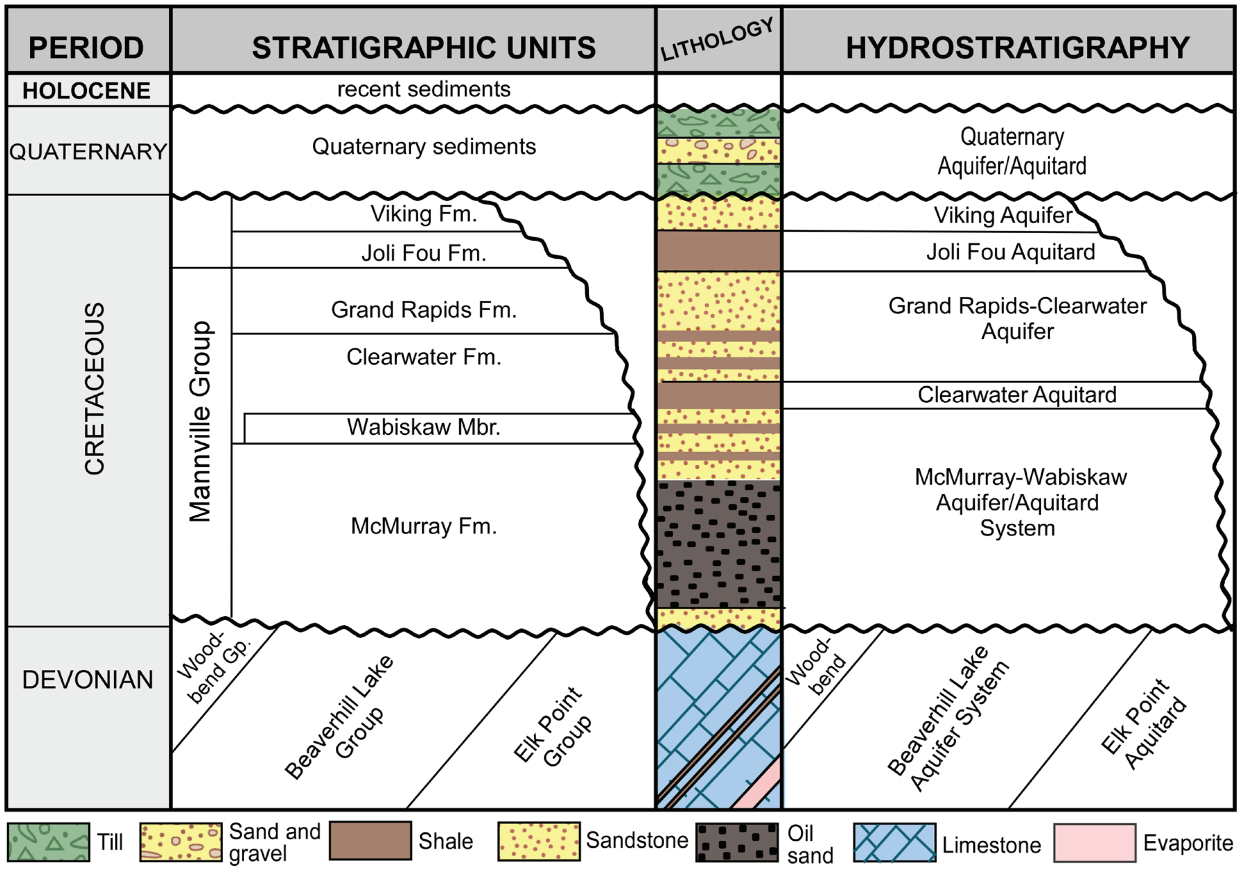


Figure 4. Stratigraphic and hydrostratigraphic nomenclature for the study area. Hydrostratigraphy from Bachu et al. (1996).

Across most of the study area, the sub-Cretaceous unconformity overlies the Waterways and Slave Point formations of the Beaverhill Lake Group; however, at some locations, erosion by the Athabasca and Clearwater rivers has exposed strata as old as the Keg River Formation (Elk Point Group). The unconformity surface represents a depositional hiatus of approximately 250 million years.

The McMurray Formation is the basal unit of the Lower Cretaceous Mannville Group. It directly overlies the sub-Cretaceous unconformity and consists of fluvio-estuarine clastic deposits which are commonly bitumen saturated. Stacked channels provide a range of lithofacies, including blocky channel sands, interbedded sandstone, and shale in the form of inclined heterolithic strata, channel abandonment mud plugs, breccia horizons, and intervals deposited on muddy flood plains and tidal flats. The regional McMurray-Wabiskaw resource has been extensively characterized and mapped in the study area (Carrigy and Kramers, 1973; Hein and Langenberg, 2003; Hein and Cotterill, 2006: Hein et al., 2012; ERCB, 2003; Ranger and Gingras, 2003, 2008).

Directly overlying the McMurray Formation is the Clearwater Formation: a succession of marine mudstone and siltstone including, at its base, the Wabiskaw Member. The Wabiskaw Member is subdivided, from top to bottom, into the Wabiskaw A sandstone (a typically thin unit of water-saturated sandstone and silty mudstone), the Wabiskaw A shale (a 2–5 m unit with similar lithology to that of the lower Clearwater), and the Wabiskaw C sandstone (a thin, ~1 m, glauconitic water sand unit which can be interpreted as the uppermost unit and has the potential of direct communication with the Wabiskaw-

McMurray deposit). The Wabiskaw Member may also include a lowermost Wabiskaw D sandstone and shale, which typically contains wavy interbeds of bitumen rich sand and thin steely grey mud.

The Clearwater Formation is a laterally continuous unit which consist largely of silty shale with a minor component of interbedded siltstone or sandstone. Where the Grand Rapids Formation is eroded, the Clearwater Formation subcrops Quaternary sediments. The Clearwater Formation has been eroded in the northeastern corner of the study area and in the Clearwater and Athabasca River Valleys.

Hydrostratigraphically, the Clearwater Formation is considered a regional aquitard. However in the study area, the lithology of the Clearwater Formation is variable so that the upper part of the formation was included with the Grand Rapids aquifers, and the sandstones of the Wabiskaw Member at the base were included as part of the McMurray-Wabiskaw aquifer (Bachu et al., 1996; Figure 4). The remainder of the Clearwater Formation unit was classified as the Clearwater aquitard.

The Clearwater Formation is overlain by the alternating sandstone and mudstone shoreface deposits of the Grand Rapids Formation. The Grand Rapids Formation is limited to the southwestern portion of the study area. The Grand Rapids Formation may be overlain by the Joli Fou and Viking formations of the Colorado Group, but these units have been removed by erosion prior to deposition of the Quaternary sediments across most of the study area with the exception of the southwest corner.

The Quaternary sediments rest unconformably on Lower Cretaceous strata (Figure 4). Andriashek and Atkinson (2007) completed an extensive study of the buried channels and glacial-drift aquifers in the Fort McMurray region. They described the sedimentary succession overlying the post-Cretaceous unconformity in the study area as being composed of finer grained sediments deposited during the advance and retreat of Quaternary ice sheets as well as a sequence of coarser fluvial sediments. Figure 5 shows the location of buried channels that are indicative of erosion by subglacial meltwater. Within this study area there is currently no indication of the presence of preglacial Neogene sand and gravel within the buried valleys (Andriashek and Atkinson, 2007). Hein et al. (2012) determined that caprocks may be removed by erosion associated with the development of incised valleys that cut down from the post-Cretaceous unconformity.

4 Clearwater Formation Pick Description

Two cross-sections (Figure 6 and Figure 7) illustrate the regional stratigraphic correlations in the study area. The locations of the cross-sections can be found in Figure 2. The northeast-oriented structural cross-section A–A′ (Figure 6) illustrates the consistent thickness of the lower Clearwater shale unit across the study area with the exception of where it is eroded along the Athabasca River. The filled logs highlight intervals where gamma-ray values exceed 90 API. This study used gamma-ray value of 90 API and 60% vshale in maps and cross-sections; this is a the conservative cutoff for separating shale from nonshale deposits for visualization purposes only and may not reflect values used for regulatory requirements. The north-oriented stratigraphic cross-section B–B′ (Figure 7) shows the incision of the Clearwater River in the south and the beginning of the erosional thinning of the lower Clearwater shale at the northern extent of the cross-section.

Representative wells AA/11-27-094-03W4/0 (Figure 8) and AA/07-13-095-13W4/0 (Figure 9) depict the stratigraphic picks on geophysical logs in detail. When the logs are compared it becomes apparent that the lower Clearwater shale log signature is consistent and distinctive with high gamma-ray API. The Clearwater Formation strata overlying the lower Clearwater shale exhibit more variability due to changes in the number and thickness of interbedded sandstone units with low gamma-ray signature.

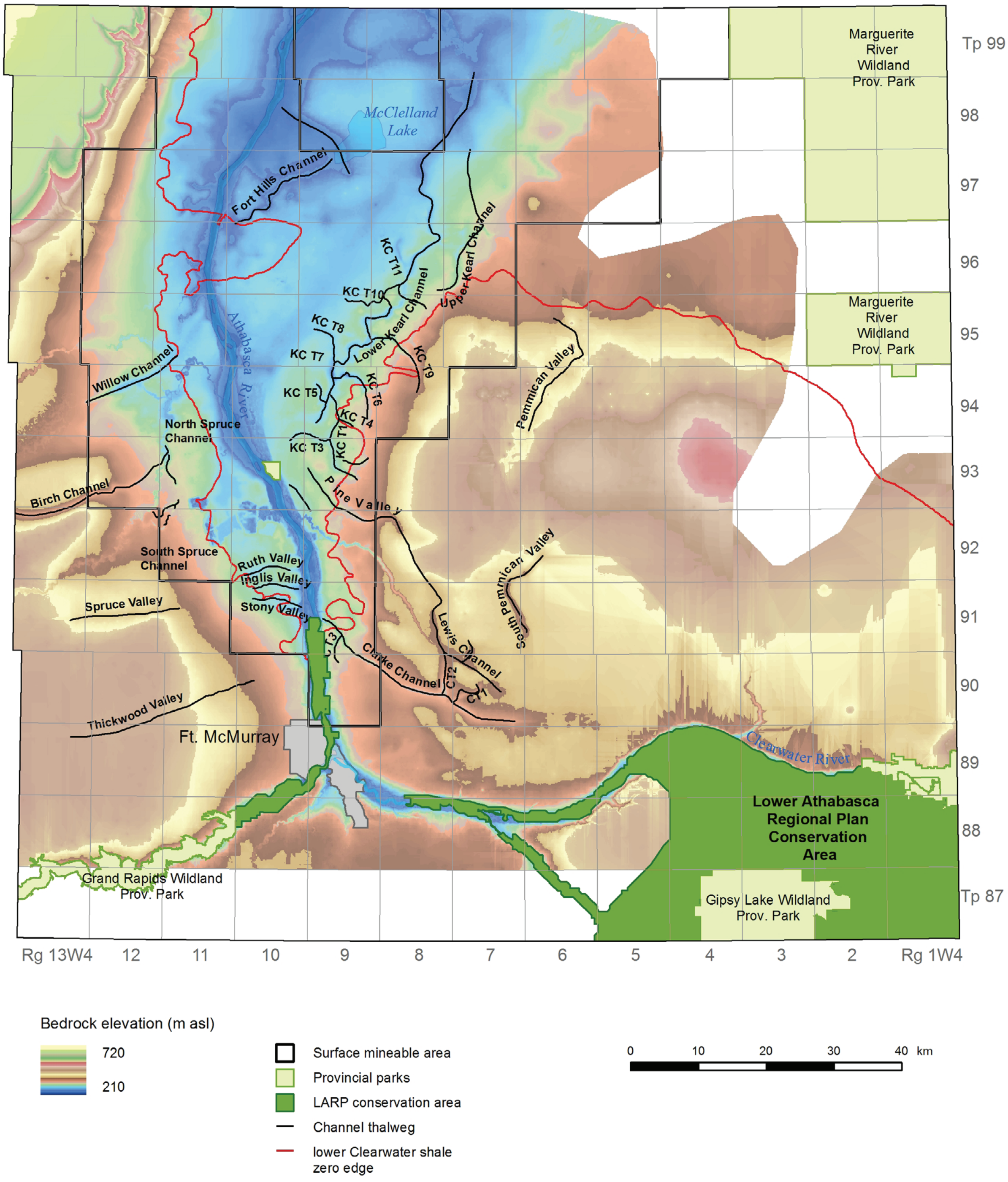


Figure 5. Bedrock topography and preglacial buried channels (modified from Andriashek and Atkinson, 2007).

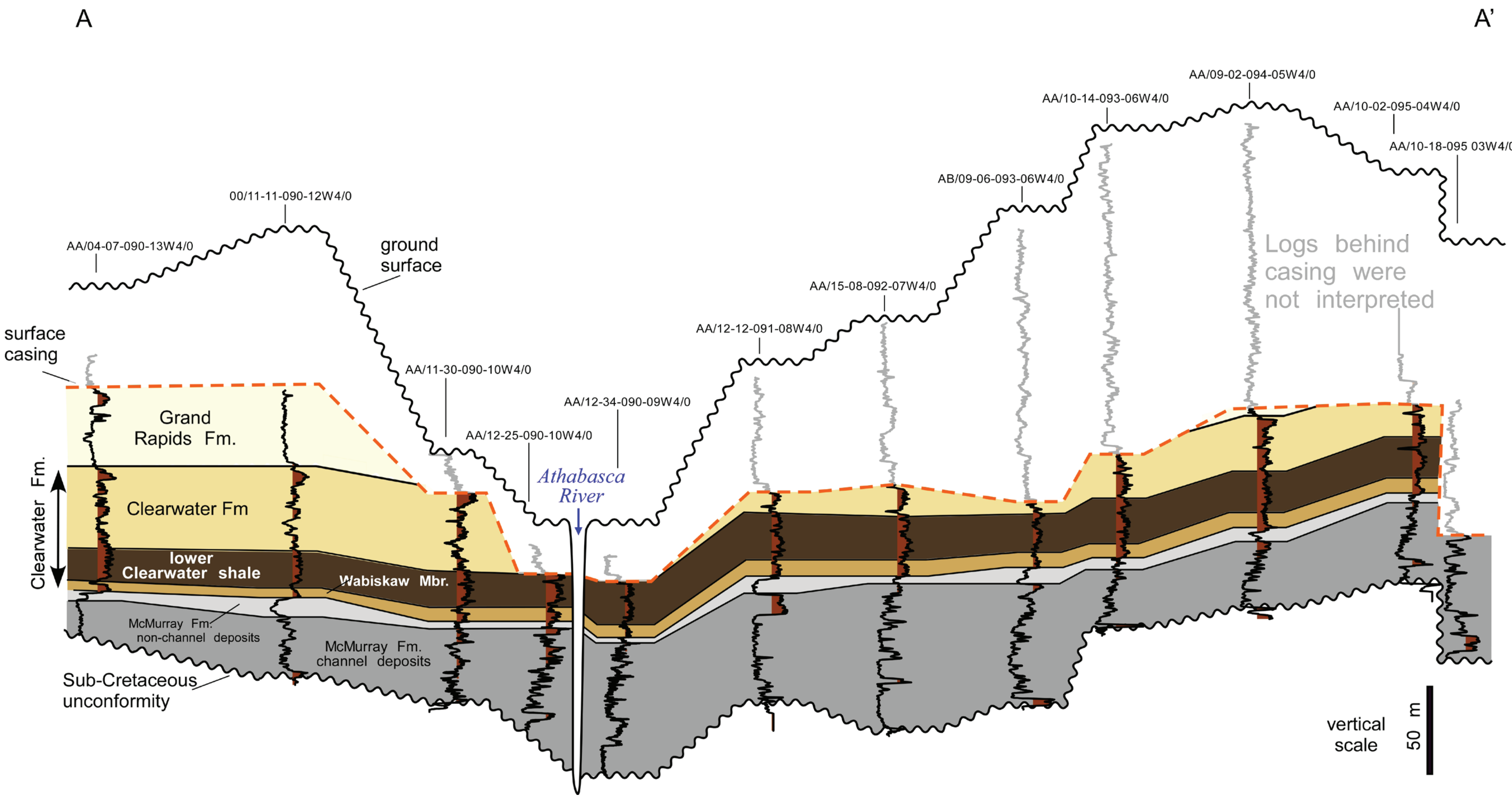


Figure 6. Northeast-oriented structural cross-section A–A′ of the study area. Gamma ray signature larger than 90 API filled in with brown.

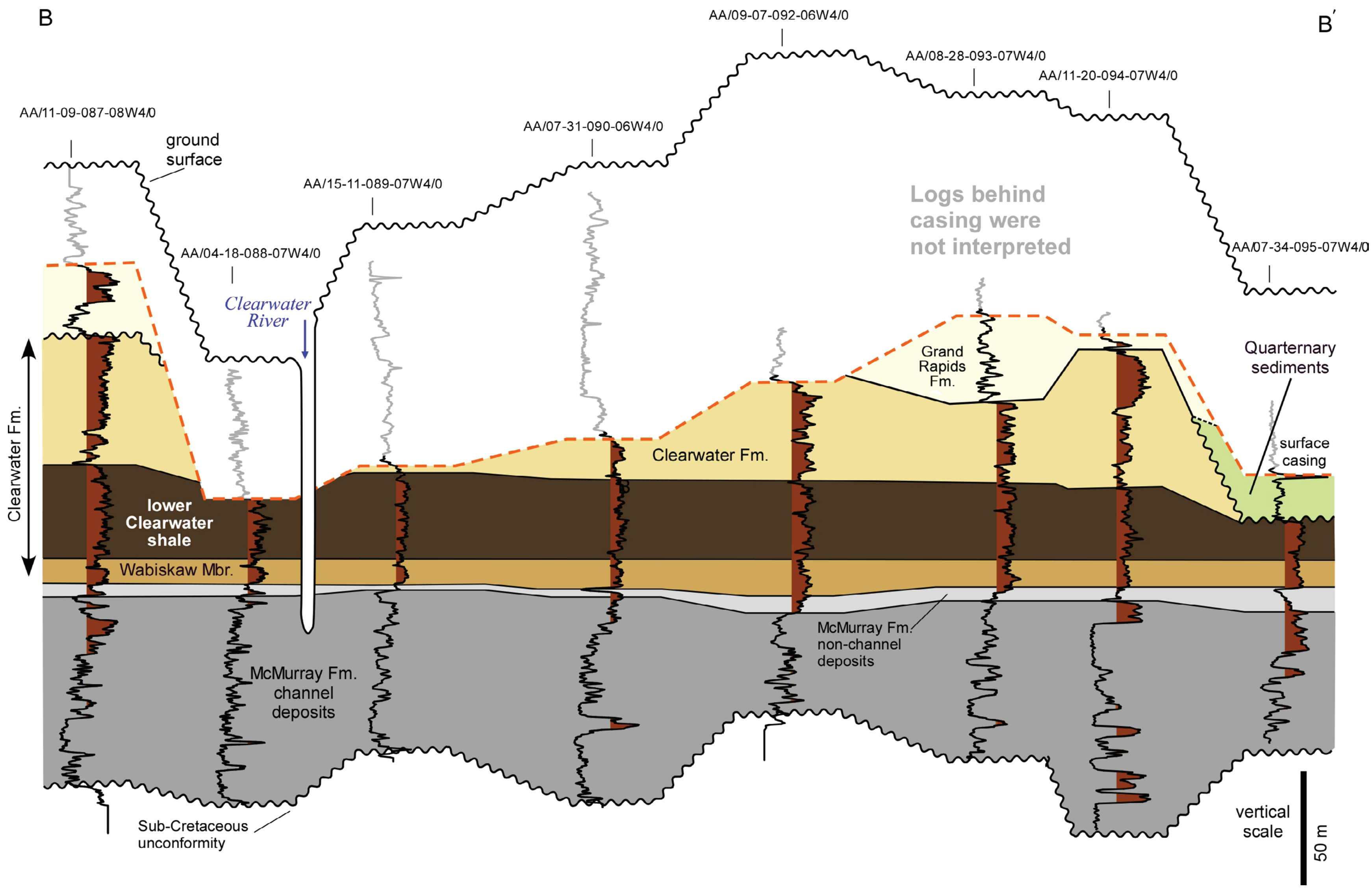


Figure 7. North-oriented stratigraphic cross-section B–B′ of the study area. Datum is the top of the Wabiskaw Member (base of the lower Clearwater shale). Gamma-ray curves with values larger than 90 API filled in with brown.

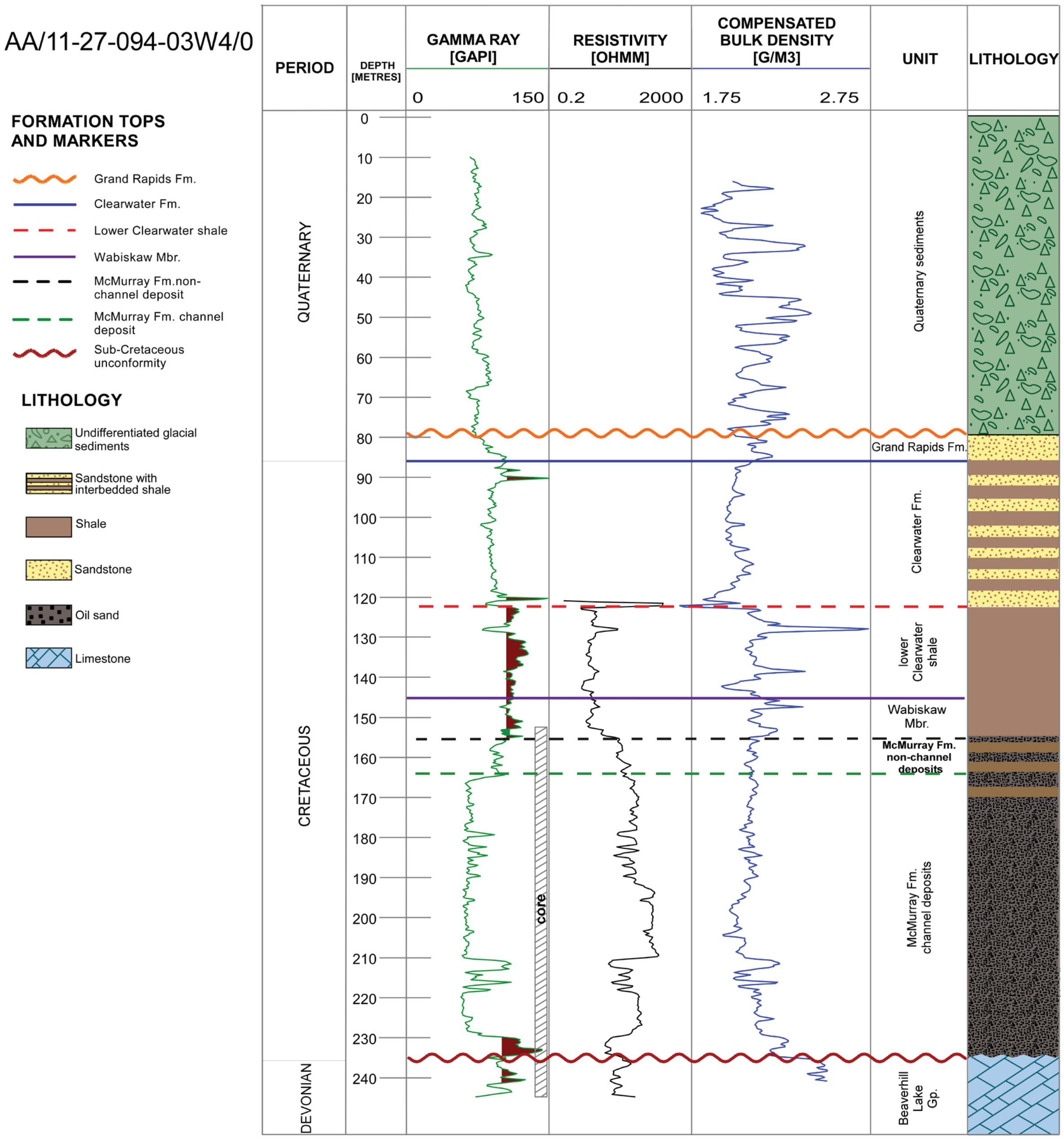


Figure 8. Type log for well AA/11-27-094-03W4/0. Gamma-ray curve with values larger than 90 API filled in with brown.

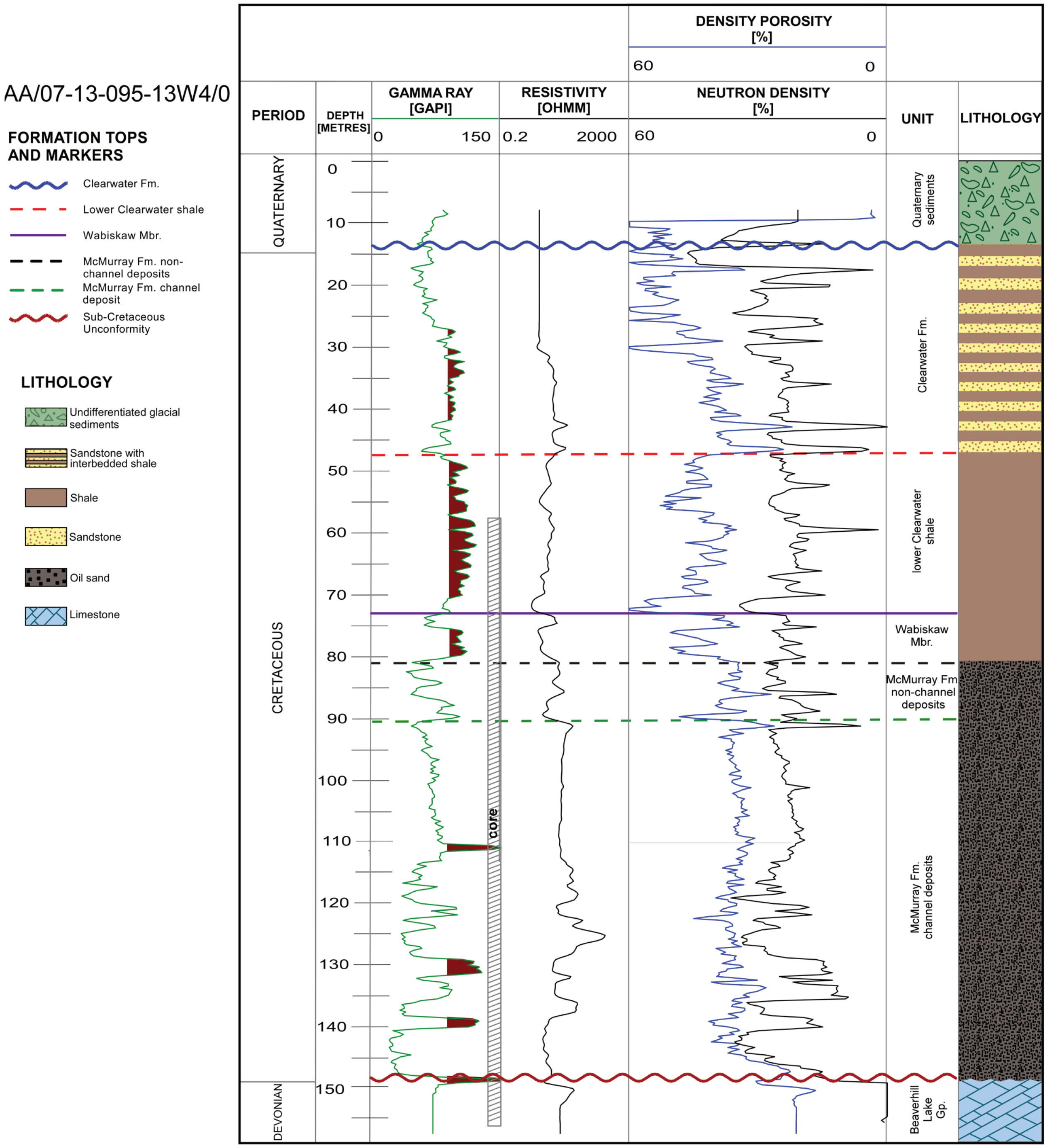


Figure 9. Type log for well AA/07-13-095-13W4/0. Gamma-ray curve with values larger than 90 API filled in with brown.

Stratigraphic picks were made on the following unit tops: Wabiskaw Member (separated into Wabiskaw A, Wabiskaw C, and Wabiskaw D units where present), lower Clearwater shale, Clearwater Formation, and top of bedrock (base of preglacial and glacial deposits). It was out of the scope of the project to pick the member units at a resolution fine enough to map across the study area. Figure 10 shows a representative well across the Wabiskaw Member.

The Wabiskaw D unit consists of alternating sandstone and wavy nonparallel dark grey shale interbeds. The shale portions of the Wabiskaw D unit are fissile organic shale that can be up to 3 m in thickness. On logs, the contact between the Wabiskaw D sandstone and the overlying Wabiskaw C unit is marked by a step-like fining-upward trend, indicated by an upward increase in gamma-ray API value, which commonly lies beneath a double density spike at the base of the Wabiskaw C unit. The Wabiskaw D sandstone is commonly bitumen saturated, resulting in a resistivity signature that is higher than that of the Wabiskaw C sandstone but generally not as high as that observed in the McMurray Formation (Figure 10). Hein et al. (2012) gave a range of gamma-ray values from 20–30 API for Wabiskaw D sand and 75–90 for Wabiskaw D shale.

The Wabiskaw C unit consists of a thin (1 to 2 m thick), fining-upward interval of quartzose and glauconitic sandstone. It is identified on logs by a lowered gamma-ray signature and a corresponding increase on the density log. Hein et al. (2012) found the gamma-ray signature of the Wabiskaw C unit to range from 60–90 API and density porosity to be up to 30%. The unit can readily be identified within the Wabiskaw Member as the first large inflection to the right on both the neutron-porosity and resistivity logs.

The Wabiskaw B unit does not occur within the study area, and the Wabiskaw C sandstone is conformably overlain by the Wabiskaw A shale, which is typically 4 to 7 m thick and is present over the entire extent of the Wabiskaw Member in the study area. The Wabiskaw A shale is a blocky to moderately fissile shale, with a negligible sandstone and siltstone content, and little bioturbation. It is characterized in logs by a consistent, fairly high gamma-ray, high density, and low resistivity log signature.

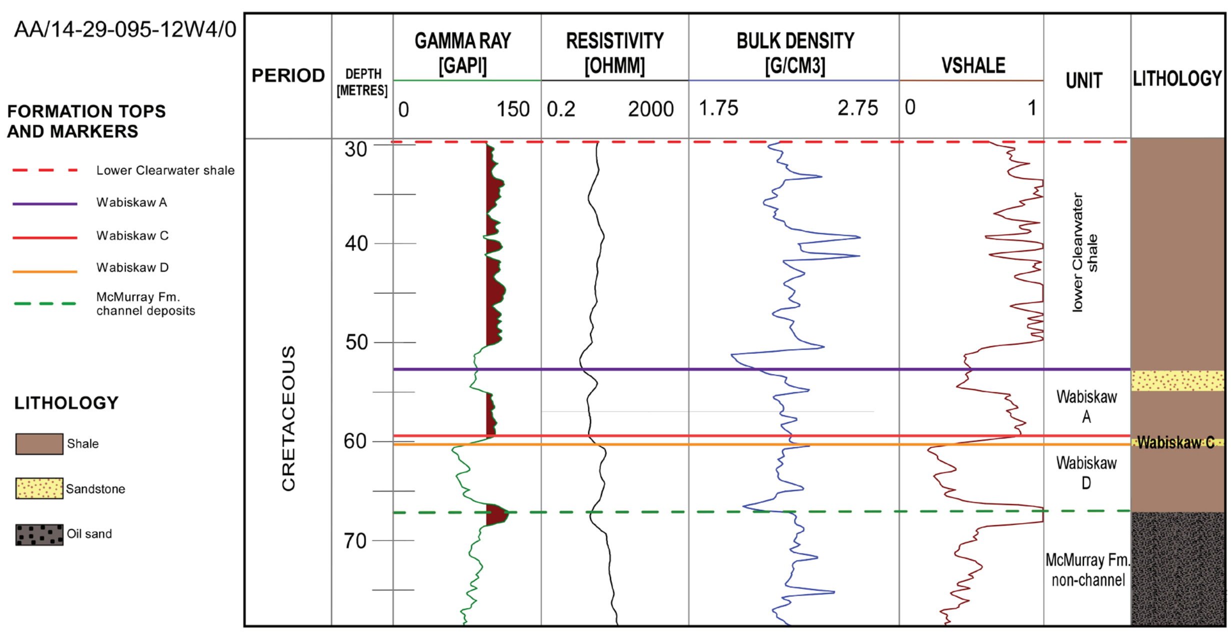


Figure 10. Cropped type log for well AA/14-29-095-12W4/0 – Representative log highlighting Wabiskaw Member units. Gamma-ray curve with values larger than 90 API filled in with brown.

The uppermost unit of the Wabiskaw Member is the Wabiskaw A sandstone. This unit is generally 2 to 3 m thick, although in the western portion of the study area it can be substantially thicker. It consists of bioturbated, moderately glauconitic sandstone and interbedded shale and has a conformable lower contact on the underlying Wabiskaw A shale. The log response and lithology of the Wabiskaw A sandstone are similar to those of the Wabiskaw C sandstone, with a lowered gamma-ray signature, which can lead to confusion with the overlying T21 marker (see below).

The top of the Wabiskaw Member is defined by the T21 transgressive or flooding surface of Wynne et al. (1994), which is placed at the base of a distinctive low-resistivity mudstone interval termed the Wabiskaw Marker. This mudstone is usually less than 5 m thick and tends to have a high neutron porosity (Wynne et al., 1994). The Wabiskaw Marker mudstone is easily identifiable; however, the gamma-ray log response can be misleading with respect to determining lithology. The marker has a high organic content, causing the gamma-ray and density log response to be similar to that of a sandstone; however, the neutron-porosity and resistivity curves inflect too far to the left, indicating shale.

The top of the lower Clearwater shale was picked from core and logs as being the base of a sanding-upward interval with lower gamma-ray values than those seen in the underlying shale. The uppermost unit of the lower Clearwater interval is regionally correlatable. It consists of a shale unit approximately 5 m thick, deposited during the regional flooding event associated with the T31Marker. Much like the T21 shale, this shale typically exhibits distinctively low resistivity and high neutron porosity curves. Core photos of the lower Clearwater Formation shale typically show a massive grey mudstone with occasional thin silty or indurated interbeds. Figure 11 shows core from well AA/07-13-095-13W4/0 (see also Figure 9 for type log), and Figure 12 shows core from well AA/11-30-090-10W4, which is included in cross-section A–A′ (Figure 6).

Siltstone and sandstone in the lower Clearwater shale do not show gamma-ray values as low as those of Wabiskaw-McMurray sandstone, and a small inflection may reflect a higher sand or silt content (Figure 10 and Figure 11). In the lower Clearwater shale, the gamma-ray values should, with little exception, remain above 75 API, the density porosity below 27%, and the resistivity below 10 ohm·m.

Above the lower Clearwater shale interval, the Clearwater Formation consists of 20–30 m of variable shale with a blocky silt or sand interbeds, showing little bioturbation and negligible amounts of bitumen. The average gamma-ray value is usually at least 15 API less than that of the lower Clearwater shale (Figure 8 and Figure 9). The resistivity values are generally low (<1 ohm·m) and average density porosity is generally 3–6% less than that of the lower Clearwater shale.

The unconsolidated Quaternary glacial deposits have a varied clastic composition but generally show a consistent low gamma-ray signature. The base of drift can be difficult to pick from logs and is best determined directly from core. The drift may include thick rafted intervals of Clearwater Formation (including the Wabiskaw Member) or McMurray Formation, and these will show the log signature of those Cretaceous bedrock units. In parallel with correlation to adjacent wells, the base of drift was often picked by determining the point at which the logs collectively stop behaving in a predictable fashion for a Cretaceous lithology. The pick can often be made more complicated by the tendency for casing to be cemented at or near the base of drift, further skewing log signatures.

5 Lower Clearwater Shale Mapping

A contour map of the elevation of the top of the lower Clearwater shale illustrates the study area structure (Figure 13). The elevation of the lower Clearwater shale top rises steadily from southwest to northeast to highs of up to 375 m above sea level. The apparent trough with lows of <325 m above sea level

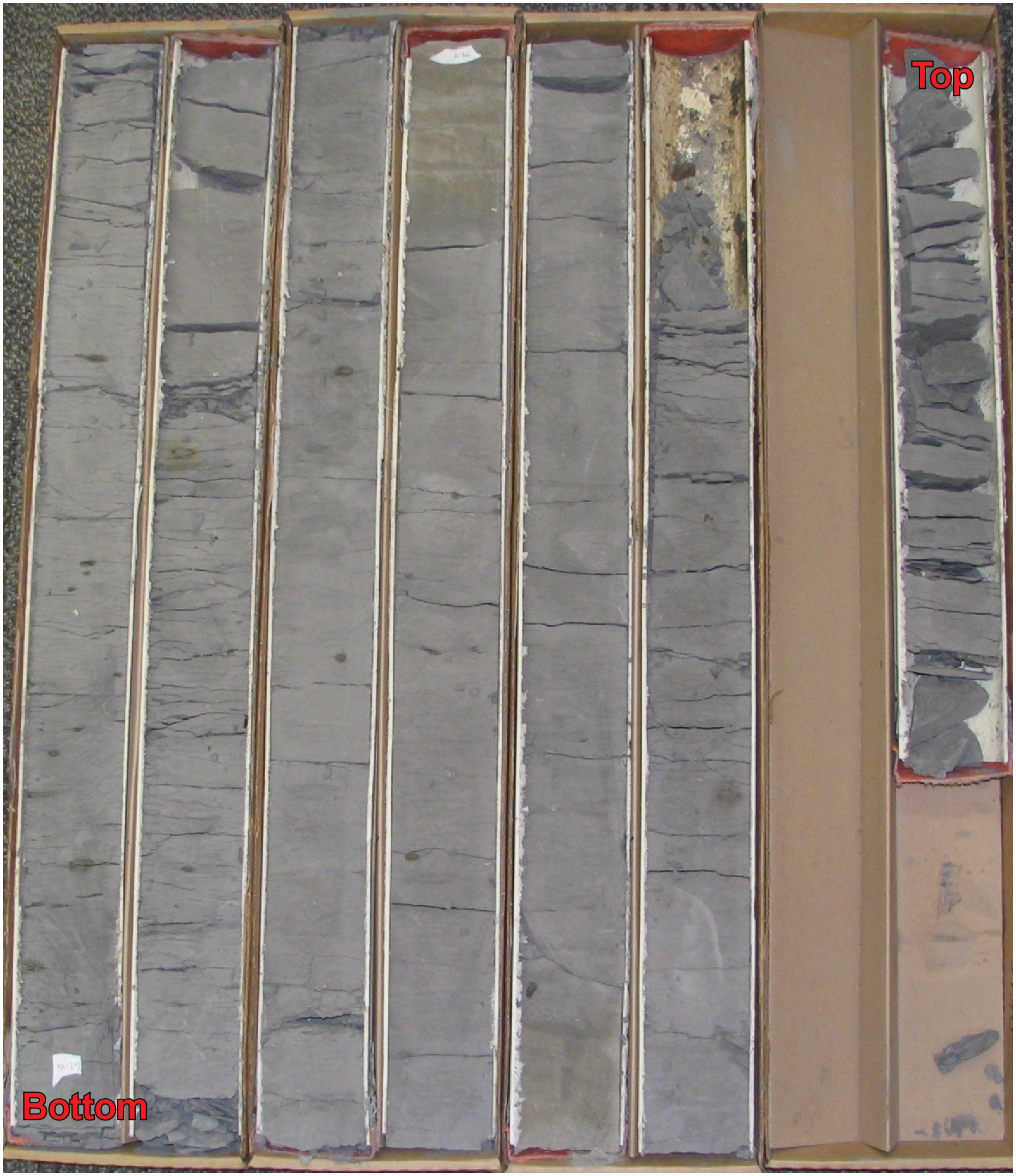
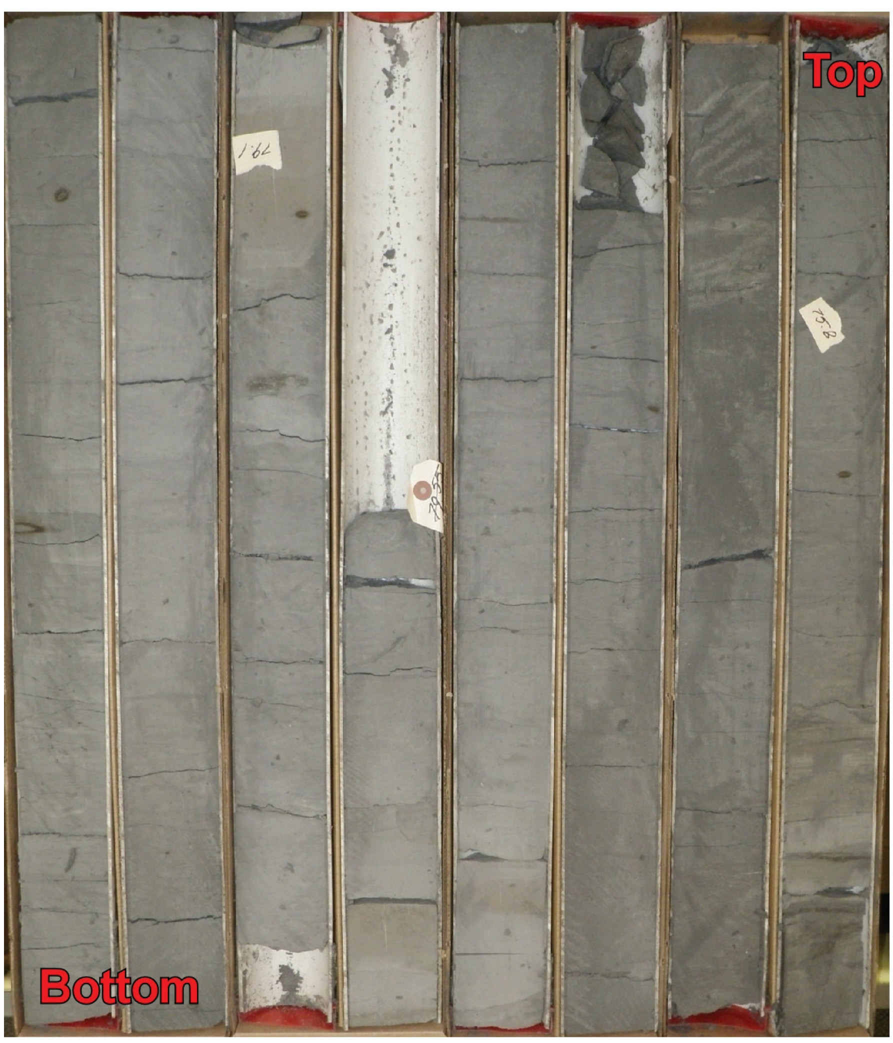


Figure 11. Core photo of lower Clearwater shale in well AA/07-13-095-13W4/0; depth 57.5 to 63 m.

a)



b)

Figure 12. Well AA/11-30-090-10W4/0, lower Clearwater shale; depth (a) 71.1 to 75.75 m (b) 75.8 to 81.3 m.

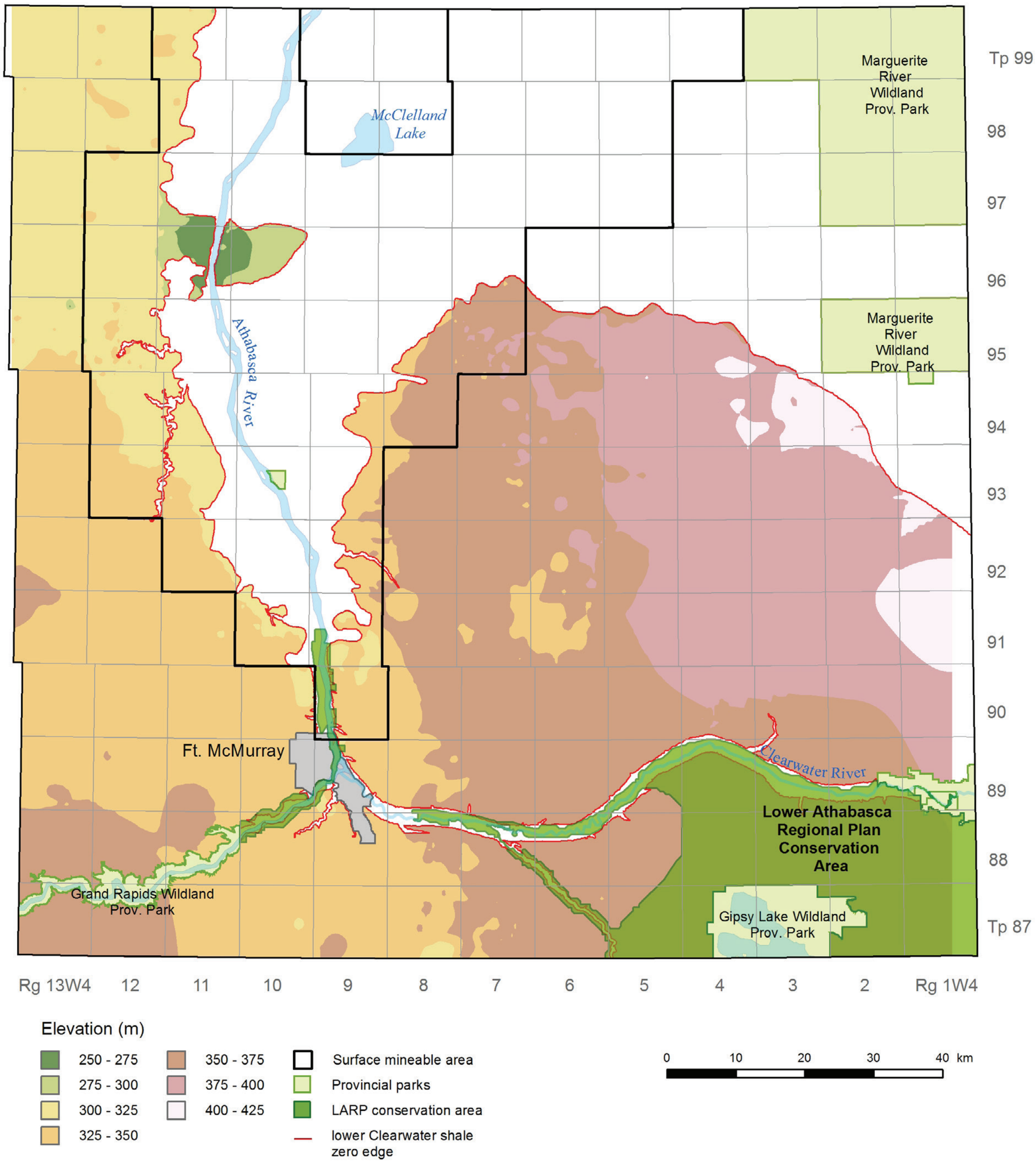


Figure 13. Structure contour map of the top of the lower Clearwater shale. Contour values are elevation in metres above sea level.

trending along the Athabasca River valley is a reflection of the post-Cretaceous erosion in that area. The Clearwater Formation is absent in the northeastern portion of the study area also due to post-Cretaceous erosion.

An isopach map for the lower Clearwater shale shows its thickness in the study area (Figure 14). The isopach was created by subtracting the Wabiskaw Member top pick elevations from those of the lower Clearwater shale and kriging the resulting thicknesses. Within the study area, the Clearwater Formation (including the Wabiskaw Member) thins to the northeast from about 80 m to its erosional zero edge. Where it is not removed by post-Cretaceous erosion, the lower Clearwater shale interval (above the Wabiskaw Member) forms a laterally continuous interval with an average thickness of 20 to 30 m (Figure 14).

An estimate of shale volume (V_{sh}) can be determined directly from the gamma-ray log by determining the maximum and minimum average gamma-ray values. Vsh methods should be considered a rough approximation since the radioactivity may not be due only to shales but also to microclines, micas, etc., and because there are variations in the radioactivity levels of shales and clays (Clavier et al., 1971). A linear V_{sh} is calculated as follows:

$$V_{sh} = \frac{(GR - SAND)}{(SHALE - SAND)}$$

where *GR* is the raw gamma-ray log, *SAND* is the GR 0 percentile from each log, and *SHALE* is the GR 100 percentile from each log.

This linear calculation of V_{sh} is not considered accurate because of the lack of a scientific basis for a linear relationship and tends to give an upper limit to the volume of shale (Rider, 2002). The Clavier method (Clavier et al., 1971) is a nonlinear, empirical relationship that will underestimate the V_{sh} content and can be considered a conservative representation of the shale volume. The Clavier method was used to correct for variation in radioactivity content in clay and is considered a good fit for consolidated units older than Paleogene.

$$V_{sh(CLAV)} = 1.7 - (3.38 - (V_{sh} + 0.7)^2)^{0.5}$$

Figure 15 shows the gross thickness of V_{sh} content greater than 60% in the lower Clearwater Formation shale. Using the average V_{sh} cutoff of 60%, the gross thickness is predominately 10–15 m thick where the lower Clearwater shale is present. Using a V_{sh} cutoff of 60% is roughly equivalent to a gamma-ray signature of 90 API.

Although the lower Clearwater shale underlies the Grand Rapids Formation or subcrops beneath the Quaternary deposits across most of the study area, it is absent in the northeast and along the river valleys. This means in the northeast corner of the study area there is a significant area of bitumen-bearing Wabiskaw-McMurray succession that does not have Clearwater shale but rather Quaternary deposits directly upon potential resource (Figure 16). Core from well AA/10-25-095-04W4/0 shows Quaternary deposits directly overlying a bitumen-bearing McMurray Formation interval (Figure 17).

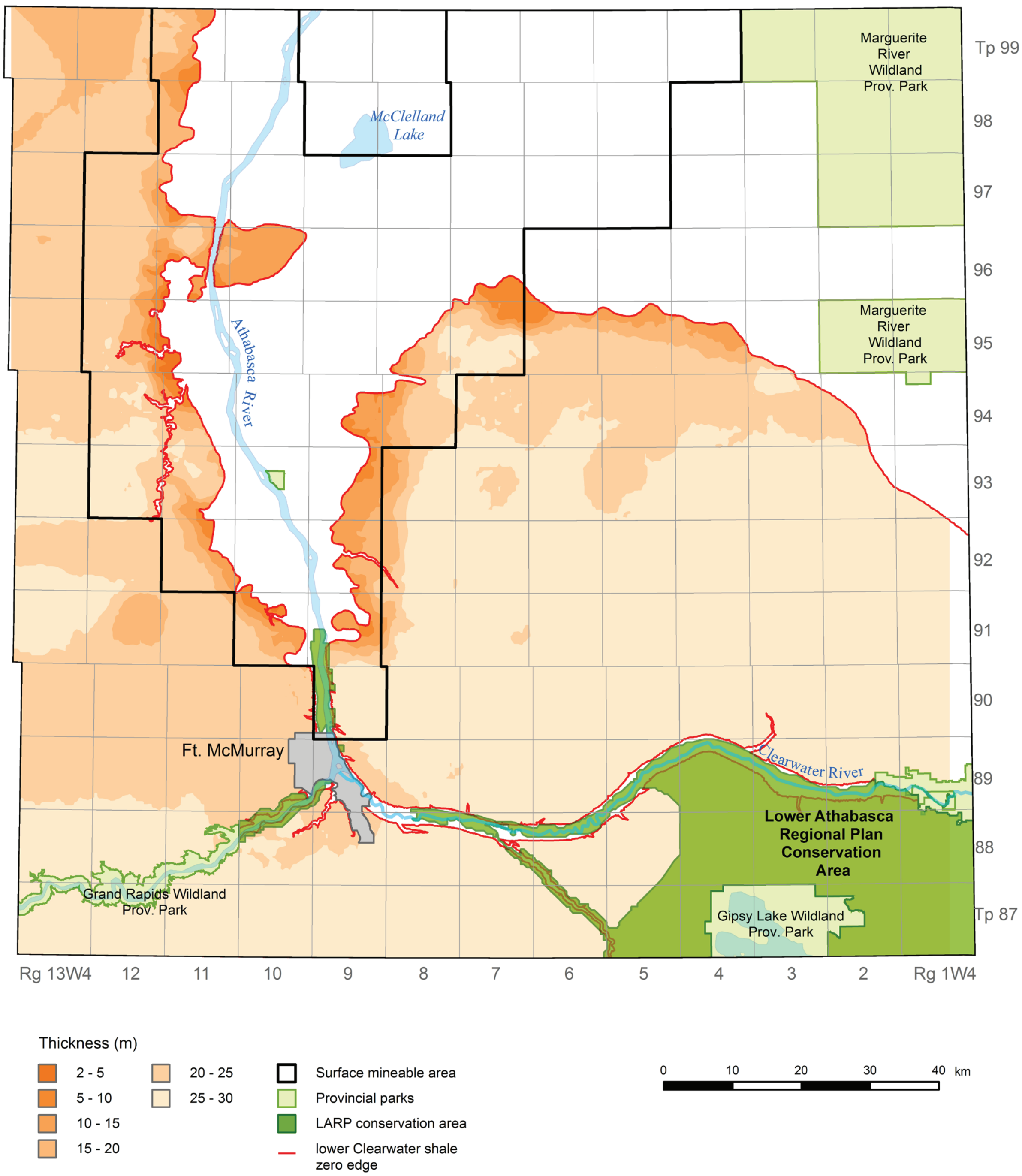


Figure 14. Isopach contour map of the lower Clearwater shale.

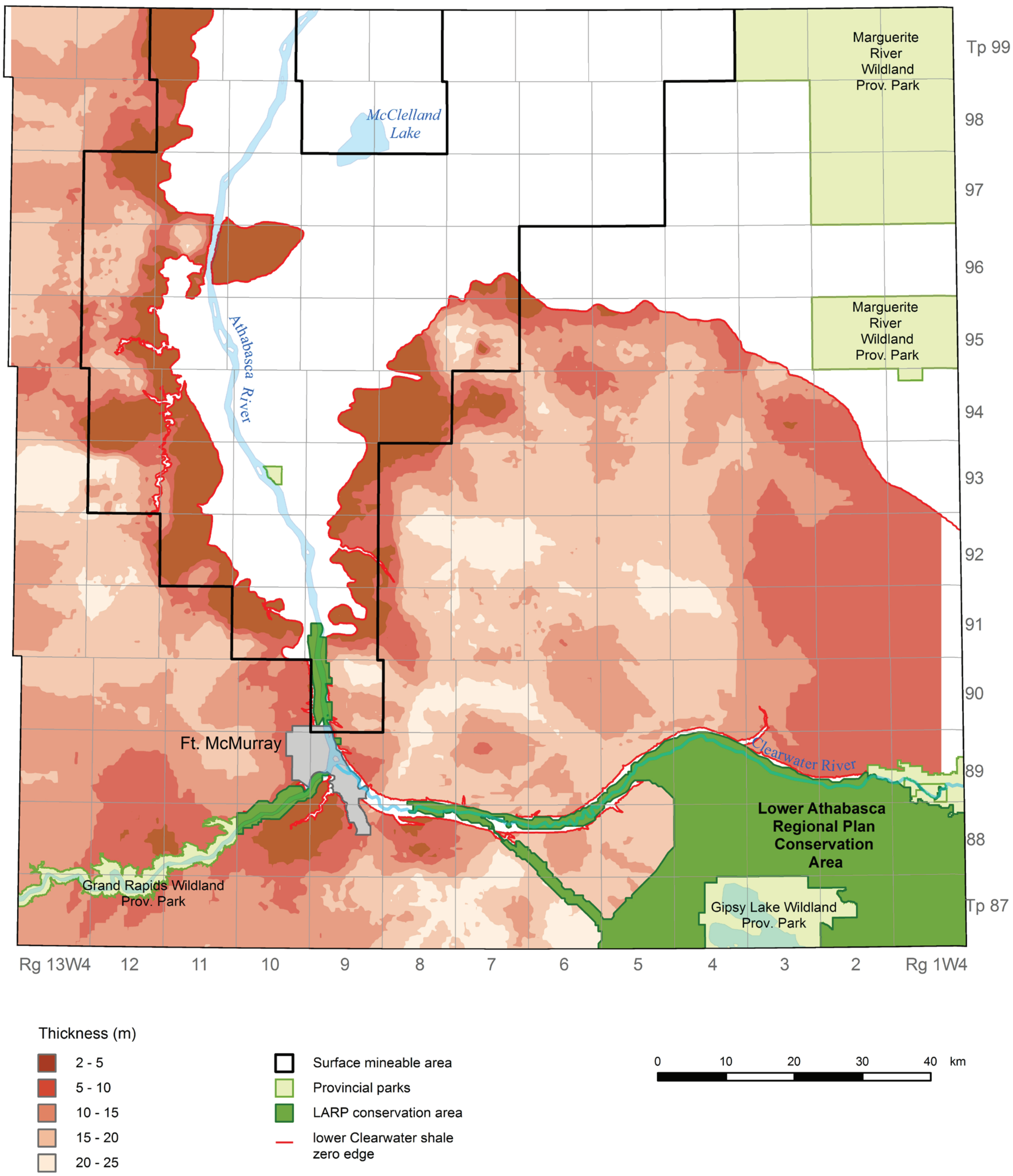


Figure 15. Gross thickness contour map of the lower Clearwater shale with 60% V_{sh}.

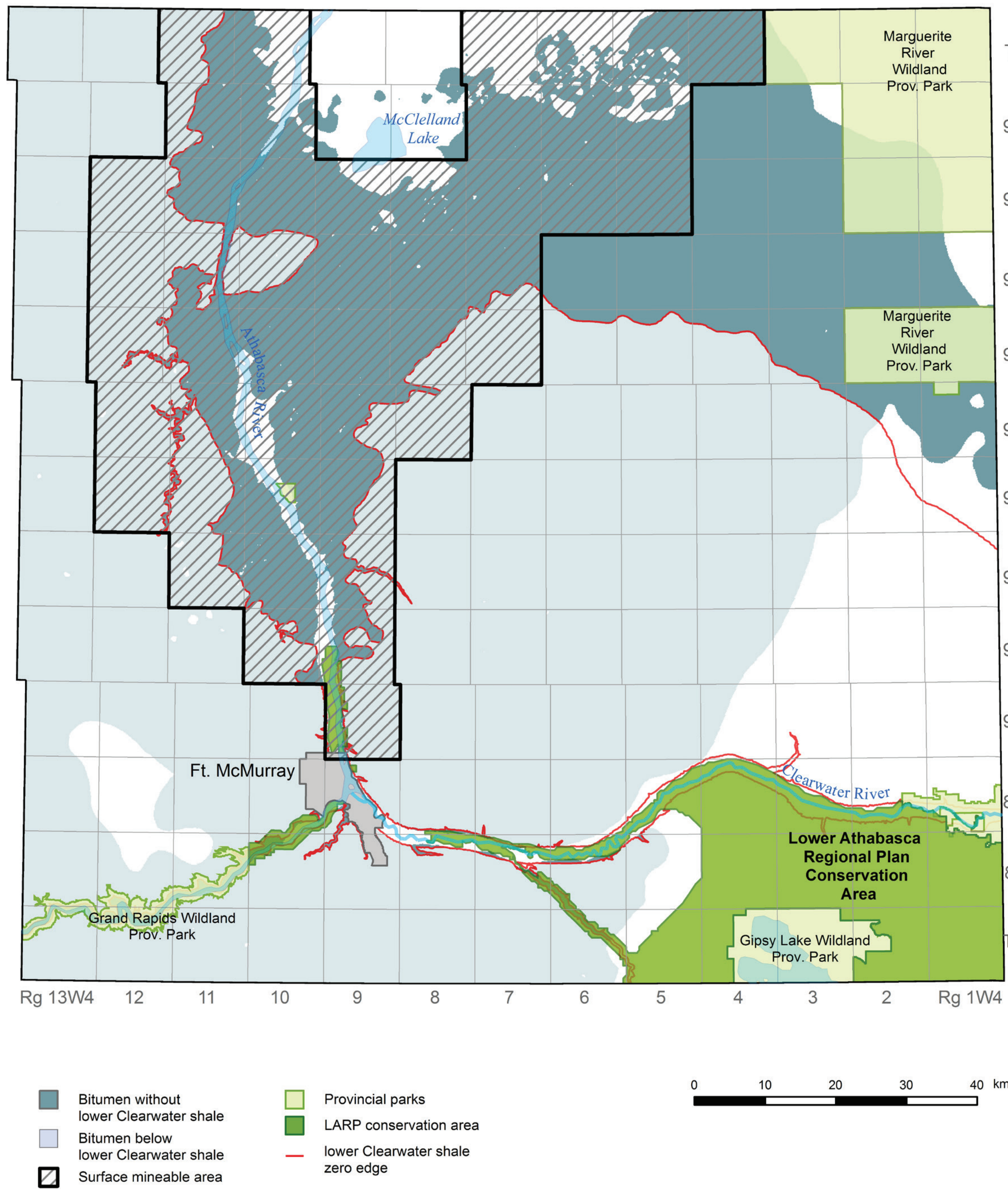


Figure 16. Map showing extent of bitumen-bearing Wabiskaw-McMurray deposit within and outside of lower Clearwater shale zero edge, respectively, in the study area.

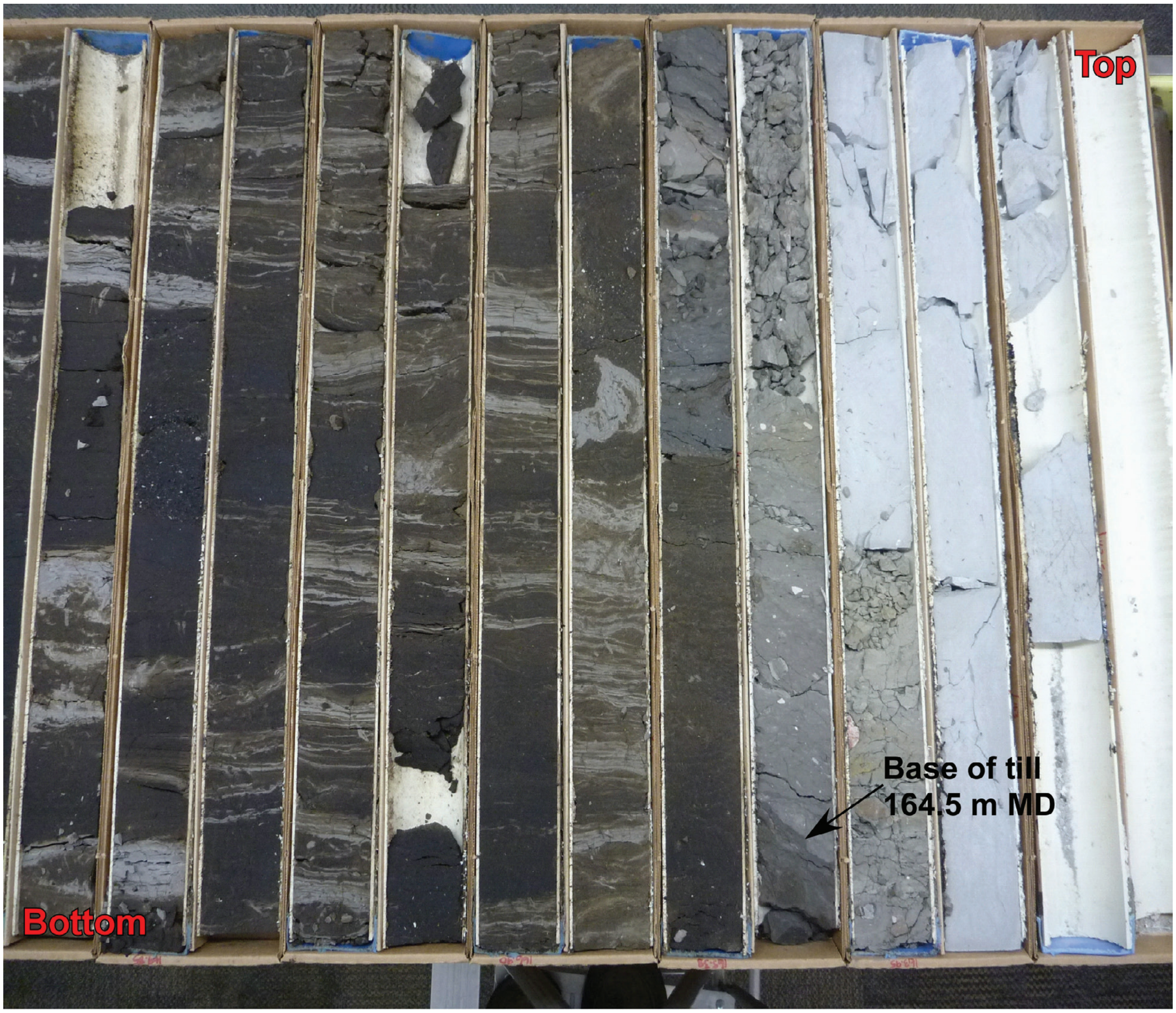


Figure 17. Core photo of bitumen-bearing McMurray Formation and overlying Quaternary sediments in well AA/10-25-095-04W4/0; depth 162.9–169.8 m.

6 Clearwater Formation Petrography and Mineralogy

Six samples from well AA/14-29-095-12W4/0 were analysed by GR Petrology Consultants Inc. (GR Petrology) for thin section petrography and bulk and glycolated x-ray diffraction (XRD) analyses. The samples were taken from core from depths between 29.58 and 58.82 m (Table 2). Four samples are from the lower Clearwater shale and two from the Wabiskaw A shale unit. Figure 18 shows the type log for the well with the location of the samples annotated on the log. Based on preliminary observation of the texture of the samples, sample 2, 4, and 5 were chosen for comprehensive thin section analysis, including grain size porosity measurements (Table 3).

Figure 19 shows a core photo of the lower Clearwater shale from 31.07 to 33.94 m depth. A thin section photomicrograph of sample 3 is shown in Figure 20. The lower Clearwater shale in this well was characterized as carbonaceous, variably bioturbated, quartz-rich shale, silty shale, and silty shale to argillaceous siltstone (Table 3). The Wabiskaw A shale samples are characterized as carbonaceous silty shale.

Table 2. Clearwater lithology from well AA/14-29-095-12W4.

Sample number	Unit	Depth (m)	Lithology
1	lower Clearwater shale	29.58–29.69	carbonaceous quartz-rich shale
2	lower Clearwater shale	31.62–31.72	carbonaceous silty shale to argillaceous siltstone
3	lower Clearwater shale	35.07–35.13	carbonaceous quartz-rich shale
4	lower Clearwater shale	45.36–45.43	carbonaceous silty shale to argillaceous siltstone
5	Wabiskaw A shale T21 marker	52.62–52.69	carbonaceous silty shale
6	Wabiskaw A shale	58.74–58.82	carbonaceous silty shale

Table 3. Petrographic grain size, porosity, and permeability estimates.

Sample number	Unit	Depth (m)	Mean grain size (min – max) (mm)	Estimated total porosity (MA%)	Thin section porosity (%)	Estimated permeability (mD)
1	lower Clearwater shale	29.58–29.69	n/m*	<2	<0.3†	<0.001
2	lower Clearwater shale	31.62–31.72	0.026 to medium silt (0.004–0.061)	<8	1.0	<0.001
3	lower Clearwater shale	35.07–35.13	n/m	<3	<0.5†	<0.001
4	lower Clearwater shale	45.36–45.43	0.027 to medium silt (0.004–0.188)	<6	0.3	<0.001
5	Wabiskaw A shale T21 marker	52.62–52.69	0.037 to coarse silt (0.004–0.123)	<3	0.3	<0.001
6	Wabiskaw A shale	58.74–58.82	n/m	<3	<0.5†	<0.001

* no measurement

† estimated

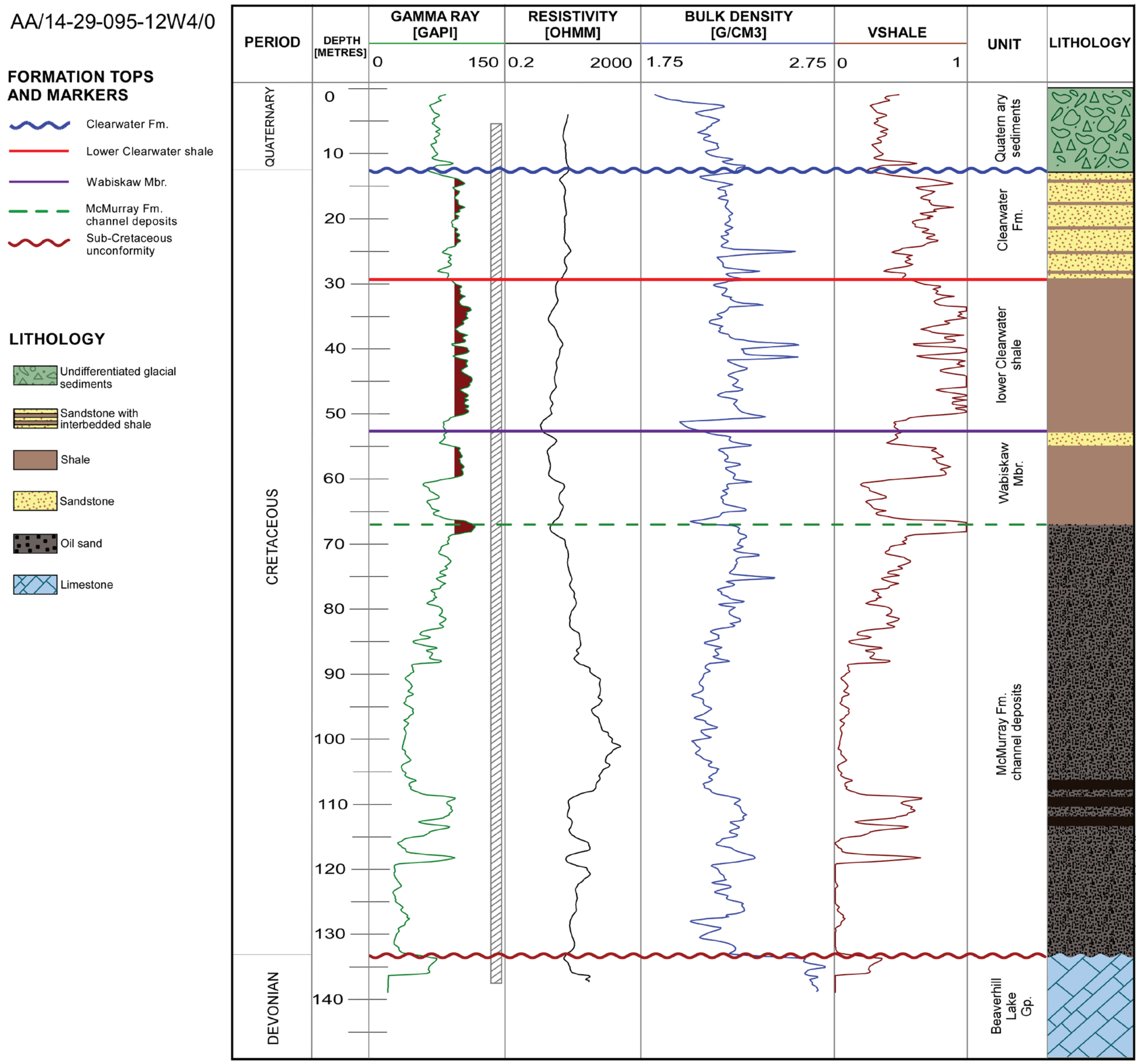


Figure 18. Representative type log for well AA/14-29-095-12W4/0. Gamma-ray signature larger than 90 API filled in with brown.

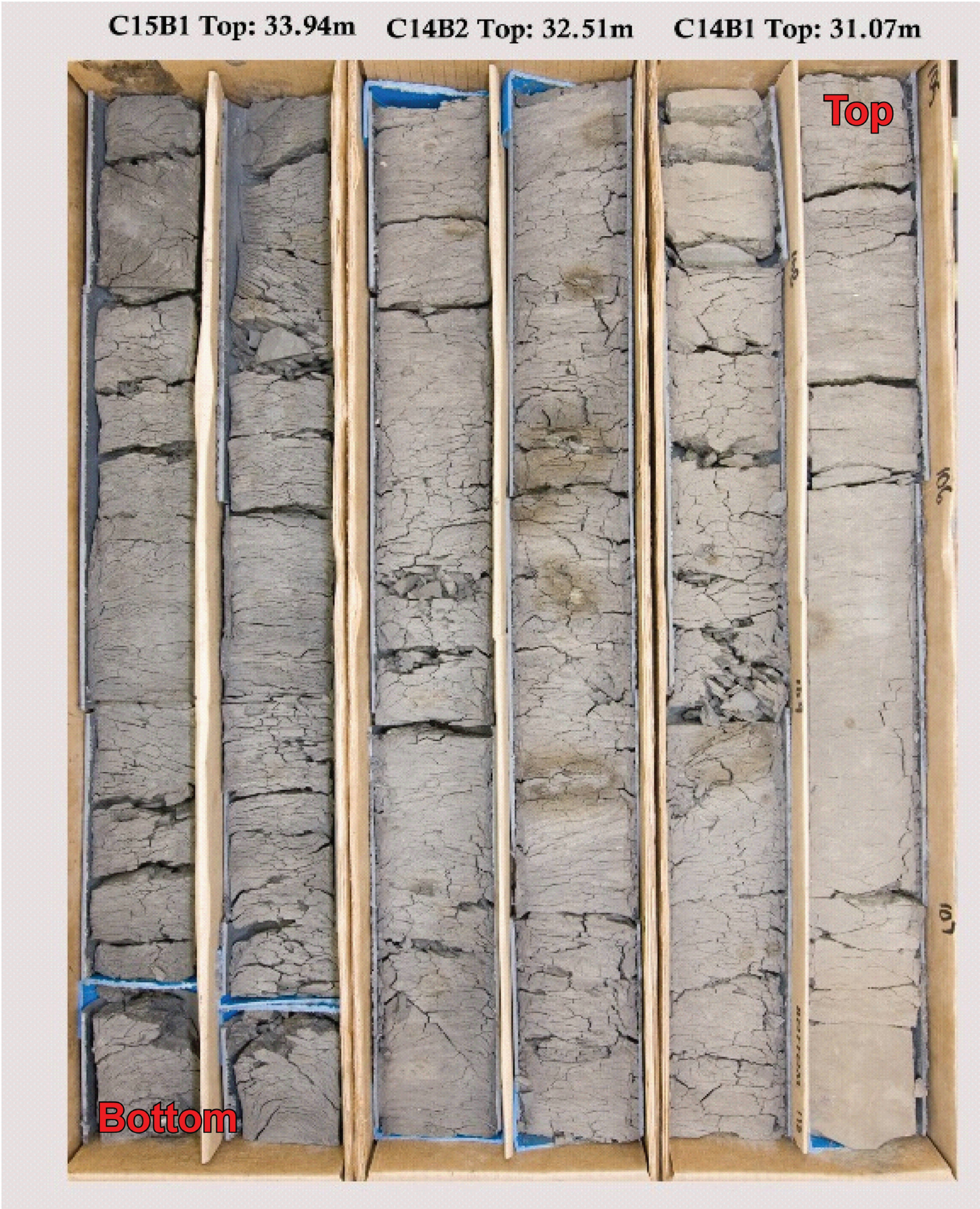


Figure 19. Core photo of lower Clearwater shale from well AA/14-29-095-12W4/0; depth 31.07 m to 33.94 m. (Photo by M. Shepley.)

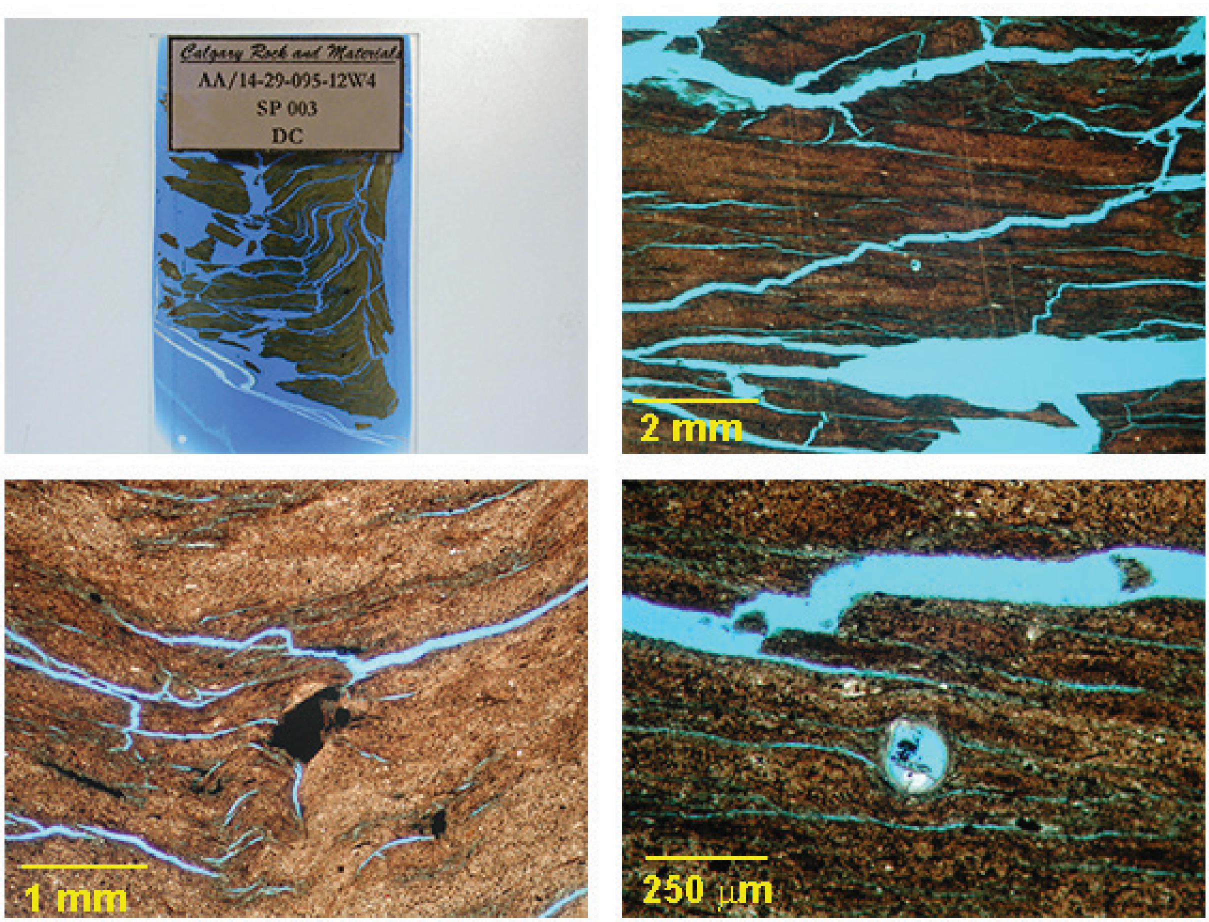


Figure 20. Thin section photomicrograph of sample 3 from well AA/14-29-095-12W4/0. Fractures seen on thin section are artifacts of coring, pressure release, and sample desiccation.

The lower Clearwater shale and Wabiskaw A shale samples are very similar in this well. Thin section petrography suggests total porosity is likely to vary from 2% and 8% (Table 3). Log-derived porosity values are typically different from thin-section-derived porosity, most likely due to sample scale. Total porosity in the lower Clearwater shale sample suite consists of very minor to minor visible effective porosity and moderate to high volumes of microporosity. Modal analysis detected very low to low visible effective porosity in samples 2, 4, and 5. GR Petrology estimated very low effective porosity for samples 1, 3, and 6. Effective pores consist of scattered grain moulds, bio-moulds, and intergranular pores. Most of the visible effective porosity occurs in the silt-size fraction, which commonly fills burrows. Non-effective microporosity occurs in the clay fabrics and leached grains. Based on the fabric and texture of the analyzed material, GR Petrology estimates less than 0.001 mD permeability for the shale intervals represented by the samples.

The principal objectives of the XRD analysis were the identification of rock composition, clay abundance, and clay composition. The XRD data allow for a semiquantitative assessment of the mineralogical composition (in weight percent) of the samples. Bulk XRD results (in weight percent) are presented in Table 4 and graphically in Figure 21. The results show a very similar mineralogical composition for the lower Clearwater shale and the Wabiskaw A shale samples. Non-clay minerals dominate the rock composition of all samples, with quartz as the most abundant mineral, with a moderate amount of plagioclase and potassium feldspar, minor to moderate amounts of pyrite, and moderate volumes of calcite (except for sample 5). Samples 2 and 6 contain moderate to significant amounts of siderite. There was a moderate volume of dolomite in samples 2, 4, 5, and 6. Sample 1 was the only one with minor amounts of ankerite, and sample 3 was the only sample to contain phosphate.

Clay minerals detected in the bulk fraction include dominant illite, moderate volumes of kaolinite and chlorite, and lesser mixed-layer clays (only detected in sample 5) and smectite (present in samples 1 and 5). Table 5 shows the bulk fraction XRD breakdown of clay content. The predominant clay type is kaolinite, followed by illite, with smaller amounts of chlorite. Smectite was only detected in samples 1 and 5. Table 6 lists the glycolated clay fraction XRD results and shows the smectite range for these samples was 4.2% of total clay in sample 1 and 24.1% of total clay in sample 6.

Cenovus Energy Ltd. published XRD results for Clearwater Formation samples from the Telephone Lake Project (Cenovus, 2011). Their analyses of Clearwater Formation samples at depths of 141.88 to 178.65 m in well AB/08-07-094-03W4M showed total clay contents ranging from 44 to 74% and total smectite contents ranging from 14 to 47%. ConocoPhilips also published XRD results with very high clay content of greater than 60% total clay at their Surmont operation (ConocoPhilips, 2011). Those clay contents are considerably higher than those found in the samples analyzed in this study. Their samples also differed from the ones analysed for this report in that they had much lower amounts of quartz, less than 30% compared to 46–58% in this study. This study involved a very small dataset, and more analyses are needed to determine if this is a reflection of regional variation or sampling different intervals within the lower Clearwater shale.

Table 4. Bulk fraction XRD data (in weight percent).

Sample number	Unit	Depth (m)	Quartz	Plagioclase	Potassium Feldspar	Siderite	Pyrite	Calcite	Dolomite	Halite	Ankerite	Hydroxyl-apatite	Total clay
1	lower Clearwater shale	29.58–29.69	52.0	11.0	7.4	-	2.5	4.6	-	-	1.5	-	21.0
2	lower Clearwater shale	31.62–31.72	46.9	4.9	3.2	14.4	2.7	1.7	12.8	-	-	-	13.4
3	lower Clearwater shale	25.07–35.13	44.6	7.7	6.5	-	4.6	3.5	-	-	-	2.0	31.1
4	lower Clearwater shale	45.36–45.43	58.2	6.1	4.1	-	1.7	3.1	10.0	-	-	-	16.8
5	Wabiskaw A shale T21 marker	52.62–52.69	46.1	4.5	3.9	-	3.4	-	5.1	-	-	-	37.0
6	Wabiskaw A shale	58.74–58.82	54.2	6.0	3.9	2.5	3.6	2.8	7.9	-	-	-	19.1

Table 5. Bulk fraction XRD data – breakdown of clay content (in weight percent).

Sample number	Unit	Depth (m)	Total clay	Kaolinite	Illite	Chlorite	Mixed layer	Smectite
1	lower Clearwater shale	29.58–29.69	21.0	8.0	8.3	4.7	-	present
2	lower Clearwater shale	31.62–31.72	13.4	4.3	5.3	3.8	-	-
3	lower Clearwater shale	25.07–35.13	31.1	11.0	12.8	7.3	-	-
4	lower Clearwater shale	45.36–45.43	16.8	6.4	7.2	3.2	-	-
5	Wabiskaw A shale T21 marker	52.62–52.69	37.0	5.2	17.6	6.3	7.9	present
6	Wabiskaw A shale	58.74–58.82	19.1	6.6	7.6	4.9	-	-

Table 6. Glycolated clay fraction XRD data (in weight percent of total clay).

Sample number	Unit	Depth (m)	Total clay	Kaolinite	Illite	Chlorite	Smectite
1	lower Clearwater shale	29.58–29.69	21.0	37.1	38.0	20.7	4.2
2	lower Clearwater shale	31.62–31.72	13.4	26.1	51.1	22.8	-
3	lower Clearwater shale	25.07–35.13	31.1	36.7	46.2	17.1	-
4	lower Clearwater shale	45.36–45.43	16.8	33.9	49.2	16.9	-
5	Wabiskaw A shale T21 marker	52.62–52.69	37.0	9.7	48.6	17.6	24.1
6	Wabiskaw A shale	58.74–58.82	19.1	29.9	52.2	17.9	-

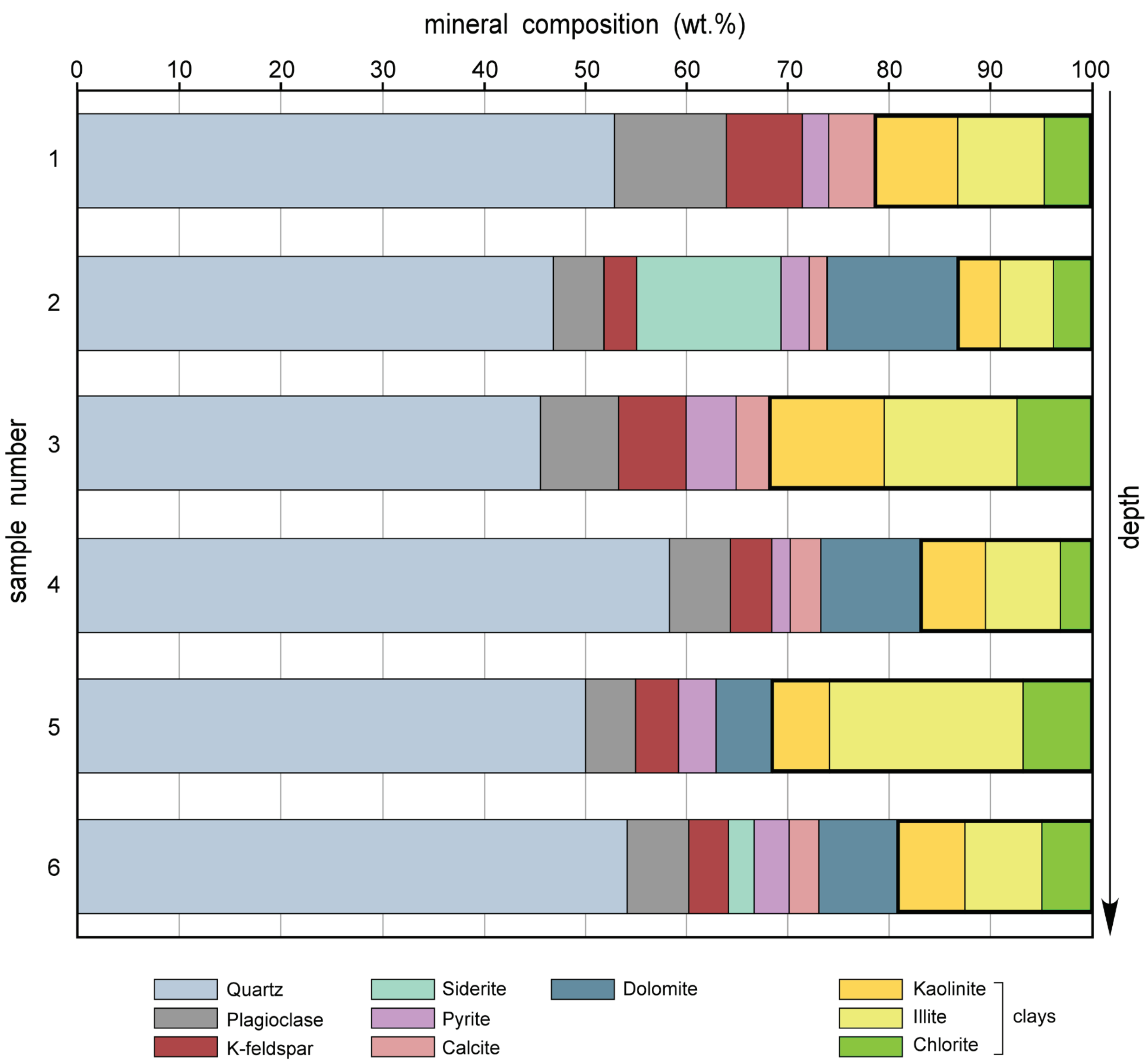


Figure 21. Graphical representation of mineralogical composition from bulk XRD analysis of samples from well AA/14-29-095-12W4/0.

7 LiDAR

Light detection and ranging (LiDAR) bare-earth DEM images were used to identify surface expressions of potential sinkholes across the whole study area. The strata of the Devonian Beaverhill Lake and Elk Point groups underwent structural deformation and collapse related to the dissolution of the Prairie Evaporite Formation evaporites (halite and anhydrite) and karst development in the limestones of the Beaverhill Lake Group. Collapse of the strata overlying the Prairie Evaporite Formation in areas affected by evaporite dissolution has resulted in active and relict sinkholes, brecciation, and enlarged joints. Preliminary observations of the LiDAR coverage suggest that the location of surface expression of sinkholes occurs preferably east of the zone of partial halite dissolution and predominately in the region surrounding the McClelland Lake.

Bayrock (1971) mapped karst sinkholes near McClelland Lake in the 1970s. Figure 21 shows a LiDAR bare-earth DEM image of the area southwest of McClelland Lake highlighting the sinkholes identified by Bayrock and additional possible sinkholes identified during this project. These sinkholes are aligned along a northwest to southeast linear trend and range from 30 to 160 m wide and up to a depth of 7 m. Cotterill and Hamilton (1995) stated that "these sinkholes often appear as small, circular ponds and may occur as single holes or in swarms. Occasionally, drill holes intersect these sinkholes, some of which contain brecciated limestone intermixed with oil sand from the overlying McMurray Formation."

Broughton (2013) described the sinkhole distribution pattern on the sub-Cretaceous paleotopography as varying from randomly dispersed individual sags to clusters with tens to hundreds of sinkholes across fault block lows. Broughton interpreted the linear sinkhole trend in Figure 22 to be rooted in the underlying fragmented Upper Devonian succession along a linear differential compaction trend, although Broughton noted that there is no direct evidence for this. The presence of sinkholes in the study area draws attention to a potential source of uncertainty in the continuity of the units above the reservoir.

8 Conclusions

This report focused on regional geological mapping of Cretaceous strata showing the extent and thickness of the lower Clearwater shale unit, which overlays the Wabiskaw-McMurray bitumen deposit. We mapped the erosional zero edge of the unit in the northern part of the study area highlighting where the lower Clearwater shale unit is thin (<5 m thick) or absent. Over most of its extent in the study area, the lower Clearwater shale was found to be between 20 and 30 m thick. Results from petrographic and mineralogical analyses on shale, silty shale, and siltstone samples showed that the lower Clearwater shale sampled ranged from a quartz-rich shale to a carbonaceous silty shale to argillaceous siltstone. The total clay content of the samples ranged from 13 to 31%.

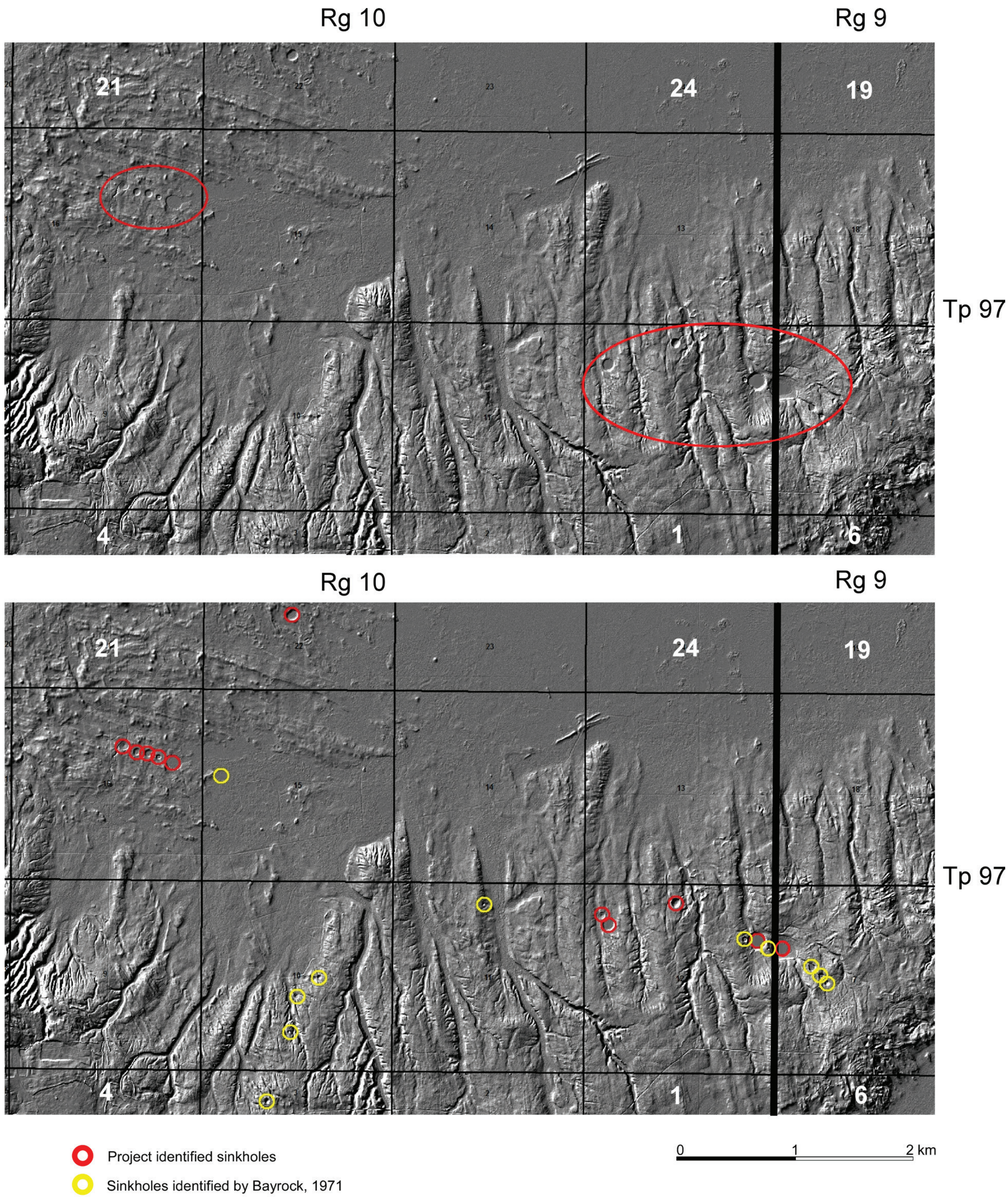


Figure 22. LiDAR bare-earth DEM image showing possible sinkholes near McClelland Lake, northern Alberta, Canada. Sinkholes identified by Bayrock (1971) are circled in red and those identified by this project in yellow.

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