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Alberta Energy Regulator

Regional Cross-Sections of Devonian Stratigraphy in Northeastern Alberta (NTS 74D, E)

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Regional Cross-Sections of Devonian Stratigraphy in Northeastern Alberta (NTS 74D, E)

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Abstract

Three regional cross-sections through Devonian strata in northeastern Alberta (two east–west and one north–south) capture the wedge-shaped erosional truncation of Devonian strata and the eastward loss of evaporite minerals in the Prairie Evaporite Formation. Lowermost Devonian strata, the La Loche and Contact Rapids formations, fill topographic lows on the surface of the Precambrian basement, forming a nearly flat horizontal submarine surface before the onset of deposition of the Keg River Formation. Thickness of the Keg River Formation in the study area is controlled by the presence or absence of bioherms. East–west cross-sections do not reveal a distinct salt scarp in the Prairie Evaporite Formation, but instead show a gradual eastward thinning of the formation. Within the study area, the Prairie Evaporite Formation can be divided into three zones: (1) a western zone of partial halite dissolution, (2) a central zone of total halite dissolution and active loss of anhydrite, which roughly parallels the Athabasca River, and (3) a zone of total dissolution of all evaporite minerals along the eastern portion of the study area. Post–Prairie Evaporite Devonian strata have a regional dip to the southwest, but in the eastern portion of zone 1 and all of zone 2 follow a reverse dip, in which all strata dip eastward because of subsidence and collapse over the dissolving and thinning Prairie Evaporite Formation. In zone 3, post–Prairie Evaporite strata resume a southwestward dip over the thin insoluble residue of the Prairie Evaporite Formation and follow the contour of the surface of the Keg River Formation. The sub-Cretaceous unconformity is variable in its topography and has the lowest elevation in the northern portion of the study area along the Athabasca River.

1 Introduction and Background

Devonian stratigraphy in northeastern Alberta was affected by dissolution of evaporites of the Prairie Evaporite Formation, the collapse of post–Prairie Evaporite Devonian strata, and erosion prior to the deposition of the Cretaceous McMurray Formation. The resulting topography of the sub-Cretaceous unconformity surface influenced the thickness distribution of the Lower McMurray Formation (Carrigy, 1959; Hein et al., 2000). Dissolution-related subsidence likely continues locally to the present day, but its timing, distribution, and effect on overlying strata are not well understood.

Herein, we present three regional cross-sections of the Devonian in subsurface along east–west and north–south trend lines in a study area encompassing Twp. 87 to 98, Rge. 3 to 15, W 4th Mer. (Figure 1). The work herein is part of the AER Oilsands Caprock Integrity Project (OSCRIP). Devonian strata are included in OSCRIP in order to understand both the structure of Devonian strata, with emphasis on the effects from the dissolution of Prairie Evaporite Formation strata, and the nature of the sub-Cretaceous unconformity.

2 Geological Background

2.1 Cross-Sections of Regional Geology

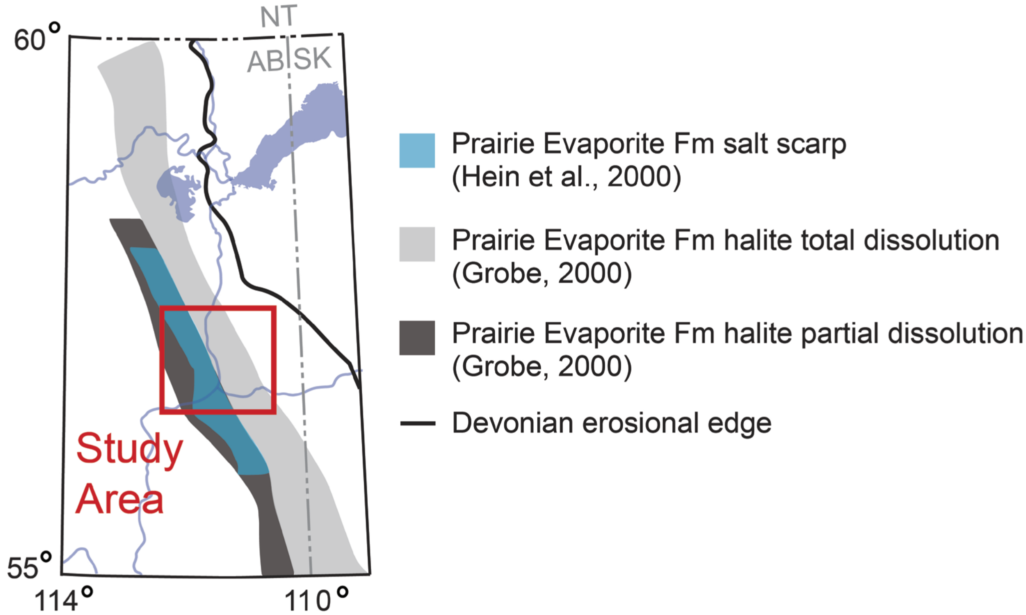
Regional dip of Devonian strata is generally southwestward at a rate of 3.8 m/km (Norris, 1963; Martin and Jamin, 1963). Where dissolution of the Prairie Evaporite Formation has occurred, post-Prairie strata dip eastward, a “reverse dip” opposite the regional dip, because of the collapse of post-Prairie Devonian strata over the diminished Prairie Evaporite Formation.

Carrigy (1959) and later stratigraphers described the deformation of the Waterways Formation as low-amplitude domes and basins. Folding occurs on multiple scales, from 50 m parasitic folds through kilometre-scale domes. The largest structure is the regional anticline caused by the reverse dip in post–Prairie Evaporite Formation strata (Schneider, 2011; Schneider et al., 2012).

Carrigy (1959) constructed two cross-sections of Devonian and Cretaceous strata. Although data were more sparse during the time of his study, his cross-sections capture an eastward dissolutional pinch-out of the Prairie Evaporite Formation and the erosional thinning of Devonian strata.

Bachu et al. (1993) presented two cross-sections of Devonian and Cretaceous stratigraphy that included the present study area: one trending northeast–southwest and the other northwest–southeast (Figure 2). Their northeast–southwest cross-section captures a rapidly thinning Prairie Evaporite Formation in the northeast. The northwest–southeast cross-section contains a thinning Prairie Evaporite Formation in the southeastern portion of the cross-section, but does not capture the dissolutional pinch-out of the Prairie Evaporite halite.

Cotterill and Hamilton (1995) presented four cross-sections of Beaverhill Lake Group strata for northeastern Alberta, two of which contain outcrop and core data from the Athabasca and Clearwater rivers. The other two (Figure 3) are similar in trend to those of Bachu et al. (1993) and contain only Beaverhill Lake Group strata and are based entirely on subsurface data. By placing a stratigraphic datum at the top of the Watt Mountain Formation, Cotterill and Hamilton’s cross-sections emphasize the topographic complexity of the sub-Cretaceous unconformity and eastward downcutting of the erosional surface into Waterways Formation strata.



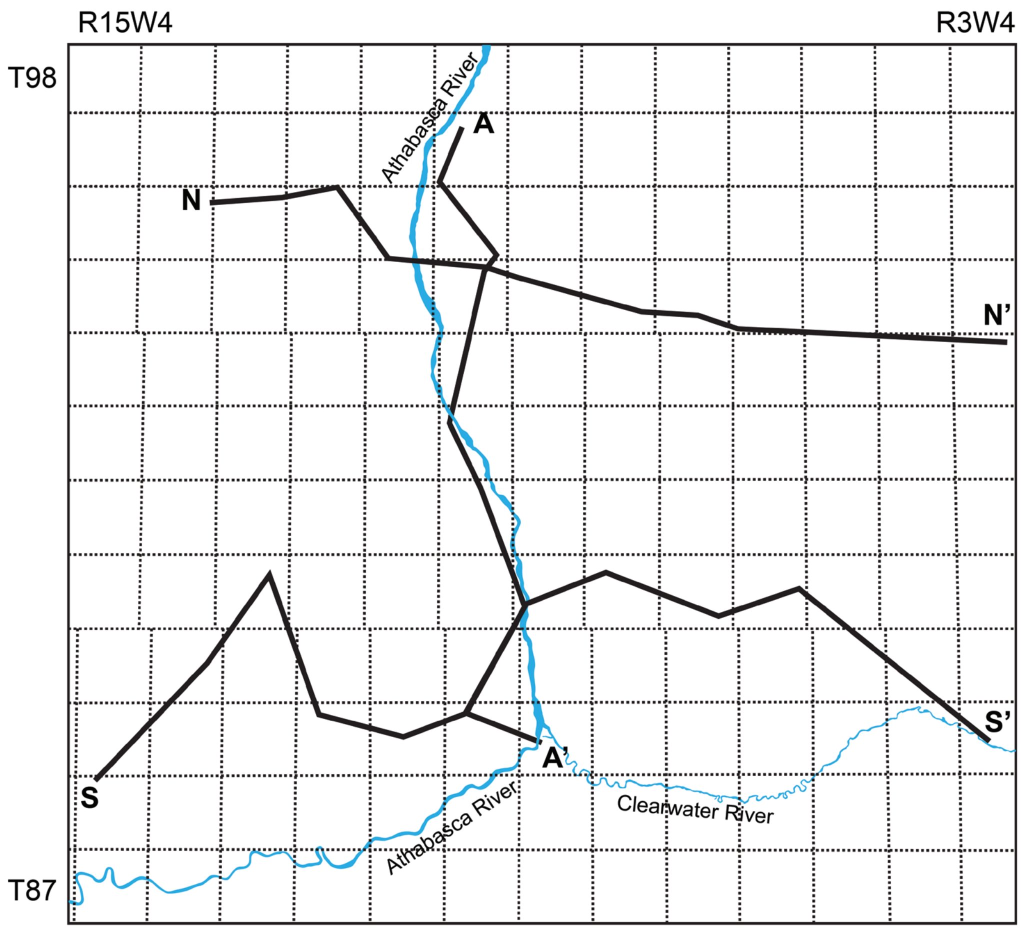


Figure 1. The study area with locations of cross-section lines and N–N′, S–S′, and A–A′ presented in this report (see Figures 5 to 7).

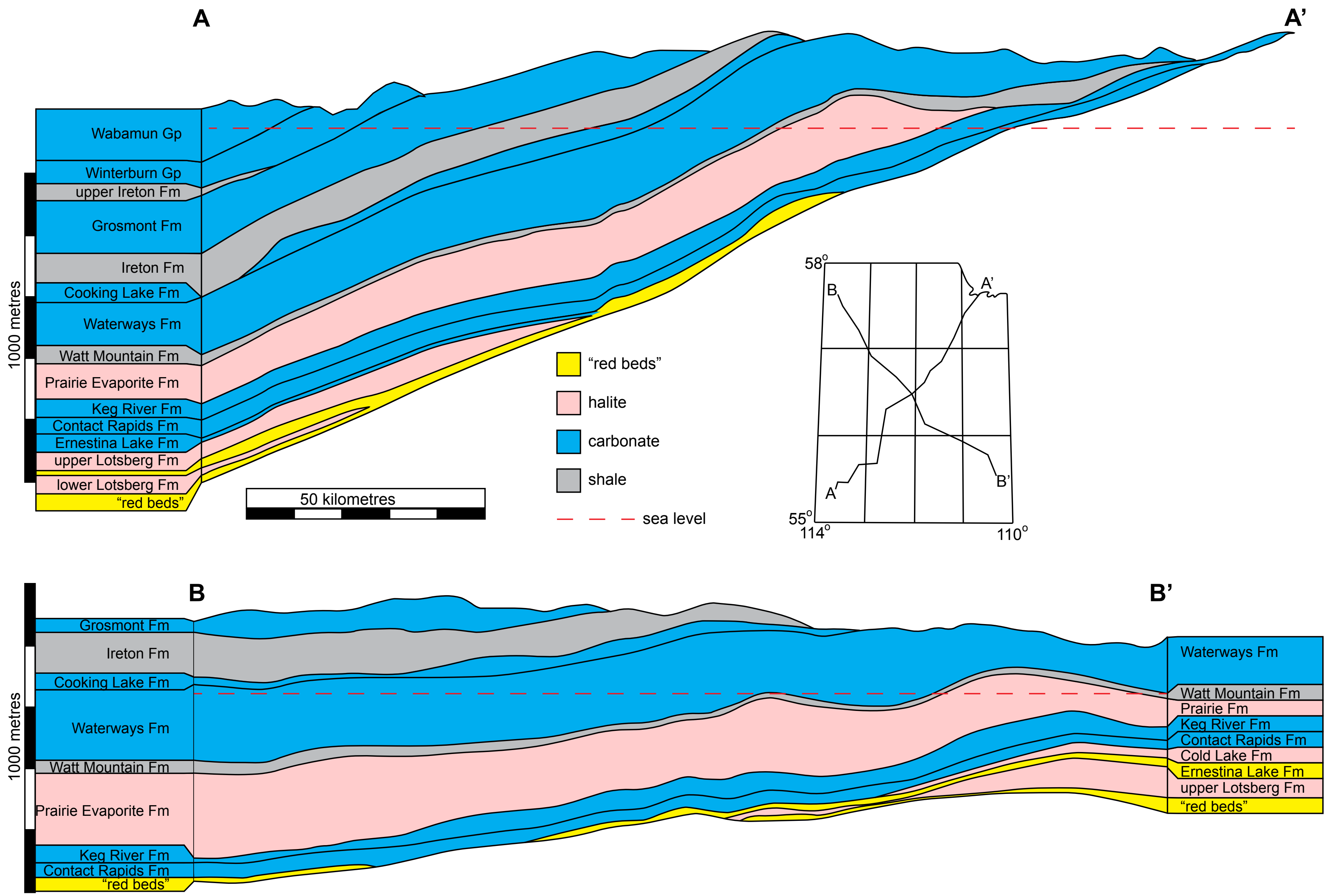


Figure 2. Structural cross-sections through Devonian stratigraphy in northeastern Alberta modified from Bachu et al. (1993). Only the Devonian portions of their cross-sections are presented and nomenclature has been updated.

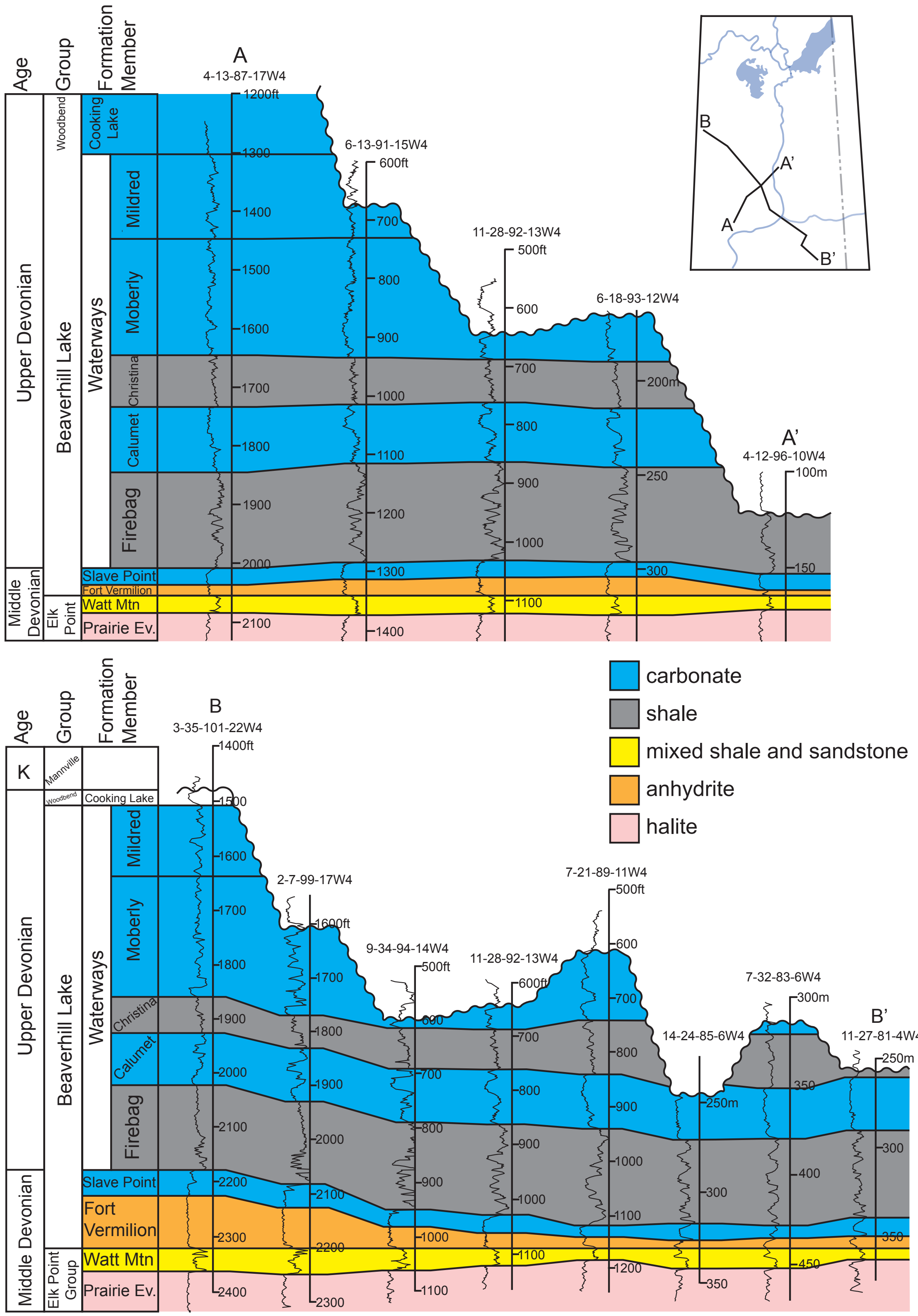


Figure 3. Stratigraphic cross-sections of Beaverhill Lake Group strata in northeastern Alberta from Cotterill and Hamilton (1995). Datum is the top of the Watt Mountain Formation. Well spacing is not to horizontal scale.

2.2 Prairie Evaporite Formation Salt Scarp and Dissolution of Evaporites

Dissolution of evaporite minerals in the Prairie Evaporite Formation removed rock from the subsurface, causing subsidence and collapse of overlying Devonian strata. In northeastern Alberta, an evaporite dissolution zone underlies much of the region, stretching from the Devonian erosional limit to west of the Athabasca River. Since the onset of dissolution, the Prairie Evaporite Formation salt scarp, a zone of evaporite loss, has continuously migrated towards the basin centre (Bachu et al., 1993). The process of salt dissolution at depth is ongoing, as suggested by active saline springs in the area (Carrigy, 1959).

Bachu et al. (1993) defined the salt scarp as an eastward tapering, 20 km wide dissolution zone that roughly corresponded to the north–south trend of the Athabasca River north of Fort McMurray. They reconstructed the deflection of Devonian strata over the scarp, in which the normally westward-dipping Beaverhill Lake Group is tilted eastward. Bachu et al. (1993) described the reversal in dip across the Prairie Evaporite Formation salt scarp as the Athabasca anticline-syncline pair; McPhee and Wightman (1991) named it the "asymmetrical Athabasca anticline." Bachu et al. (1993) also found that the salt scarp structure is echoed upsection in Cretaceous strata along a north–northwest trending, linear feature. From the scarp eastward, many hydrostratigraphic units that are isolated in the central basin come into contact and are hydraulically continuous (Bachu et al., 1993).

Hein et al. (2000) also recognized the influence of dissolution of the Prairie Evaporite Formation on the deformation and karstification of younger Devonian strata and the impact on the sub-Cretaceous unconformity. Their definition of the Prairie Salt Scarp is a roughly north–northwest, south–southeast trending depression in the sub-Cretaceous unconformity that corresponds to a dissolution front within the Prairie Evaporite Formation at depth. The effects on post-Prairie Devonian strata include collapse, small-scale deformation, karstification, and basin formation (e.g., Bitumount Basin) (Carrigy, 1959; Norris, 1963; Hein et al., 2000; Schneider, 2011; Schneider et al., 2012).

Grobe (2000) suggested that intermittent dissolution of halite led to a partial-to-complete removal of salt and the collapse of overlying strata. In places, the loss of salt and the ensuing subsidence of younger formations caused collapse breccias in some units. Grobe (2000) also suggested that anomalies in overburden thickness resulted from a combination of modern topographic features and subsurface salt dissolution.

2.3 Sub-Cretaceous Unconformity

Ells (1926) described the sub-Cretaceous surface as fairly uniform over large areas, but Hume (1949) noticed that deposition of the Cretaceous McMurray Formation responded to irregular topography on the limestone surface. He measured 165 feet (50.3 m) of relief on the top of the Waterways Formation, in which McMurray sandstone thins over topographic highs ("knobs") of Waterways limestone and thickens within depressions in the Devonian erosional surface.

Carrigy (1959) produced the first contour map of the "Pre-Cretaceous Erosion Surface". Although well data was considerably sparser than the present day, his map still shows the topographic low of the Bitumount Basin and a gradual shallowing to the southwest. Carrigy (1959) suggested that the contour of the pre-Cretaceous unconformity parallels that of the top of the Prairie Evaporite Formation and was the result of dissolution of "water soluble strata" in the Prairie Evaporite Formation.

Hein et al. (2001) reported that the topographic relief of the sub-Cretaceous surface ranges up to 130 m. A major topographic low coincides with the Prairie salt scarp (Hein et al., 2000, 2001) and roughly parallels the Athabasca River. Initial McMurray Formation sediments were restricted to steep-walled valleys (Gingras et al., 2003; Crerar and Arnott, 2007) or accumulated as paleosols and swamps in these topographic lows (Hein et al., 2000). Dominant drainage flow during McMurray deposition was to the northeast towards an open embayment over the Canadian Shield (Leckie, 2008) through channels carved into the exposed Devonian rock.

3 Stratigraphy: Lithology and Well Log Characterization

In the study area, Devonian strata form an eastward-tapering wedge between the Precambrian basement and Cretaceous rock or Pleistocene sediments. Prior to the deposition of the Cretaceous McMurray Formation, Devonian strata were tilted westward (Norris, 1963). Pre–McMurray Formation erosion truncated the dipping strata resulting in the progressively eastward subcrop of older formations at the sub-Cretaceous unconformity.

The following overview of lithology and well log characterization is based on observations from field and subsurface investigations carried out over the past three years, including the cross-section work herein (Figure 4). Devonian stratigraphic units within the study area include the following, from base to top.

3.1 La Loche Formation (Granite Wash)

In northeastern Alberta, the La Loche Formation is a red to occasionally mottled red, green, and grey sandstone. The base of the formation is often an unsorted to poorly sorted lithic sandstone with angular to sub-rounded grains, which locally can form the matrix for a conglomerate. In many localities, the sandstone overlies a brecciated regolith of the basement surface. At some localities, the granite wash directly overlies the unaltered basement, presumably where the regolith has been eroded before the deposition of sand.

The basal sandstone grades upward into fine- to medium-grained, well-sorted sandstone with rounded to subrounded grains and usually transitions into a quartz arenite or a quartz-rich arkosic sandstone towards the top of the formation. Thin shale beds are common. No fossils are known from the La Loche Formation.

Sedimentary structures in the La Loche Formation are best seen in outcrop. At Contact Rapids on the Clearwater River in Saskatchewan, the La Loche Formation contains graded beds and decimetre-scale, asymmetrical cross-beds.

Thickness of the La Loche Formation is controlled by the topography of the basement. The La Loche Formation thins over topographic highs in the basement and thickens within topographic lows (Norris, 1963). Within the study area, Norris (1963) reported the thickness of the La Loche Formation as varying between less than one to over 18 m.

The La Loche Formation is easily recognizable in core by its red colour from hematite cement. The Contact Rapids Formation directly overlying the La Loche Formation can also be red, but more often is mottled with the typical green colour of the Contact Rapids silty shale. The contact between the La Loche and Contact Rapids formations is often arbitrarily placed because of its gradational nature.

In well logs, the La Loche Formation is characterized by a high gamma-ray count. The base is easily picked at the top of the basement, which has a very high GR count, low resistivity, and low density and neutron porosities. In most cases, the top is arbitrarily placed in the gradational and negative-trending gamma ray transition between the sandstone of the La Loche Formation and the silty shale of the Contact Rapids Formation, where the increase in gamma ray is most steep.

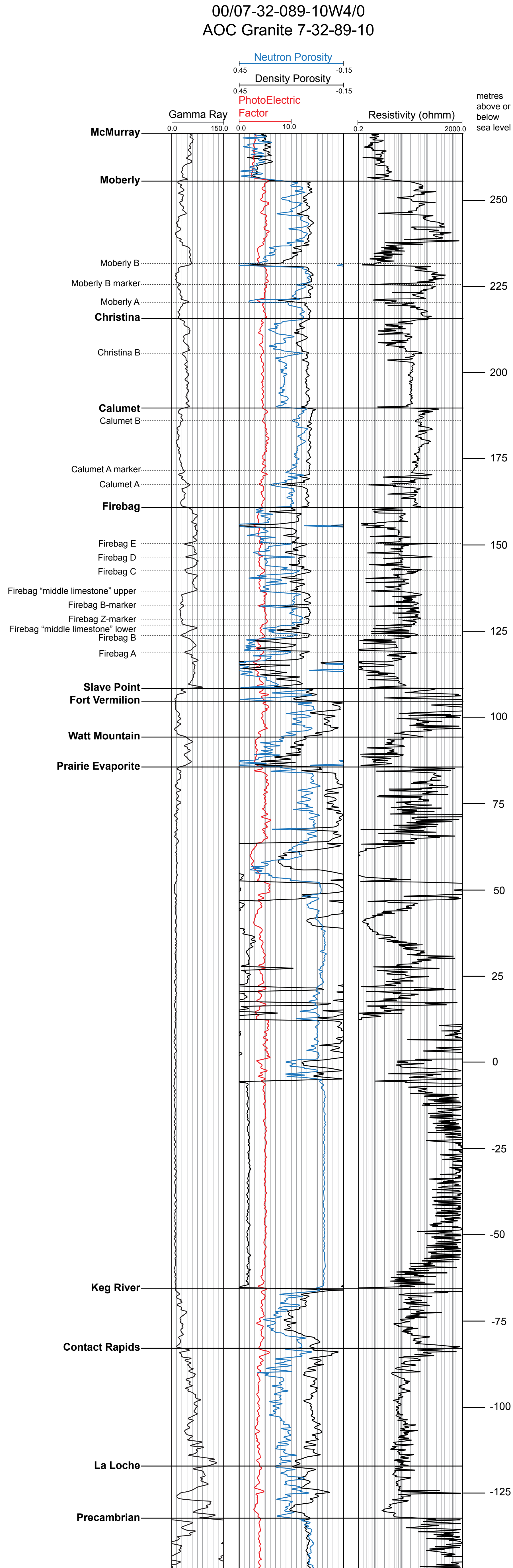


Figure 4. Sample well log from the study area. Formation and member tops are in bold and use solid lines. Marker beds are in smaller, non-bold font and use dotted lines.

3.2 Contact Rapids Formation

The Contact Rapids Formation is a dolomitic, shaly siltstone to silty shale. It is easily recognized in core by its green colour and by the abundant, approximately 1 cm thick, sub-horizontal fractures containing white, fibrous gypsum. The lower several metres of the formation are often mottled red and green and grade into the red siltstone and sandstone of the La Loche Formation below.

The Contact Rapids Formation varies greatly in thickness, also controlled by topographic highs and lows on the crystalline basement, the degree of filling of basement topography by La Loche sandstone, and sea level relative to basement topographic highs. Above some topographic highs of the basement, the Contact Rapids Formation was never deposited because the basement knoll remained above sea level during the interval of Contact Rapids deposition. In all but one core in this study, the Contact Rapids Formation is present; the core lacking Contact Rapids strata did not penetrate deeper than the Keg River Formation. In the present study, thickness of the Contact Rapids Formation varies between 13.4 and 71 m.

In well logs, the Contact Rapids generally decreases in radioactivity upsection. The base of the formation is often arbitrarily placed where the decrease in gamma-ray counts is most steep. In contrast, the top pick is more concise and is placed at a distinctive and consistent radioactive spike which occurs at an approximately 0.3 m thick green shale that underlies the Keg River Formation dolostone.

3.3 Keg River Formation (Methy Formation, Winnipegosis Formation)

Throughout the study area, the Keg River Formation is a beige to brown dolostone. The Keg River Formation varies greatly in thickness, ranging between 17.5 and 102 m in the present study. Thicker Keg River sections likely reflect the presence of bioherms.

The lower part of the Keg River Formation is usually a dolomitized brachiopod- and crinoid-bearing floatstone to rudstone. Where a patch reef is present, the brachiopod and crinoid floatstone to rudstone grades over a short interval into a coral and stromatoporoid rudstone to framestone. In cores containing inter-reef facies, the brachiopod and crinoid floatstone to rudstone grades upward into tidal flat facies. This tidal flat facies occurs in all of the upper Keg River cores examined and overlies both reef and inter-reef facies.

Porosity types in the Keg River dolostone range from large mouldic and vuggy porosity in the patch reef facies to intercrystalline and fenestral porosity in tidal flat facies. Evidence for several episodes of paleokarst, ranging from syndepositional subaerial exposure surfaces to post-Devonian collapse breccias, can be seen at several outcrops along the Clearwater River.

Locally, the Keg River Formation is argillaceous. In most wells, the lowermost few metres of the Keg River Formation are more radioactive than the rest of the formation, which is usually a non-radioactive, non-argillaceous dolostone. Minor anhydrite beds in the upper tidal flat facies can be recognized on the PE and density-neutron logs.

The base of the Keg River Formation is easily recognized throughout the area because of a comparatively radioactive shale bed at the top of the Contact Rapids Formation. The top is also sharp, picked at the first several-metre-thick bed of anhydrite or halite above the dolostone.

3.4 Prairie Evaporite Formation

In the study area, the Prairie Evaporite Formation contains both halite and anhydrite with minor dolostone, limestone, and shale. The northern portion of the study area is richer in anhydrite than the southern area, as seen in the north and south cross-sections. This northward increase in anhydrite arises from the proximity of the study area to the lateral facies transition from the Prairie Evaporite Formation halite to the Muskeg Formation anhydrite.

The Prairie Evaporite Formation contains nodular to bedded anhydrite, laminated shale, and rare dolostone ranging from carbonate mudstone to cryptalgal bindstone textures. Laminated to bedded anhydrite often occurs at the base and top of the Prairie Evaporite Formation and is variable in thickness.

The thickest Prairie Evaporite Formation interval within the study is 285 m in well PC Dover 11-26-91-13 (00/11-26-091-13W4/0). In general, the Prairie Evaporite Formation thins gradually eastward until it disappears into an interval of brecciated, insoluble residue.

Evaporite dissolution frequently resulted in brecciation of inter-halite beds and, locally, the brecciation and mixing of overlying strata. Brecciation is most common east of the Athabasca River where the Prairie Evaporite Formation halite is either greatly reduced or missing. However, in cores where dissolution did not result in brecciation, thin beds of compacted shale may be the only remnant of thick halite deposits.

Diapirism and lateral migration of halite in the Prairie Evaporite Formation has not been observed. However, Belyea (1952) hypothesized that salt flow may have occurred in the subsurface of north-central Alberta and resulted in anomalously thick sections of halite in some wells.

Where intact, the contacts of Prairie Evaporite Formation with the underlying Keg River and overlying Watt Mountain formations are generally sharp. The base occurs where the lithology abruptly changes from Keg River Formation dolostone into anhydrite or halite and is best seen in the density-neutron curve and the PE curve when available. In some wells, the contact between the Keg River and Prairie Evaporite formations can be picked at a very minor but abrupt decrease in gamma ray counts. The top is picked where the Prairie Evaporite Formation halite or anhydrite is overlain by shale or silty shale of the Watt Mountain Formation, expressed by a distinct increase in radioactivity, density and neutron porosity, and a sharp decrease in resistivity.

Where the dissolution and brecciation obscured the contact of the Prairie Evaporite Formation with overlying strata, the top pick is difficult or impossible to make. Prairie Evaporite Formation brecciation results in a similar well log response to that of the Watt Mountain Formation. Where brecciation included overlying strata, only a collapse breccia pick is made.

3.5 Watt Mountain Formation

In the study area, the Watt Mountain Formation varies in thickness between 7 and 12 m, with an anomalously thick section in well 00/08-20-089-09W4/0 of almost 25 m. Lithology can range from shale to silty shale to argillaceous dolostone and in some places includes sandy shale and minor anhydrite. A subaerial unconformity and wave ravinement surface was observed by Meijer-Drees (1988) in northern Alberta and was interpreted to represent a widespread regression at the boundary between transgressive-regressive sequences (sequences If and IIa of Johnson et al. [1985]). This surface was not observed in the study area.

The Watt Mountain Formation is bounded by the anhydrite or halite of the Prairie Evaporite Formation below and the laminated anhydrite and shale of the Fort Vermilion Formation above. In well logs where the Prairie Evaporite Formation surface is intact, the base is distinct, but where the Prairie Formation has been brecciated, the well log appears gradational between the two formations. Where Prairie Evaporite Formation breccia continues into the Watt Mountain Formation, a distinct Prairie Evaporite Formation top, and sometimes a Watt Mountain Formation top, cannot be picked.

The contact between the Watt Mountain Formation and the Fort Vermilion Formation is gradational. In core, the top of the Watt Mountain Formation is placed at the first significant anhydrite bed or where anhydrite becomes the dominant lithology. In well logs, the Watt Mountain Formation pick is either distinct because of a moderately strong anhydrite signature in the gamma-ray and PE curves at the base of the Fort Vermilion Formation or is arbitrary within an overall decreasing-upward trend in radioactivity.

3.6 Fort Vermilion Formation

Throughout the region, the Fort Vermilion Formation ranges between 1.7 and 10 m and generally decreases in thickness eastward. In most cores, the Fort Vermilion Formation is dominantly laminated brown shale and anhydrite with lesser intertidal dolostones of carbonate mudstone to cryptalgal bindstone textures.

In well logs, the Fort Vermilion Formation often shows a strong decrease in the gamma-ray curve and a minor to moderate influence by anhydrite in PE and density-neutron curves. The base can be sharp or gradational with the Watt Mountain Formation, as discussed above. The Fort Vermilion Formation top pick is placed at the top of a thin interval of increased gamma ray values, coincident with a metre-thick shale to argillaceous carbonate in core. The transition into the limestone of the overlying Slave Point Formation, particularly seen in the shift to a limestone PE and in the loss of anhydrite in the density-neutron log, also supports the top pick.

Where Prairie Evaporite Formation dissolution resulted in brecciation of the Fort Vermilion Formation, the top cannot be picked.

3.7 Slave Point Formation

The Slave Point Formation ranges in thickness between 3.5 and 13 m, with thicker sections generally in the northern portion of the study area. In core, it is a brown limestone ranging from mudstone to rudstone textures and contains brachiopods and crinoids. Locally, the Slave Point Formation can contain dark brown shale interbeds. A small phosphatic brachiopod, *Lingula spatulata*, is beige to brown and is locally common in the Slave Point Formation and in the basal few metres of the overlying Firebag Member of the Waterways Formation.

In core, the base is picked at the topmost argillaceous bed of the Fort Vermilion Formation. In well logs, this contact can be quite sharp.

The top of the Slave Point Formation is consistently sharp and is picked at the abrupt contact between the Slave Point Formation carbonate and the Firebag Member shale. This contact is easily recognizable in the gamma-ray log by an abrupt increase in gamma ray values.

Where Prairie Evaporite Formation dissolution resulted in brecciation of overlying strata, the Slave Point Formation may be impossible to identify on logs and instead is included in an undefined collapse breccia.

3.8 Waterways Formation

In the study area, the Waterways Formation is a shallow-water calcareous shale to argillaceous limestone. The base is easily recognized in the transition between the Slave Point Formation limestone and the Firebag Member shale. In most of the study area, the top of the Waterways Formation has been truncated by erosion prior to the deposition of the Cretaceous McMurray Formation such that progressively older Waterways Formation strata subcrop at the sub-Cretaceous unconformity from west to east.

The members of the Waterways Formation, from base to top, include the Firebag, Calumet (Calmut), Christina, Moberly, and Mildred members, each of which have distinct lithological characteristics and well log signatures.

3.8.1 Firebag Member

The Firebag Member is dominantly green-grey calcareous shale with minor argillaceous limestone. Most of the shale is unfossiliferous, but some of the limestone beds contain abundant brachiopods and occasional crinoid columnals. Thickness of the Firebag Member in the study area ranges between 47 and 52.5 m, with thicker sections generally within the southern portion of the study area.

Limestone beds in the Firebag member form distinct markers, most of which can be traced over the entire study area. The thickest of these limestones (Middle Limestone) occurs in the middle of the member and contains a thin, very calcareous shale, which can be recognized as a sharp decrease (Firebag B-marker) on the gamma-ray curve.

The contact of the Firebag Member shale with the underlying Slave Point Formation limestone is sharp, as is the contact with the overlying Calumet Member limestone. Both contacts are easily picked on gamma-ray logs.

3.8.2 Calumet (Calmut) Member

The Calumet Member limestone is generally a grey to beige, heavily bioturbated, brachiopod and crinoid floatstone to local rudstone. Several shale beds in the member result in positive gamma-ray responses and are regionally correlatable across the region. The Calumet Member ranges between 22.5 and 30.5 m throughout the study area.

In core, the Calumet Member limestone is easily recognized by a distinctive brachiopod fauna dominated by concavo-convex strophomenide brachiopods like *Douvellina* and *Strophodonta* and the orthide *Schizophoria*. This distinctive fauna is present in all but the uppermost few metres of the Calumet Member, where atrypide brachiopods increase relative to a decline in strophomenides and *Schizophoria*. In core where the entire Waterways Formation is captured, fossil identification is not critical, but where cores contain only a few metres of uppermost Devonian limestone below the pre–McMurray Formation unconformity, the identification of brachiopods is helpful in determining the general interval in the Calumet Member or whether the limestone is from the Calumet or Moberly member or the middle limestone of the Firebag Member.

The base of the unit is placed at the base of the first clean limestone bed of the Calumet Member. Like the top of the Firebag Member, the top of the Calumet Member is easily picked on gamma-ray logs because of an abrupt lithology change to shale of the Christina Member. In core it contains at its top a three-dimensionally complex hardground up to 5 cm thick with a thin overlying and hardground-infilling grainstone of fossil fragments and millimetre-scale phosphate nodules.

3.8.3 Christina Member

The thickness of the Christina Member varies between 22.7 and 29 m throughout the study area. In core, the Christina Member is dominantly green-grey shale but grades upward into interbedded argillaceous lime mudstone and shale. The unit is largely unfossiliferous and not bioturbated. Hardgrounds are common in this member, particularly in the lime mudstone beds of the upper portion of the unit. In the shalier lower portion of the member, hardgrounds typically are associated with overlying phosphate pebble and intraclast packstones to grainstones that may or may not contain fossil fragments. Many hardgrounds have been broken and reworked to form layers of rounded phosphate pebbles.

On gamma-ray logs, the Christina Member is consistently radioactive with occasional declines in gamma radiation from carbonate-rich beds or thin limestones, particularly in the upper third of the unit. Some of these limestone beds are traceable over various portions of the study area, creating good marker beds for portions of the study area.

The base of the Christina Member is placed at the top of the clean limestone of the Calumet Member and is separated from that underlying member by a hardground. The Christina Member top is easily picked in well logs where the shale rapidly grades into Moberly Member limestone, and is placed at the base of the first high-amplitude negative spike in gamma radiation of the basal Moberly Member limestone (Figure 4). In core, the top of the Christina Member is placed just below the first of a hardground couplet that occurs in the lowermost beige to grey, fossiliferous and argillaceous limestone of the Moberly Member.

3.8.4 Moberly Member

Throughout most of the study area, the top of the Moberly Member was eroded. The Moberly Member was observed in its entirety only within two cores in the southwestern part of the study area The Moberly Member is 62.1 and 79.5 m thick in these two cores.

The Moberly Member is the most lithologically variable of the Waterways Formation members in that it contains calcareous shale through non-argillaceous limestone. The limestone ranges from nodular, *Thalassinoides*-bioturbated wackestone to brachiopod rudstone to a stromatoporoid bindstone. Tempestite coquinas of shingled brachiopod shells are common in the lower beds of the member.

A 2+ m thick stromatoporoid biostrome can be traced throughout the study area and provides a good stratigraphic marker bed for correlation. Branching, bulbous, tabular, and massive stromatoporoids are common, particularly in the northern portions of the study area, forming rudstone to bindstone with a packstone to grainstone matrix. Bitumen commonly fills the pores in the fossils and the matrix. On gamma-ray logs, this biostrome is often the least radioactive interval of the entire Moberly Member.

Several shale and argillaceous limestone beds in the Moberly Member are good markers throughout the region. Over most of the area where the Moberly Member subcrops beneath the Lower Cretaceous McMurray Formation, the upper Moberly Member has been eroded; thus, only marker beds in the lower Moberly Member were identified for the region.

The base of the Moberly Member is placed at the base of the first high-amplitude negative spike in gamma radiation of the basal limestone. In core, this change is easily recognized by two features: First, the Christina Member is green-grey, non-fossiliferous, interbedded calcareous shale and argillaceous lime mudstone, whereas the Moberly Member is beige, bioturbated, fossiliferous argillaceous limestone. Second, the Moberly Member contains two complex hardgrounds that are separated by up to 1 m of Moberly limestone; the lowermost of the two hardgrounds is the base of the Moberly Member. This hardground couplet occurs throughout the study area.

The top of the Moberly Member is picked at the base of a succession of two shale-limestone couplets in the top of the Waterways Formation. This pick corresponds to the contact proposed by Keith (1990), which places the base of the Mildred Member higher in the section than originally proposed by Crickmay (1957) and separates the dominantly limestone interval from the dominantly shale to very argillaceous limestone interval. In the study area, the Mildred Member is a series of two shale-limestone couplets. The Moberly/Mildred boundary is placed at the base of the shale of the lowermost couplet (Figure 5).

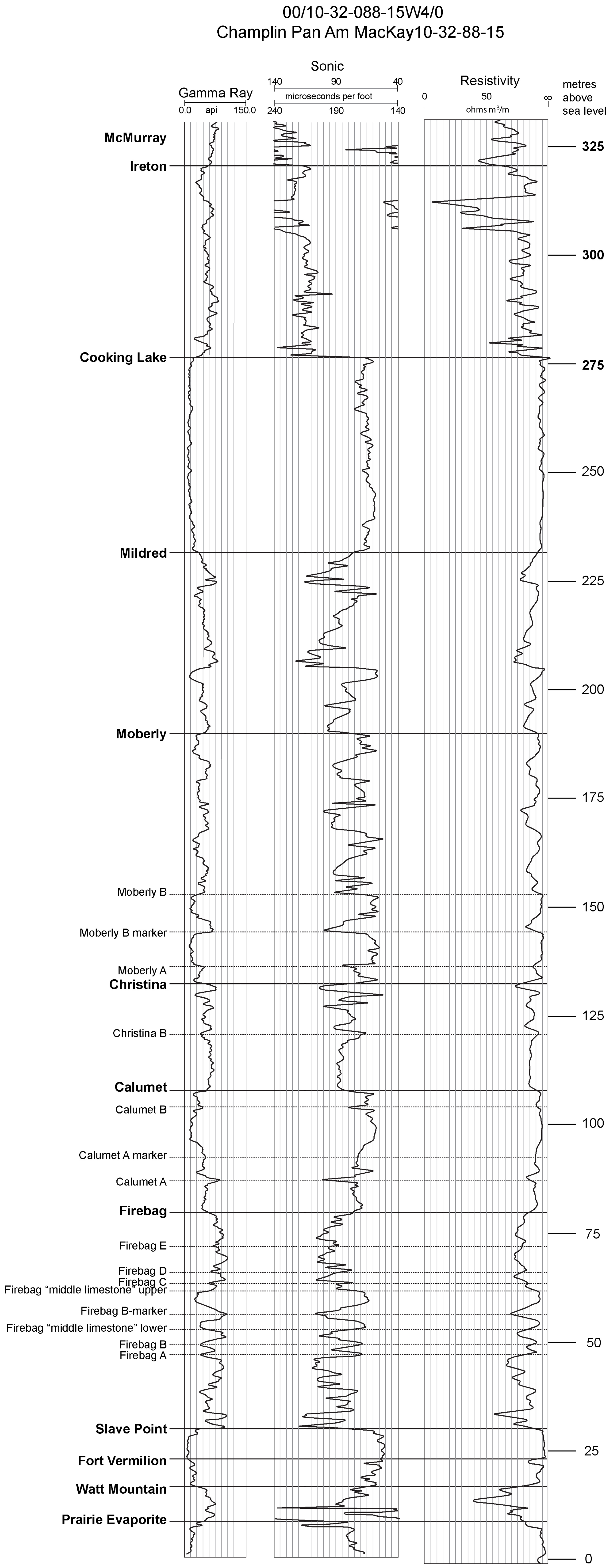


Figure 5. Sample well log of Beaverhill Lake Group and younger strata from the southeasternmost well log in the present study. Formation and member tops are in bold and use solid lines. Marker beds are in smaller, non-bold font and use dotted lines.

3.8.5 Mildred Member

The Mildred Member occurs only in the southwesternmost portion of the study area, where pre–McMurray Formation erosion did not erase the member. In the present study, the Mildred Member occurs only in the westernmost well of the southern cross-section and is 39.3 m thick.

The Mildred Member within the study area contains two sets of shale-limestone couplets. Shale portions of these couplets range from calcareous shale to very argillaceous limestone. Limestones are heavily bioturbated, argillaceous, and range from wackestones of fine fossil debris to rudstone dominated by brachiopods. Most limestone beds are nodular to wavy-bedded. The limestone of the upper couplet grades upward into the cleaner carbonate of the overlying Cooking Lake Formation.

The base of the Mildred Member is placed at the base of the first shale-limestone couplet. The top argillaceous limestone has a rapid transition into the non-argillaceous Cooking Lake Formation and is picked at the inflection point of decreasing gamma-ray counts, which usually is near the onset of 'clean' carbonate.

3.9 Cooking Lake Formation

In the study area, the Cooking Lake Formation was observed only in one well in the southwesternmost part of the study area and was not observed in core. Here, the Cooking Lake Formation is 53.6 m thick. In the Bear Biltmore no. 1 well (7-11-87-17W4) outside of the study area, the Cooking Lake limestone is 43.3 m thick. Lithology of the Cooking Lake Formation in the Bear Biltmore no. 1 core ranges between unfossiliferous and nodular lime mudstone, brachiopod and crinoid floatstone, and stromatoporoid rudstone to bindstone.

The base of the Cooking Lake Formation is gradational over one to two metres through an increase in limestone and a decrease in Mildred Member shale. The base of the Cooking Lake Formation was picked at the inflection point of decreasing gamma-ray counts, which occurs near the onset of 'clean' limestone. The top of the Cooking Lake formation is picked at the boundary between low gamma-ray counts (indicating clean carbonate) and a sharp inflection towards higher values (indicating the presence of more radioactive shale of the Ireton Formation).

3.10 Ireton Formation

The Ireton Formation is a green to green-grey, unfossiliferous calcareous shale and only occurs in the southwesternmost corner of the study area, where the lower portion of the Ireton Formation subcrops beneath the McMurray Formation; the remainder of the Ireton has been lost to post-Devonian erosion. The base of the Ireton Formation is easily recognized by its sharp contrast of higher gamma-ray counts against the 'clean' carbonate of the underlying Cooking Lake Formation limestone.

4 Methods

The study area encompasses Twp. 87 to 98, Rge. 3 to 15, W 4th Mer. (Figure 1). Wells that penetrate to the basement are sparse in this region. Wells for the cross-sections were chosen based on the availability of continuous well logs or core through the entire or most of the Devonian succession.

Gamma-ray, photoelectric, density-neutron, and resistivity well logs were used to pick stratigraphic tops for most wells (Figure 4). Core data for the cross-sections were taken from new descriptions and the descriptions provided in Norris (1963). Cross-section data is presented either as gamma-ray logs or as core data (Figures 6 to 8), except for well 00/07-21-089-11W4/0 in the southern cross-section (Figure 6), which is a neutron log.

Wells containing most or all of the Devonian section are rare in the study area. From the available wells, we constructed three cross-sections: a southern west–east cross-section (Figure 6), a northern west–east cross-section (Figure 7), and a north–south cross-section that roughly parallels the Athabasca River (Figure 8).

4.1 Southern Cross-Section: S–S′

The southern cross-section (Figure 6) captures the southwestern edge of the study area where the Mildred Member through lower Ireton Formation strata subcrop beneath the Lower Cretaceous McMurray Formation. The Devonian section thins eastward because of Prairie Evaporite Formation dissolution and pre–McMurray Formation erosion of Waterways Formation through later Paleozoic strata. Some features observed in this cross-section are as follows:

- The strata overlying the Prairie Evaporite Formation form an anticline with the axis over a thickened section of Prairie Formation evaporites in well 00/11-26-091-13W4/0. The western limb of the anticline follows the regional dip of Devonian strata, and the eastern limb contains the reversed dip of post–Prairie Evaporite strata overlying a zone of evaporite mineral dissolution. This anticline may be analogous to the “Athabasca anticline-syncline pair” of Bachu et al. (1993) and the “asymmetrical Athabasca anticline” of McPhee and Wightman (1991).
- The La Loche Formation is variable in thickness throughout the study area, as observed by Norris (1963).
- The Contact Rapids Formation thins slightly eastward.
- The Keg River Formation is variable in thickness.
- The thickness of the Prairie Evaporite Formation decreases eastward because of halite dissolution. Within this cross-section, there are some notable features:
  - Halite may not have dissolved in substantial amounts in the westernmost wells.
  - Where halite dissolution was incomplete, the Prairie Evaporite Formation contains an upper anhydrite unit of relatively constant thickness at the top. A lower anhydrite unit occurs only in the westernmost two wells. Sporadic anhydrite beds occur in the section and are either localized or can be traced through several wells.
  - The Prairie Evaporite Formation thickens in well 00/00/11-26-091-13W4/0.
  - The relative portion of anhydrite within the Prairie Evaporite Formation increases eastward, particularly in well 00/7-32-89-10W4. Prairie Evaporite Formation core from well 00/05-17-091-09W4/0 (Bear Rodeo no. 2) is mostly anhydrite and contains no halite. Thin, compacted brown shales (up to 10 cm thick) in the anhydrite may be remnants of halite dissolution.
  - A distinct salt scarp is not recognized. Instead, Prairie Evaporite Formation halite thins fairly consistently between wells 00/11-26-091-13W4/0 and 00/5-17-091-09W4/0.
  - Collapse and possible brecciation of non-evaporite Prairie Evaporite Formation strata begins somewhere east of well 00/15-29-091-08W4/0, becomes more pervasive eastward, and includes the overlying Watt Mountain and Fort Vermilion formations in the easternmost core 00/11-16-089-03W4/0 (Weymarn no. 1).
- The Watt Mountain Formation has a more or less consistent thickness but is lost to collapse and possible brecciation resulting from the dissolution of halite and anhydrite in the Prairie Evaporite Formation in the easternmost core (Weymarn no. 1).
- The Fort Vermilion Formation is thin in the eastern and western portions of the cross-section and thickens between these regions. In the easternmost core (Weymarn no. 1), the Fort Vermilion Formation cannot be differentiated from the Watt Mountain and Prairie Evaporite formations.

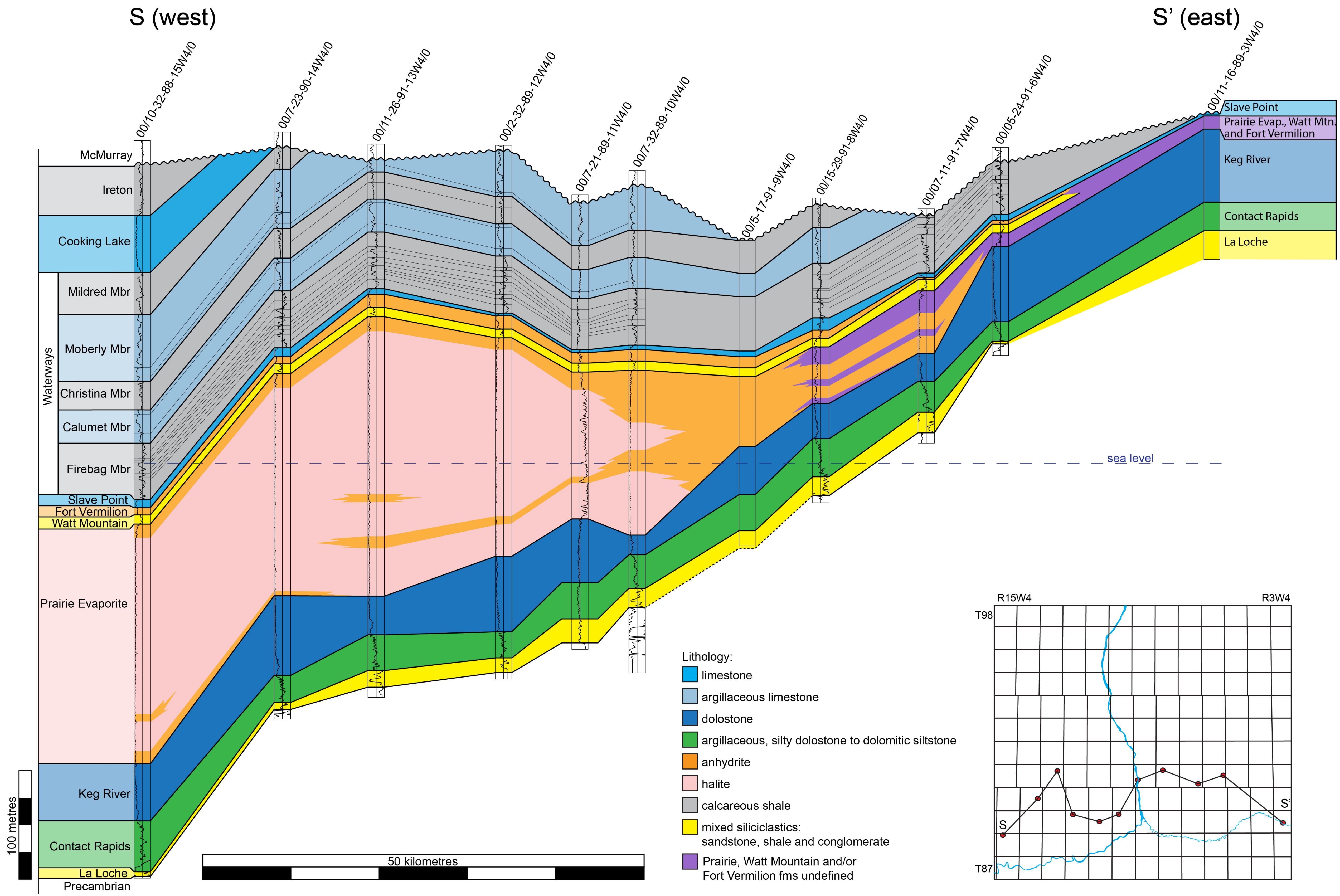


Figure 6. Cross-section of Devonian stratigraphy through the southern portion of the study area.

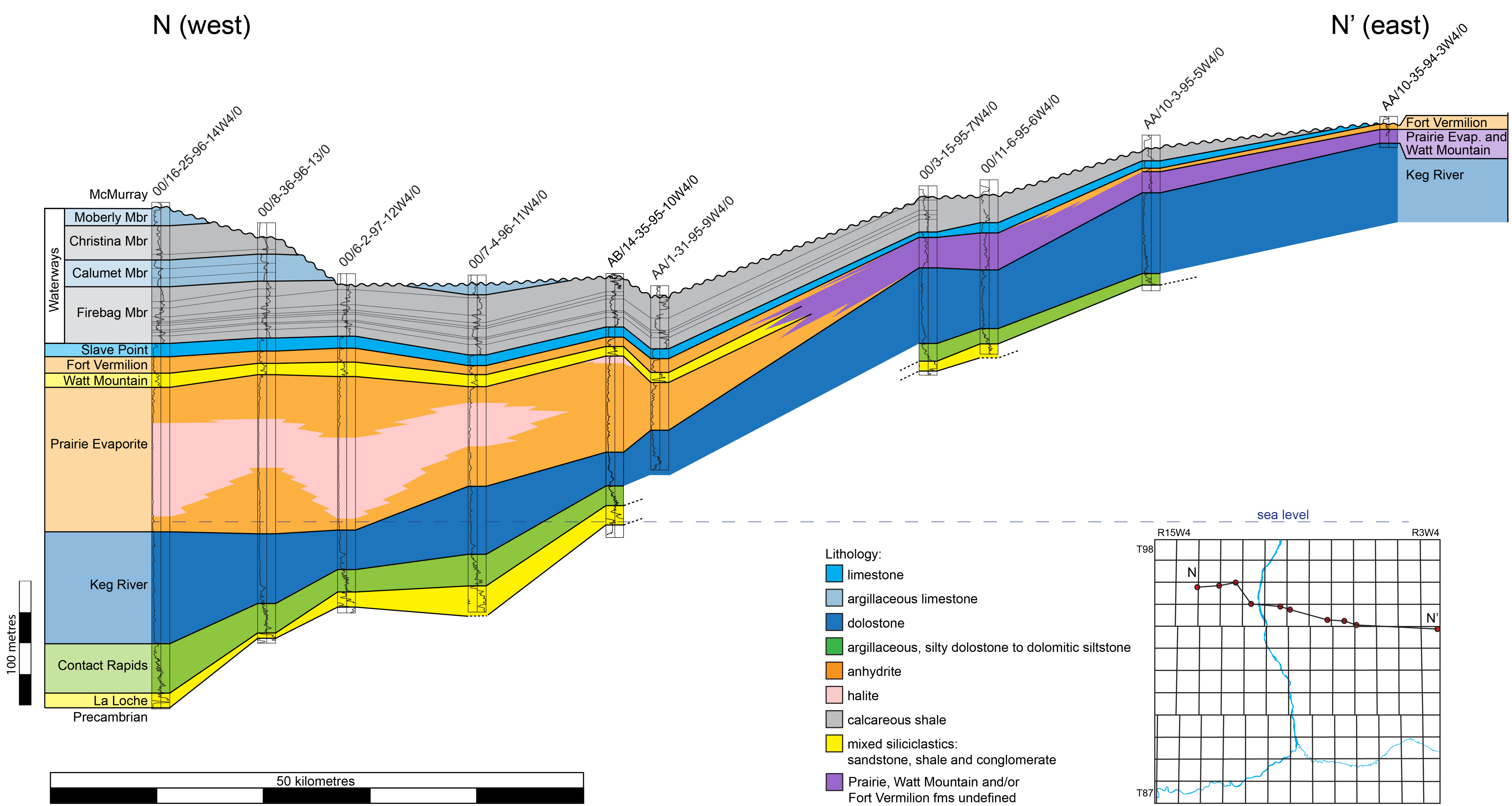


Figure 7. Structural cross-section of Devonian stratigraphy through the northern portion of the study area.

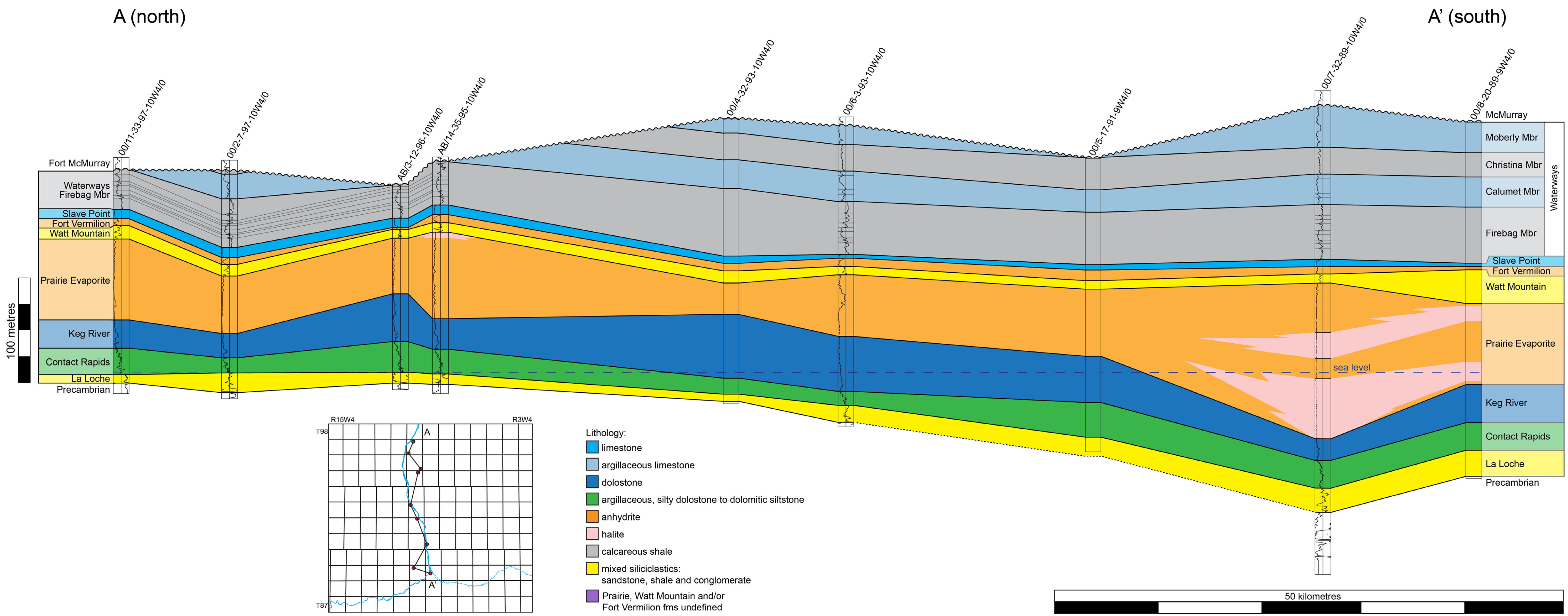


Figure 8. Structural cross-section of Devonian stratigraphy north to south through the study area.

- The Slave Point Formation varies in thickness across the section.
- Where not truncated by erosion, Waterways Formation members maintain more or less consistent thicknesses throughout the line of cross-section.
- The erosional surface of the sub-Cretaceous unconformity is highly variable and forms a topographic low between wells 00/02-32-089-12W4/0 and 00/05-24-091-06W4/0.

4.2 Northern Cross-Section: N–N′

The northern cross-section (Figure 7) shows a thinner succession of Devonian strata than the southern cross-section. The western limit of evaporite dissolution within the Prairie Evaporite Formation is further west than captured in the northern cross-section. The zone of collapse or brecciation of remnant Prairie Evaporite Formation strata begins further west than in the southern cross-section. Some features of the northern cross-section include the following:

- East of well AA/01-31-95-09W4/0, the base of the Watt Mountain Formation cannot be picked, but Beaverhill Lake Group strata dip to the west, roughly parallel to the top of the Keg River Formation.
- The La Loche Formation is variably thick, presumably reflecting the topography of the Precambrian basement. The La Loche Formation is known to thin over basement topographic highs and thicken in topographic lows (Norris, 1963).
- The Contact Rapids Formation thins eastward.
- The Keg River Formation is variable in thickness.
- The Prairie Evaporite Formation in the northern cross-section is thinner than that of the southern cross-section and likely has undergone more halite dissolution in the northern section. Other features include the following:
  - Thick anhydrite units exist at the top and base of the Prairie Evaporite Formation and a higher overall proportion of anhydrite over halite is apparent.
  - The zone of total dissolution of Prairie Evaporite Formation evaporites and resulting brecciation lies somewhere between well AA/01-31-095-09W4/0 and well 00/03-15-095-07W4/0 and continues eastward; it includes strata of the Watt Mountain Formation in four wells and Fort Vermilion Formation strata in two wells.
  - A distinct salt scarp is not seen in this cross-section; however, a distinct anhydrite scarp may exist between closely-spaced wells AB/14-35-095-10W4/0 and AA/01-31-095-09W4/0.
- Where distinct from the Prairie Evaporite Formation, the Watt Mountain Formation maintains a more or less constant thickness throughout the cross-section.
- The Fort Vermilion Formation has a nearly consistent thickness until it reaches the western extent of the zone of dissolution-related collapse and brecciation involving the Watt Mountain Formation and possibly the lower part of the Fort Vermilion Formation.
- The Slave Point Formation thins eastward.
- Most of the Waterways Formation is eroded east of well 00/16-25-096-14W4/0.
- The sub-Cretaceous unconformity is topographically highest on either end of the cross-section and has a topographic low at well AA/01-31-095-09W4/0.

4.3 North–South Cross-Section Along the Athabasca River: A–A′

This cross-section (Figure 8) roughly parallels the Athabasca River. The thickness of Devonian strata increases southward, mainly because of the southward retention of progressively younger Waterways Formation strata and thicker Prairie Evaporite and Watt Mountain formations. Features in this north–south cross-section include the following:

- The La Loche Formation has a variable thickness, likely as a result of filling in low areas on the Precambrian basement.
- The Contact Rapids Formation also is variable in thickness, unlike in the northern and southern cross-sections.
- The Keg River Formation is variable in thickness.
- The Prairie Evaporite Formation is variable in thickness and, except for the southernmost two wells, and is mostly anhydrite.
- The Watt Mountain Formation thins slightly towards the south but shows a marked increase in thickness in well 00/08-20-89-09W4/0 at the southernmost end of the cross-section.
- The Fort Vermilion Formation is variable in thickness.
- The Slave Point Formation thins southward.
- The Waterways Formation members have a more or less consistent thickness, except where truncated by pre-Cretaceous erosion. In core 00/5-17-91-09W4/0 (Bear Rodeo no. 2), the Christina Member is thickened slightly at the expense of the Calumet Member.
- The sub-Cretaceous unconformity is topographically lowest in the north, but reaches two topographic highs in wells 00/04-32-093-10W4/0 and 00/07-32-089-10W4/0.

5 Conclusions

Comparison of the three cross-sections leads to the following conclusions.

5.1 La Loche and Contact Rapids: Thickness Distribution

Previous stratigraphic studies have recognized the influence of basement topography on the thickness of the La Loche Formation (e.g., Norris, 1963). The present study is no different; the La Loche Formation varies in thickness between 5 and at least 22 m in wells that capture the Devonian-basement contact. This thickness variation presumably arises from topographic highs and lows in basement topography during the deposition of the La Loche Formation.

The Contact Rapids Formation also varies in thickness, likely reflecting the antecedent topography of the combined basement–La Loche Formation. Excepting the effects from compaction, the top of the combined La Loche Formation–Precambrian basement likely was not a flat surface, as La Loche sands likely never completely filled basement topographic lows. Conversely, the Contact Rapids Formation top likely was a flat surface, reflecting only the gentle topography of the sea floor at the time. A widespread, argillaceous marker is consistent throughout the study area and may also represent an isochron that marks the change from marginal marine sedimentation of the Contact Rapids Formation to open marine conditions of the Keg River Formation.

5.2 Keg River Formation

Strata in the Keg River Formation include three major lithofacies: biostromal dolostone, open marine, brachiopod- and crinoid-rich dolostone, and laminated dolostone. The Keg River Formation varies greatly in thickness, between 17.5 and 102 m. Thicker sections reflect the localized development of bioherms during Keg River deposition (Carrigy, 1975). Core intervals that are biostromal also include the open marine brachiopod- and crinoid-rich dolostones and the laminated dolostone facies. In thinner sections, the biostromal facies is missing and open marine facies grades upward into restricted marine, laminated dolostone. Thus, thickness distribution of the Keg River Formation in the study area reflects the aerial distribution of reefs and inter-reef areas on the Keg River carbonate platform.

5.3 Prairie Evaporite Formation and evaporite dissolution

Past studies have defined a salt scarp in the Prairie Evaporite Formation, but definitions of the scarp differ. Bachu et al. (1993) defined the salt scarp as a 20 km wide zone of salt dissolution in the subsurface. Hein et al. (2000) used the term "salt scarp" for a generally north–south trending topographic low in the sub-Cretaceous unconformity surface which presumably corresponded to a salt dissolution front in subsurface.

Although previous authors have mentioned a salt scarp, the present study did not capture a distinct scarp-like feature in the subsurface. A scarp suggests a steep slope or cliff, but the Prairie Evaporite strata gradually pinch out to eastward rather than experience a sudden decrease in thickness. Like previous studies, the cross-sections of the present study reveal an eastward thinning of the Prairie Evaporite Formation, resulting in a generally wedge-shaped thickness distribution of evaporite strata from east to west. Rather, the Prairie Evaporite Formation is best divided into three zones of dissolution (Figure 9):

1) A zone of partial halite dissolution: The Prairie Evaporite Formation contains both halite and anhydrite in this zone, which is along the western portion of the study area. Dissolution of halite was likely greater than that of anhydrite and resulted in an eastward thinning of the Prairie Evaporite Formation in this zone. In core, strata may or may not contain evidence of the loss of halite and a subsequent decrease in thickness, such as brecciation of non-halite strata or layers of insoluble residue. The reverse dip of Prairie Evaporite Formation and younger Devonian surfaces begins in the eastern portion of this zone.
2) A zone of complete halite dissolution and active loss of anhydrite: In this zone, Prairie Evaporite Formation halite has dissolved. This region may contain localized pockets where halite has not yet completely dissolved (Hein, pers. comm.). The likelihood of residual halite would be greatest along the western margin of this zone. Remaining Prairie Evaporite strata have subsided or collapsed in this zone. The rehydration and dissolution of anhydrite occurs within this zone, which roughly parallels the Athabasca River. Further deformation of post–Prairie Evaporite strata would likely occur from the expansion of the Prairie Evaporite Formation during the hydration of anhydrite to gypsum prior to dissolution. This zone contains the reverse dip of the surfaces of the Prairie Evaporite Formation and younger strata.
3) A zone of total dissolution of all evaporites: In this zone, all evaporite minerals have dissolved from the Prairie Evaporite Formation, save potential localized remnants or patches of evaporite minerals. Only carbonate beds and insoluble sediments remain in the condensed remnant of the Prairie Evaporite Formation. This zone occurs along the eastern margin of the study area. Dissolution of evaporites in this zone resulted in the collapse of insoluble Prairie Evaporite Formation remnants and post–Prairie Evaporite Devonian strata such that Prairie Evaporite and younger strata follow the topography and regional dip of the top of the Keg River Formation.

Evaporite dissolution is ongoing, given the presence of salt and sulphur springs and recent karst in the study area. Boundaries between the three zones are therefore not static and will move with continued dissolution of evaporite minerals. The present rates of halite and anhydrite loss are unknown.

5.4 The "Reverse Dip" of the Watt Mountain Formation and Younger Devonian Strata

The "reverse dip" of post–Prairie Evaporite Devonian strata has long been recognized in the study area (e.g., Norris, 1963). The dip of strata unaffected by evaporite dissolution is toward the southwest, but in the study area, an eastward-increasing loss of halite and anhydrite resulted in the subsidence and collapse of overlying strata into a generally eastward dip.

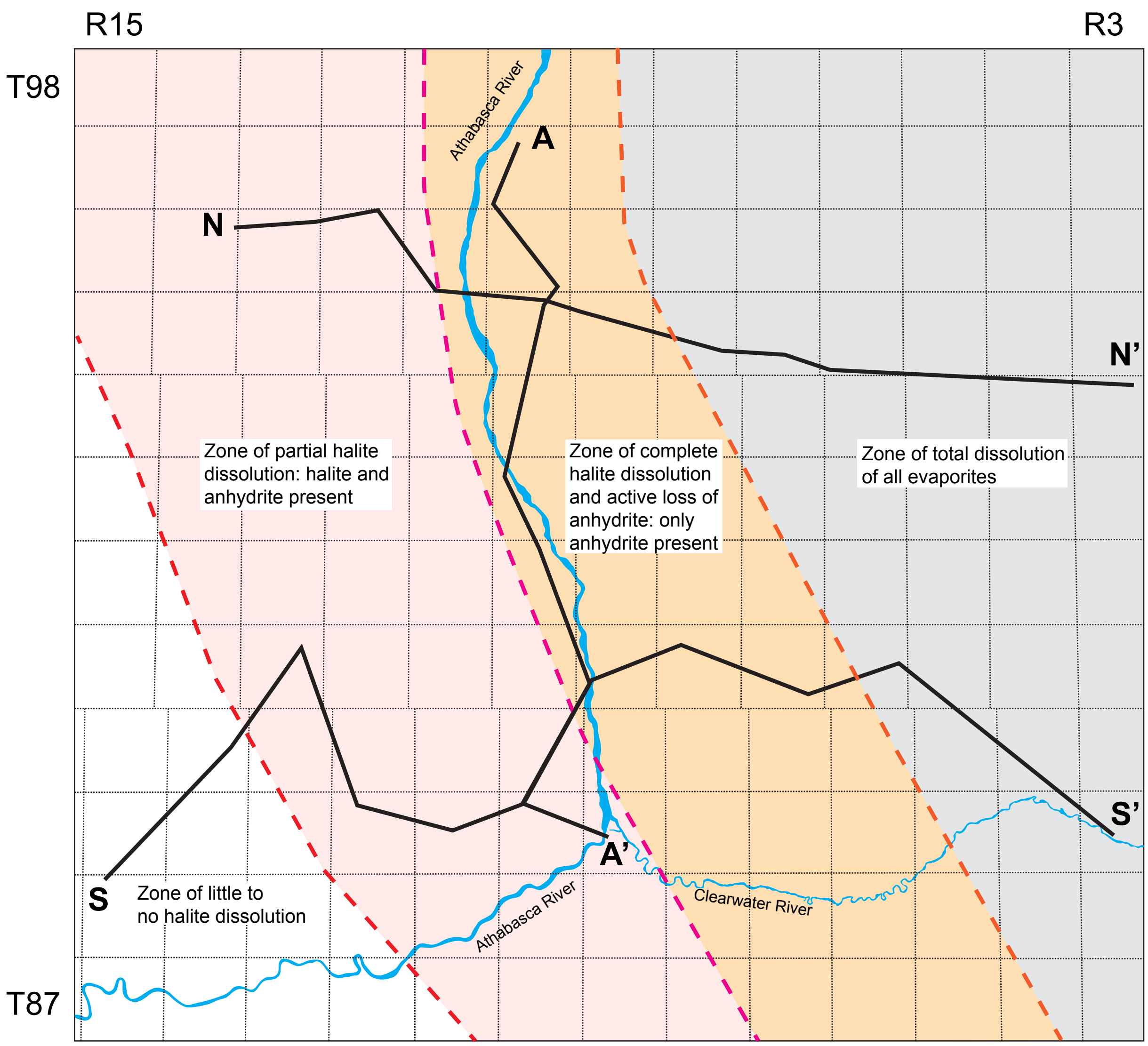


Figure 9. Dissolutional zones within the Prairie Evaporite Formation. Zone boundaries are approximated from cross-sections and data in Grobe (2000); actual zone boundaries are likely more complex. The zone of little to no halite dissolution is based on Grobe (2000) because there is little data in well logs within the southern cross-section regarding the extent of potential halite dissolution. The zone of partial halite dissolution contains both halite and anhydrite, although halite decreases in thickness from west to east until all halite is dissolved at the eastern boundary of the zone. In the zone of complete halite dissolution and active loss of anhydrite, only anhydrite remains, but it thins eastward with the rehydration of anhydrite and dissolution of gypsum and anhydrite. Remnant pockets of halite may exist in this zone and, if present, likely are near the western edge of this zone. The Prairie Evaporite Formation in the zone of total dissolution of all evaporites contains only residual, insoluble strata. Evaporite minerals in this zone, if present, are limited to localized occurrences.

In the zone of total evaporite dissolution, the dip of post–Prairie Evaporite strata has been restored to a generally southwestward dip. Prairie Evaporite dissolutional residues and post-Prairie strata conform to the surface of the Keg River Formation, which is largely unaffected by evaporite dissolution and thus maintains the southwestward dip.

The Keg River Formation contains localized bioherms that affect the thickness of the formation in the region by as much as 80 m. In the zone of total evaporite dissolution, post–Keg River Formation strata likely conform to the topography of the top of the Keg River Formation, interrupting the general southwestward dip of post–Keg River strata with the topographic highs created by bioherms.

5.5 Sub-Cretaceous Unconformity

The sub-Cretaceous unconformity generally downcuts Devonian strata eastward, resulting in an easterly subcropping of older strata. This is best represented in the eastern portion of the zone of partial halite dissolution and in the zone of total evaporite dissolution. In the zone of total halite dissolution, the pattern of Devonian subcrop is affected by a combination of the depth of erosion and the reverse dip of the area. As a result, subcropping strata in this zone are younger to the east, similar to the erosional truncation of a limb of an anticline.

The lowest topographic relief of the sub-Cretaceous unconformity is in the vicinity of the Athabasca River on the east–west cross sections. Low topography in this region likely arose from a combination of dissolution of Prairie Evaporite Formation halite and pre-McMurray Formation erosion.

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