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The Sub-Cretaceous Unconformity and the Devonian Subcrop in the Athabasca Oil Sands Area, Townships 87–99, Ranges 1–13, West of the Fourth Meridian

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The Sub-Cretaceous Unconformity and the Devonian Subcrop in the Athabasca Oil Sands Area, Townships 87–99, Ranges 1–13, West of the Fourth Meridian

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Abstract

Mapping of the Devonian strata underlying the sub-Cretaceous unconformity resulted in a refined delineation of their subcrop extents and the topography at the sub-Cretaceous unconformity in the eastern extent of the Athabasca Oil Sands Area. Results are at a higher resolution than previously available because of the abundance and density of well data used. The sub-Cretaceous unconformity surface contains a north-northwest-trending trough comprising the Bitumount Basin in the north and smaller basins in the centre and south within the study area. Comparison of the new subcrop extents with unconformity models presented below indicates a complex interaction between subaerial erosion before the deposition of the McMurray Formation and hypogenic karst processes, in which the dissolution of the Prairie Evaporite Formation at depth resulted in the subsidence to collapse of overlying Devonian strata.

1 Introduction

Devonian strata underlying the Lower Cretaceous McMurray Formation in the Athabasca Oil Sands Area between townships 87 and 99 and ranges 1 through 13, west of the Fourth Meridian (Figure 1), were investigated in order to understand both the structure, with emphasis on the effects from the dissolution of the Prairie Evaporite Formation, and the nature of the sub-Cretaceous unconformity. Investigations include both subsurface mapping and outcrop investigation, the latter of which is described in other reports in greater detail (i.e., Schneider et al., 2013a, b).

Devonian strata subcropping beneath the McMurray Formation have been affected by tilting, subaerial exposure and erosion, and deformation and collapse because of the dissolution of underlying Prairie Evaporite Formation halite and anhydrite. Because Devonian strata differ in their resistance to physical and chemical erosion, the resulting topography of the sub-Cretaceous unconformity surface and the pattern of subcropping Devonian rocks can be highly variable, even within a single township.

2 Background

Stratigraphic relationships and structure of Devonian strata within the study area are complicated by the loss of halite and anhydrite of the Middle Devonian Prairie Evaporite Formation. The dissolution of halite and the hydration and ultimate dissolution of anhydrite resulted in varying degrees of subsidence, up to outright collapse of overlying strata.

In northeastern Alberta, an evaporite dissolution zone underlies much of the region, stretching from west of the Athabasca River to the Devonian erosional limit in the east (Figure 2). Evaporite dissolution occurred as early as the Devonian, with some evidence of syndepositional evaporite loss (Park and Jones, 1985). Dissolution of evaporite strata is likely ongoing.

Based on subsurface cross-sections, Schneider and Grobe (2013) reconstructed three zones of evaporite dissolution within the Prairie Evaporite Formation (Figure 3). In the westernmost zone, halite has been partially dissolved, while the volume of anhydrite is largely unaffected. Salt thickness within this zone decreases eastwards into the zone of total halite dissolution and partial anhydrite dissolution. Here, halite is only present in remnant patches, while anhydrite hydration and dissolution is occurring in the subsurface. The easternmost zone of the Prairie Evaporite Formation contains only the insoluble residue. In this zone, except for isolated remnants, the more soluble evaporites have been lost completely. Paralleling the eastward loss of evaporites and thinning of the Prairie Evaporite Formation, overlying Devonian strata become more frequently brecciated eastward and show increased evidence of collapse.

The regional dip of Devonian strata in northeastern Alberta, in the absence of evaporite dissolution, is generally westwards at a rate of 3.8 m/km (Norris, 1963; Martin and Jamin, 1963). Where the evaporite strata of the Prairie Evaporite Formation have been partially dissolved, overlying Devonian strata are tilted eastwards in a ‘reverse dip’ (i.e., opposing the westward regional dip) because of the collapse of these younger strata over the diminished Prairie Evaporite Formation (Figure 4). Where the evaporites of the Prairie Evaporite Formation have been totally dissolved, overlying Devonian strata have subsided or collapsed onto the top of the westward-dipping Keg River Formation and thus resume the overall regional westward dip, save for topographic interference from upper Keg River patch reefs (Schneider and Grobe, 2013).

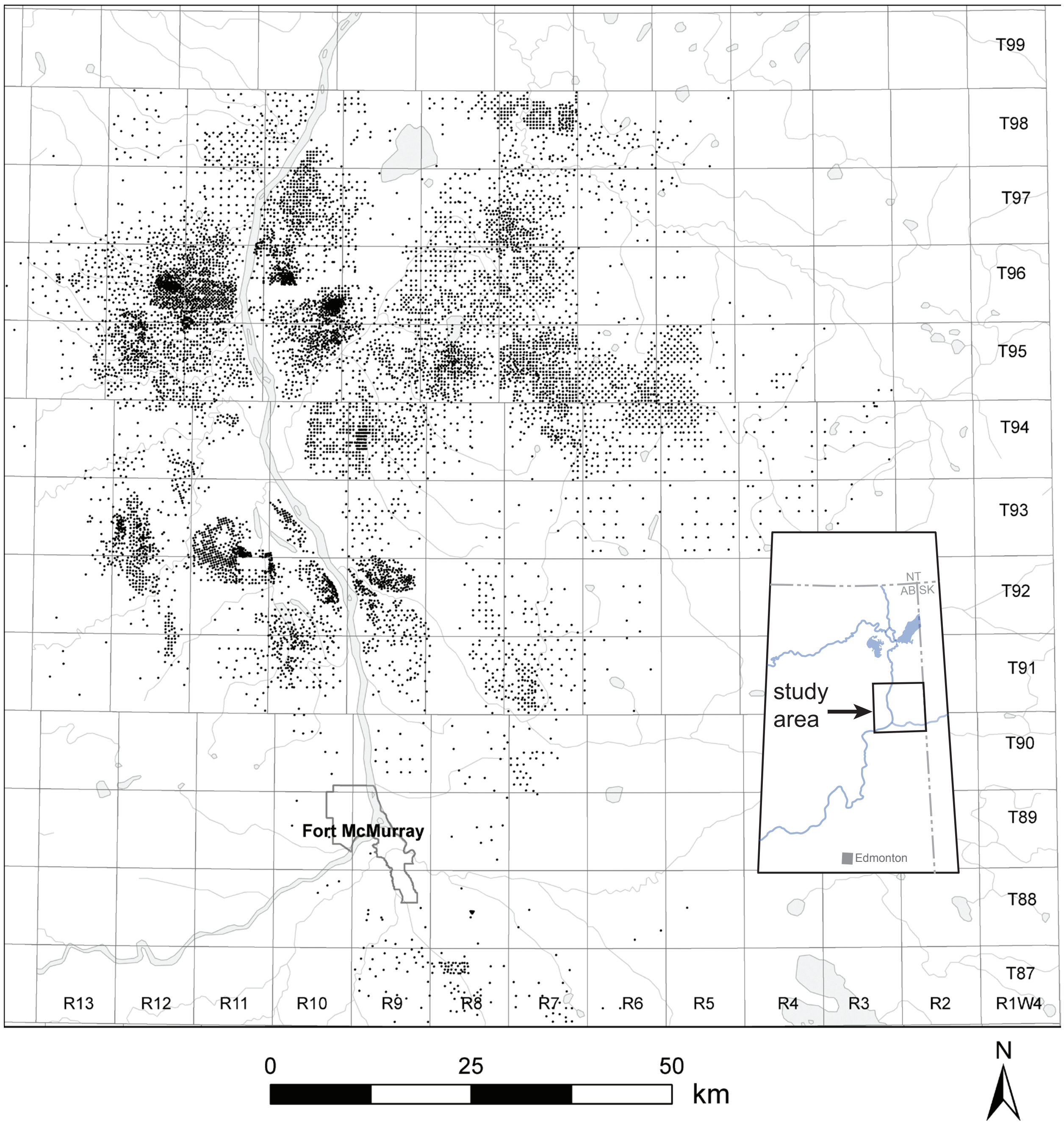

Figure 1. The distribution of wells within the study area used to construct maps of the Devonian subcrop and the sub-Cretaceous unconformity.

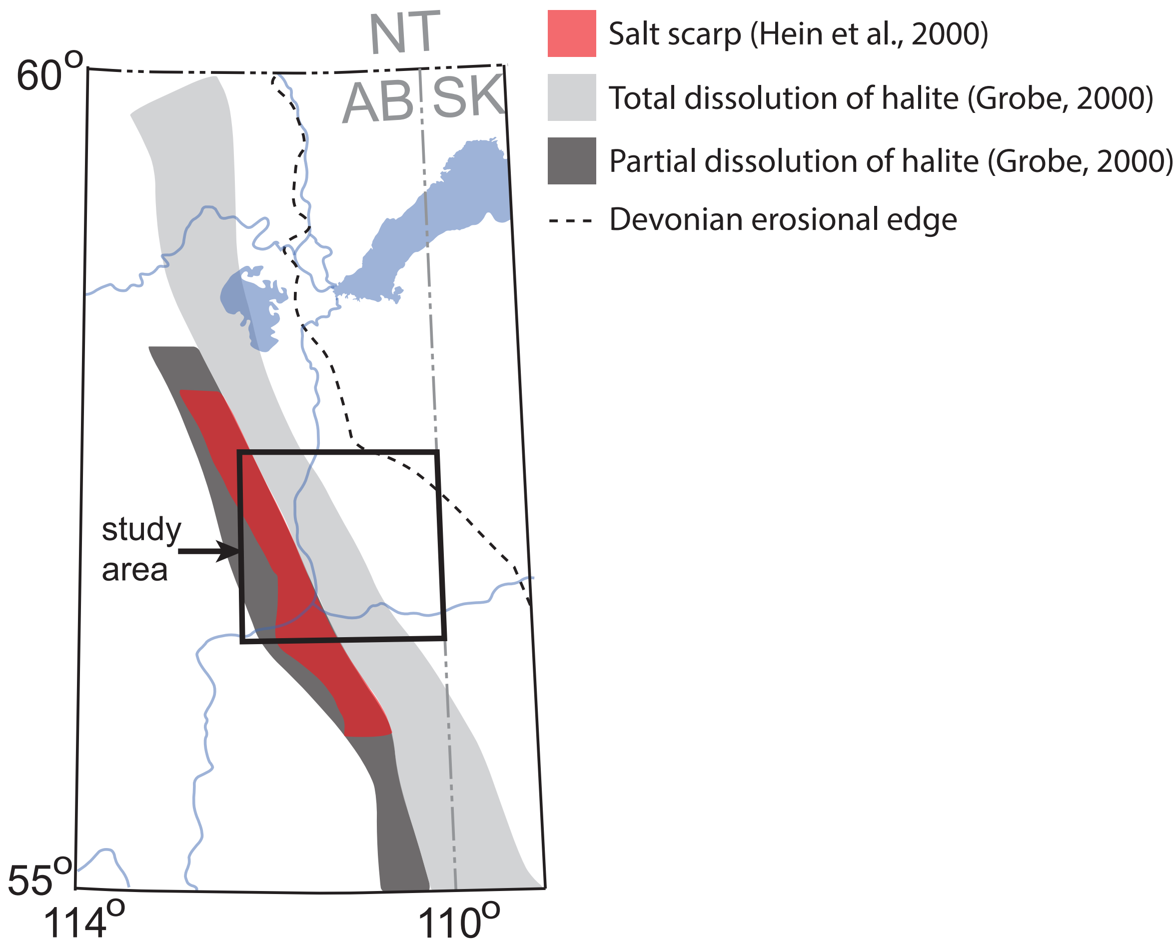

Figure 2. Halite dissolution within the Prairie Evaporite Formation in northeastern Alberta. Note that the partial and total dissolution zones of Grobe (2000) and the salt scarp of Hein et al. (2000) underlie the study area.

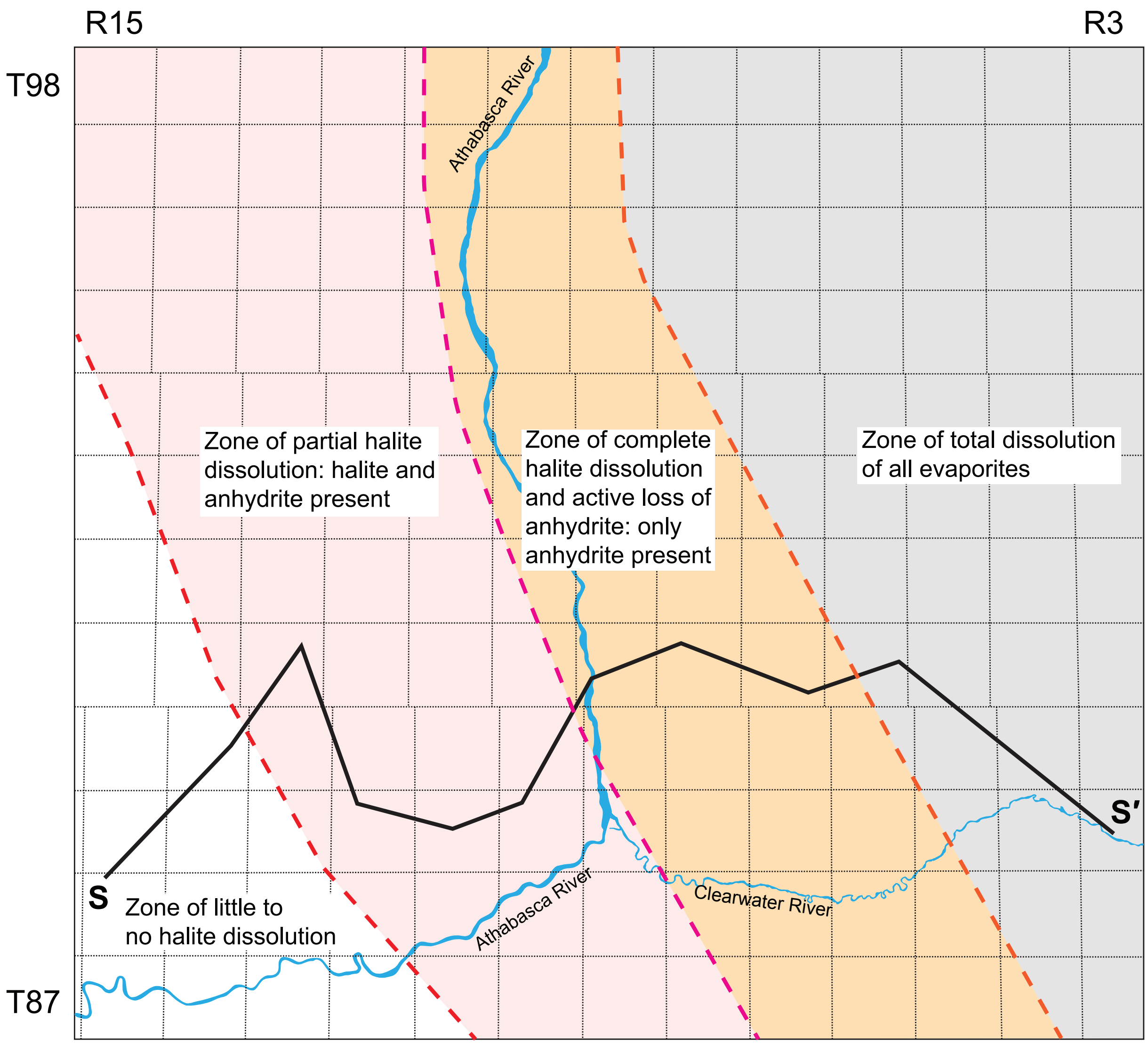

Figure 3. Dissolution zones in the Prairie Evaporite Formation interpreted by Schneider and Grobe (2013). From southwest to northeast, the volume of evaporite minerals decreases because of dissolution. In the zone of total dissolution of all evaporites, the Prairie Evaporite Formation is reduced to insoluble residue, except for localized remnants of evaporite minerals. Cross-section S to S′ refers to the cross-section in Figure 4. Figure modified from Schneider and Grobe (2013).

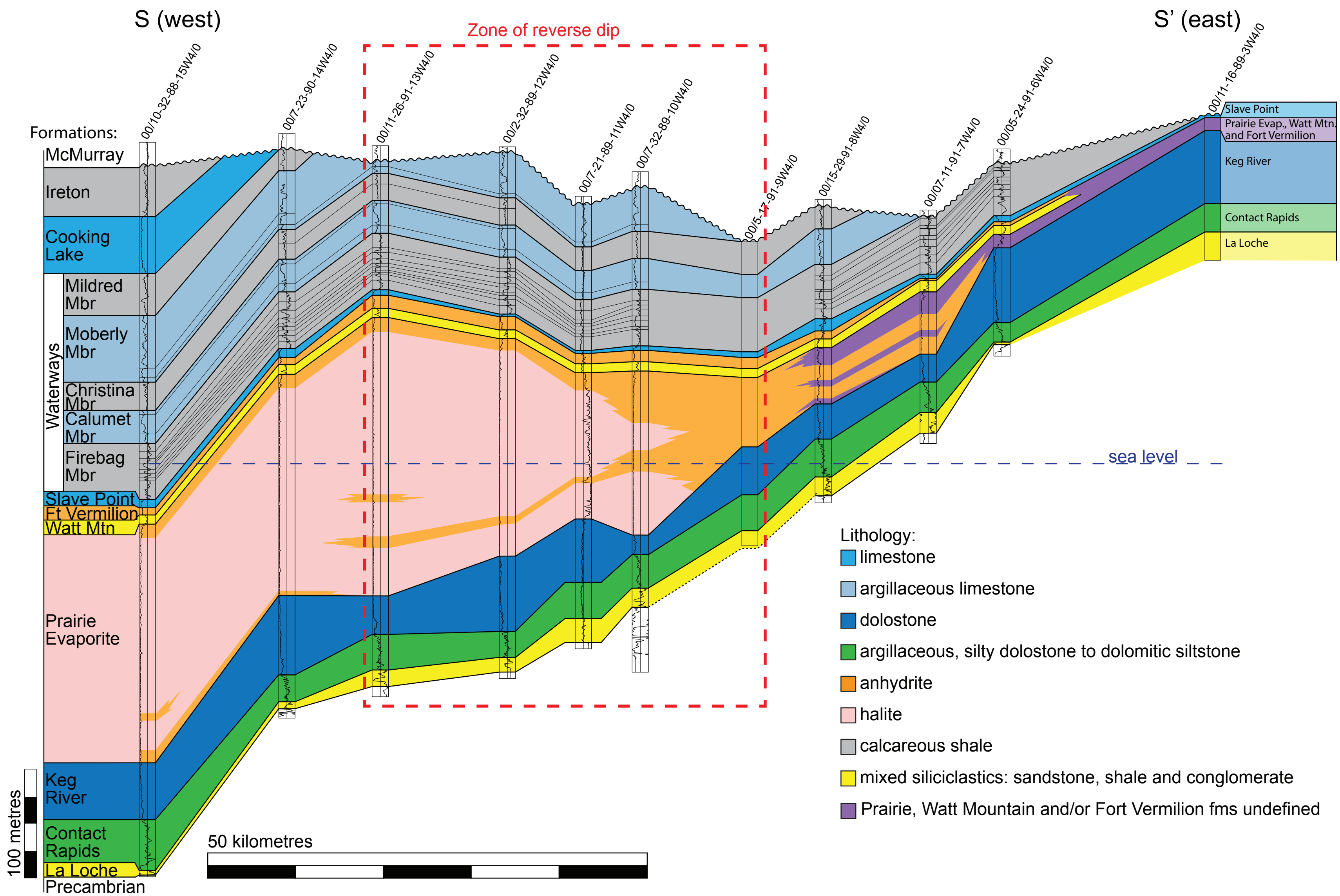

Figure 4. Cross-section of Devonian strata in the study area, from Schneider and Grobe (2013). For cross-section location, see Figure 3.

2.1 Deformation Resulting from Subsurface Evaporite Dissolution

Early explorers noticed folded limestones bordering the Athabasca and Clearwater rivers. Macoun (1877) wrote, “nearly all the strata show graceful curves, the folds never rising more than ten feet” (p. 93). Because his observations came from the northward-flowing Athabasca River, he described the dips along fold limbs as north and south, with fold axes striking perpendicular to the river.

Bell (1884) observed folded Waterways limestones below tar-bearing McMurray Formation sandstone along the Athabasca River. In his words, the limestones “generally undulate slightly” and are “usually planed down to an even surface” (Bell, 1884, p. 2).

Hume (1947) described deformation within the Waterways Formation as a series of domes and basins resulting from volumetric changes related to hydration of anhydrite in the Prairie Evaporite Formation. Later, Hume (1949) observed folding in Cretaceous strata around the Mildred and Ruth lakes area, but doubted that deformation in these post-Devonian units was related to salt dissolution in the Prairie Evaporite Formation.

Norris (1963) measured low-amplitude “flexures” in Waterways Formation limestone beds along the Clearwater and Athabasca rivers, most of which dip less than 10 degrees and a few with dips of up to 17 degrees. Norris further stated that these were minor folds in the limestone, unrelated to the overall westward dip of Devonian strata, but Norris did not suggest a cause. Later, Norris (1973) redescribed the Waterways Formation folding as domes and basins with amplitudes up to 100 feet (30.4 m) and wavelengths up to 1 mile (1.6 km). Norris also suggested that some of the structures also originated from the solution of halite and subsequent differential subsidence.

Bachu et al. (1993) recognized a “salt scarp” in the 20 km wide Prairie Evaporite Formation dissolution zone that roughly corresponded to the south-trending Athabasca River. Both Bachu et al. (1993) and Nikols (1996) reconstructed the deflection of strata over the scarp, in which the normally southwestward-dipping Beaverhill Lake Group is tilted eastwards. Bachu et al. (1993) described the reversal in regional dip across the Prairie Evaporite Formation salt scarp as the Athabasca anticline-syncline pair; McPhee and Wightman (2003) 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 eastwards, many hydrostratigraphic units that are isolated elsewhere in the Alberta subsurface come into contact east of the Athabasca River and are hydraulically continuous (Bachu et al., 1993).

Along the Clearwater and Athabasca rivers, Dufresne et al. (1994) described folded Waterways limestones with dips up to 15 degrees and suggested that the gentle warping of carbonate strata originated from gradual removal of subsurface halite. Dufresne et al. (1994) also suggested the influence of several basement faults in the region on Waterways Formation deformation, such as the Sewetakun Fault underlying the edge of Prairie Evaporite Formation halite dissolution that may have reactivated during the Devonian (Hackbarth and Nastasa, 1979). However, Dufresne et al. (1994) acknowledged that tectonic deformation of Waterways limestones is difficult to distinguish from folding caused by halite dissolution and the collapse of overlying strata.

Nikols (1996) likewise suggested that the deformation in Devonian rocks was consistent with salt solution and the collapse of overlying strata. He observed gentle folds in Waterways Formation limestones along the McKay River and reconstructed a pattern of oval structures of troughs and domes, rather than simple folds, from bedding dips. Nikols measured an average frequency of joints at 1 m spacing and determined that subaerial weathering processes did not cause jointing in Waterways Formation limestones. Because joint frequency did not increase on the flanks between troughs and domes, Nikols suggested that deformation in Waterways Formation strata was a slow process.

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, such as those reported from cores in Halferdahl (1986) and Dahrouge (2007).

Several scales of folding in outcrops occur along the Athabasca River: two smaller scales of parasitic folds ranging from 50 to 100 m, and others of hundreds of metres on the limbs of larger folds of 1 km or more in wavelength (Schneider, 2011; Schneider et al., 2012). Based on correlation of well logs and cores, cross-sections in Schneider and Grobe (2013) depicted a study-area-wide anticline of Beaverhill Lake Group strata draped over a thinning wedge of Prairie Evaporite Formation (Figure 4).

Devonian outcrops within the study area contain a few small faults, although slickensides are common on limestone faces. The largest offset in an observed fracture is 50 cm and is found at an outcrop on Beaver River at its intersection with Highway 63. Most offsets seen in limestone beds are a few decimetres or less in magnitude.

The process of salt dissolution at depth is ongoing. Since the onset of dissolution, the Prairie Evaporite Formation dissolution edge has continuously migrated towards the basin centre (Bachu et al., 1993). East of the salt dissolution zone, the Keg River (Winnipegosis) and Waterways formations are in hydraulic continuity where the Prairie Evaporite Formation is thin or missing (Bachu et al., 1993, 1996).

Recent work by Stoakes et al. (2014) in the Athabasca Oil Sands mining region indicates a complex history of several phases of evaporite dissolution and associated karst and deformation. In their model, a first phase of pre–McMurray Formation subaerial exposure combined with westward tilting and uplift of Devonian strata during the Laramide Orogeny resulted in a major loss of halite in the Prairie Evaporite Formation. During the second phase of the model, coincident with deposition of the Lower McMurray Formation, fresh water was introduced into Devonian evaporite strata. In the third and final phase of their model, during the Quaternary, fresh water was once again introduced into the Prairie Evaporite Formation as glacial meltwater.

2.2 Karst

Within the study area, karst features arose from evaporite-dissolution-related collapse, dissolution of Devonian carbonates, or both. At the surface, karst features are primarily sinkholes that are often aligned in linear trends and caves that form along dissolutionally enlarged joints in limestone outcrops. Paleokarst features in Devonian strata, such as infilled paleosinkholes, have been observed and described in outcrop and core (e.g., Hein et al., 2000; Broughton, 2013; Fustic et al., 2014).

Paleokarst features in Devonian strata are often filled with a combination of limestone breccia, sandstone, oil sand, and green clay. Green clay is commonly found along Devonian exposure surfaces elsewhere in the province, but in the study area it is most often associated with karsted Waterways Formation limestone. Green clay has been encountered as a component of karst-related fill in dissolutionally enlarged joints and fractures, along the walls of paleosinkholes in the Waterways Formation, and at places along the sub-Cretaceous unconformity at the top of the Devonian subcrop.

Outcropping paleosinkholes that penetrate Devonian strata are rare. Two sinkholes occur in an outcrop along the McKay River, each of which is steep sided, penetrate the Waterways Formation, is filled with a mixture of oil sand and breccia, and is lined with green clay that coats the limestone walls (Fustic et al., 2014). Another paleokarst feature on the Muskeg River contains a similar fill (Fustic, pers. comm., 2013).

2.3 Sub-Cretaceous Unconformity

In northeastern Alberta, the contact between Devonian and Cretaceous strata is highly variable. Devonian strata at the contact range from brecciated limestones with a thick, red, sideritized 'crust' to seemingly unaltered strata.

Hume (1949) portrayed a topographic low on the sub-Cretaceous unconformity surface in the area of Bitumount, about 90 km north of Ft. McMurray. As data were limited at the time of his report, the topographic map contains little to no data beyond a limited area around Bitumount. Hume also noted that a marker horizon at the base of the Clearwater Formation was deflected in the Bitumount area, suggesting that Cretaceous strata were locally affected by post-Cretaceous subsidence of Devonian limestone and the compaction of Cretaceous shale.

Martin and Jamin (1963) reconstructed a topographic map of the sub-Cretaceous unconformity surface in townships 61 to 105 between the Fourth and Fifth meridians. Their map portrays the general southeastward tilt of the surface in areas not overlying the Prairie Evaporite Formation dissolution zone and a more complex pattern of topographic highs and lows within the area of the present study. They reported two major topographic lows near Bitumount and Fort McMurray, speculating on possible post–McMurray Formation subsidence in these two basins. Martin and Jamin also reported two major scarps on the sub-Cretaceous unconformity surface arising from karst in the carbonates of the Grosmont and Waterways formations as well as three minor scarps formed by resistant Beaverhill Lake Group carbonate within the present study area. The sub-Cretaceous unconformity surface was also incised by an active drainage system that was enhanced by a north-northeast-trending fault.

Cotterill and Hamilton (1995) produced a map of the sub-Cretaceous unconformity from townships 81 to 103, ranges 1 through 20, west of the Fourth Meridian (Figure 5). They recognized two major topographic highs on the surface related to carbonates of the underlying Grosmont Formation and Beaverhill Lake Group. Valley incision and collapse because of subsurface salt dissolution led to complex topography along and to the east of the Athabasca River.

Hein et al. (2001) reported that the topographic relief of the sub-Cretaceous surface ranges up to 130 m (Figure 6). A major topographic low coincides with the Prairie Evaporite Formation salt scarp (Hein et al., 2000, 2001) and roughly parallels the Athabasca River. Hein et al. (2001) suggested that karstification of exposed Devonian rocks led to sinkholes and other paleokarst on the sub-Cretaceous unconformity surface. According to their maps, topography on the sub-Cretaceous unconformity surface is more complex in the vicinity of the Prairie Evaporite Formation salt scarp.

2.4 Subcrop Mapping

Within the study area, the majority of subcropping Devonian strata comprise the Waterways Formation. Because of the regional westward dip and because of post-Cretaceous erosion, subcropping Devonian strata strike generally southeast and become older to the east. Northwards along the Athabasca River and eastwards along the Clearwater River, Devonian outcrops become older, with the Moberly Member of the Waterways Formation outcropping near Fort McMurray, and older members of the Waterways Formation or Elk Point Group formations outcropping at the Devonian outcrop limit (Norris, 1963).

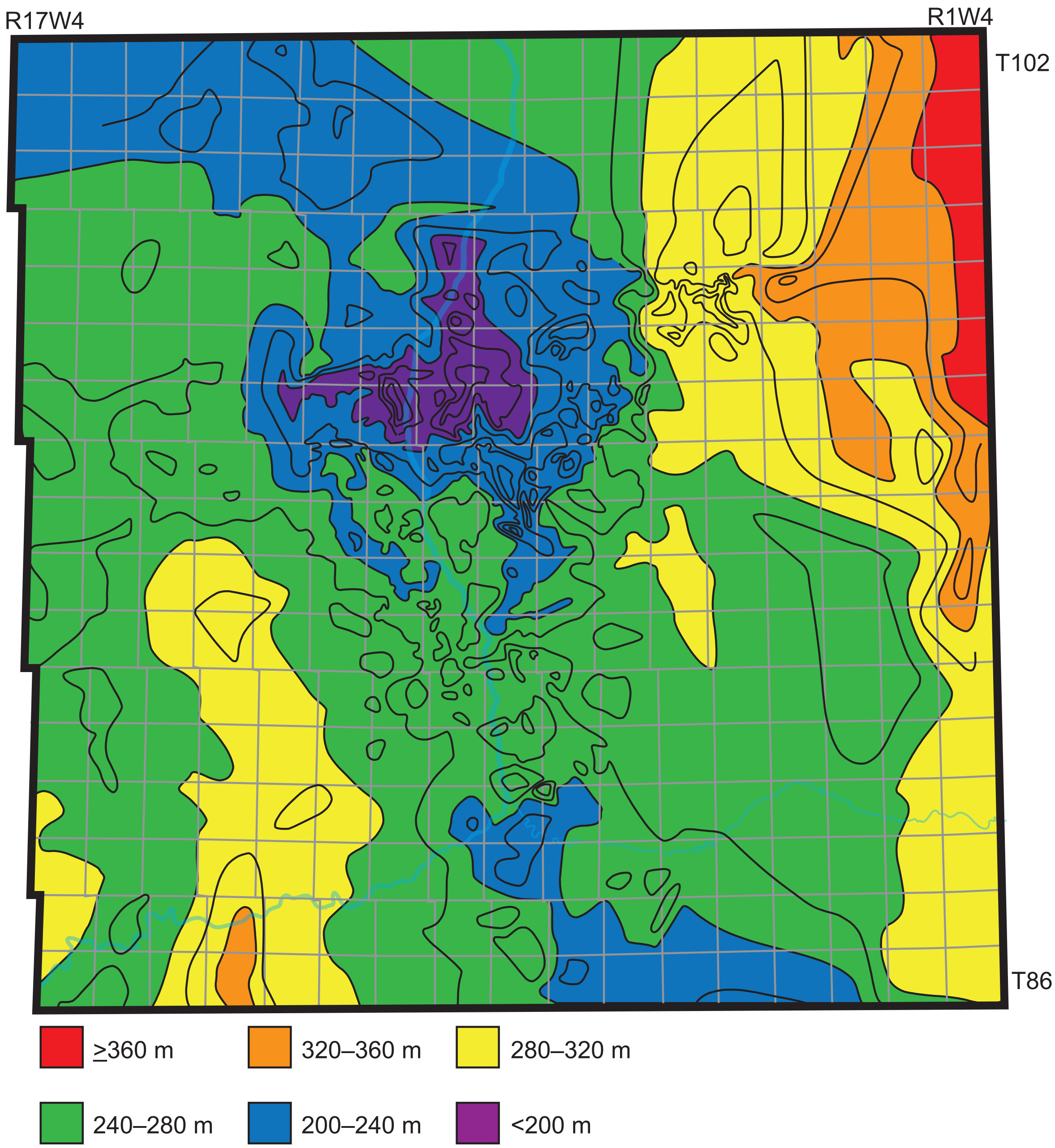

Figure 5. Residual map reconstructing the topography of the sub-Cretaceous unconformity from Cotterill and Hamilton (1995). Labelled contours from the original map are coloured; other contour lines from the original map are not interpreted here.

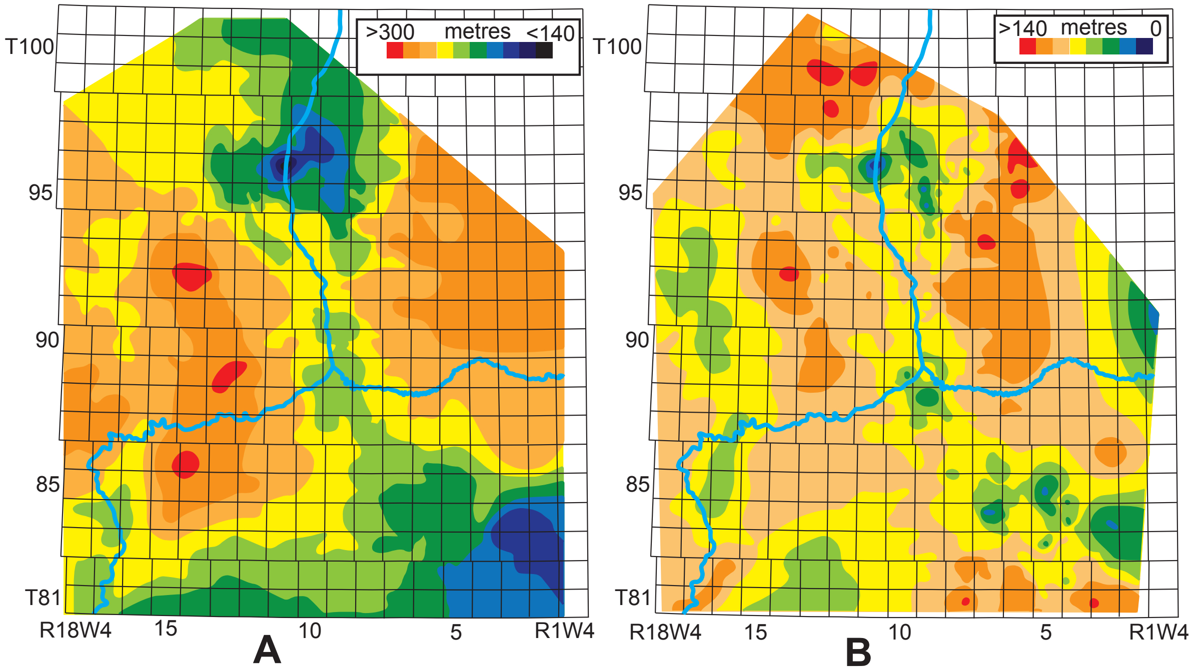

Figure 6. Reconstructions of the sub-Cretaceous unconformity surface from Hein et al. (2001); a) structural map; b) third-order residual map. Note that each map is at a different scale.

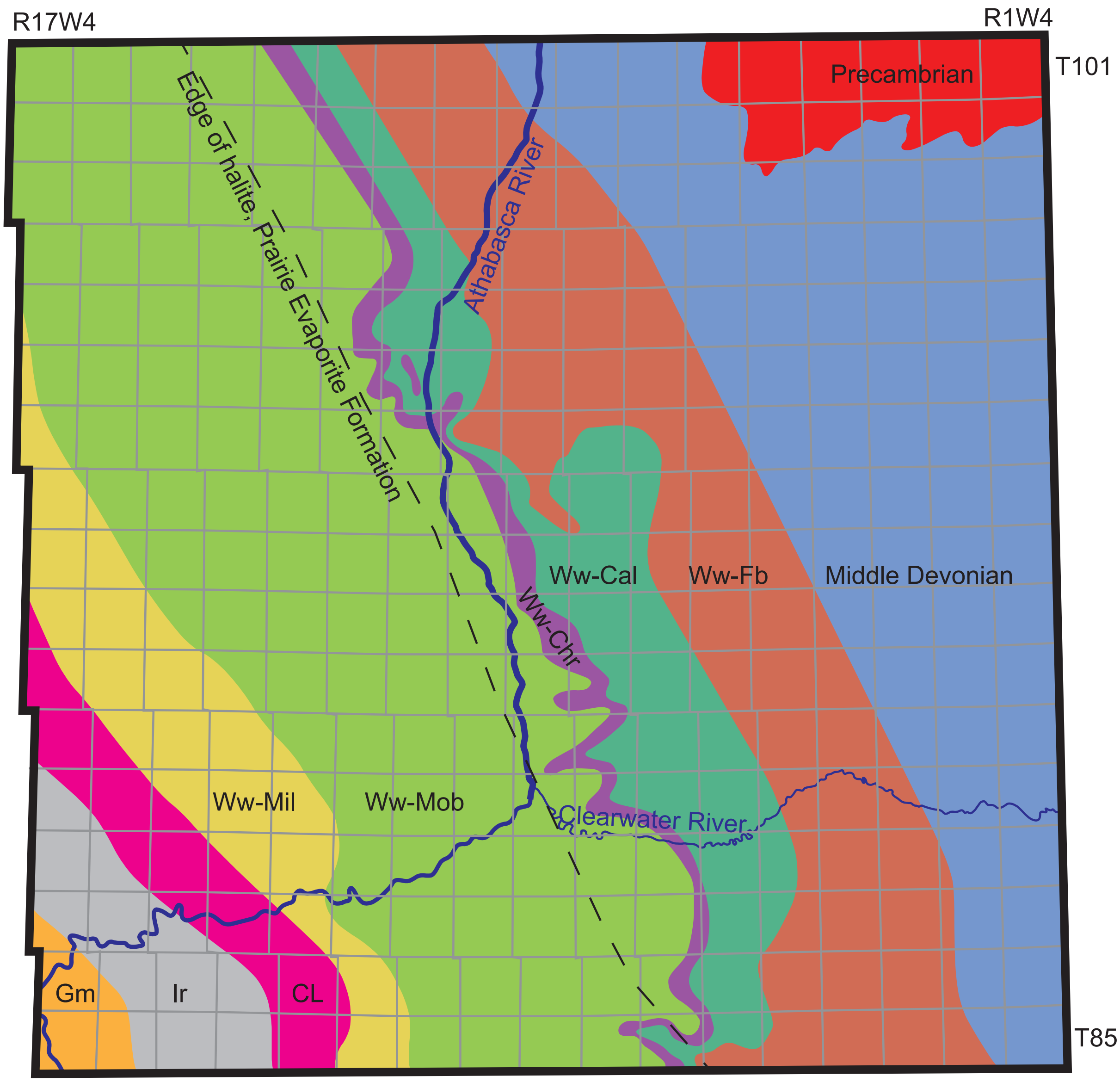

Figure 7. Devonian subcrop map from Cotterill and Hamilton (1995). Abbreviations, west to east: Gm: Grosmont Formation; Ir: Ireton Formation; CL: Cooking Lake Formation; Ww-Mil: Mildred Member, Waterways Formation; Ww-Mob: Moberly Member, Waterways Formation; Ww-Chr: Christina Member, Waterways Formation; Ww-Cal: Calumet Member, Waterways Formation; Ww-Fb: Firebag Member, Waterways Formation.

Cotterill and Hamilton (1995) produced a Devonian subcrop map from townships 81 through 104, ranges 1 to 19, west of the Fourth Meridian (Figure 7). Devonian strata generally subcrop along a south-southeast strike, but the influence of the erosional and paleokarst topography of the sub-Cretaceous unconformity on the subcropping Waterways Formation members is apparent between ranges 5 and 12 along strike.

3 Stratigraphy

In the study area, Devonian strata form an eastward-tapering wedge between the Precambrian basement and Cretaceous rock or Quaternary sediments (e.g., Figure 4). Prior to the deposition of the Lower Cretaceous McMurray Formation, Devonian strata were tilted westwards (Norris, 1963). Pre–McMurray Formation erosion truncated the dipping strata, resulting in the progressively eastward subcrop of older formations at the sub-Cretaceous unconformity (Norris, 1963, 1973).

The following overview of lithology and well-log characterization is based on observations from field and subsurface investigations carried out from 2010 through 2012 (c.f. Schneider and Grobe, 2013). Devonian stratigraphic units within the study area are described below, 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 subrounded 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 La Loche Formation directly overlies the unaltered basement, presumably where the regolith has been eroded before the deposition of sand.

The basal sandstone grades upwards into fine- to medium-grained, well-sorted sandstone with rounded to subrounded grains, and usually transitions into a quartz arenite or a quartz-rich subarkosic 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 Precambrian basement. The La Loche Formation thins over topographic highs in the basement and thickens within topographic lows (Norris, 1963). Within the study area, Norris reported the thickness of the La Loche Formation as varying from less than 1 m 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 generally high but variable gamma-ray count. The base is easily picked at the top of the basement, which has a variable gamma-ray count, low resistivity, and low density and neutron porosities (Figure 8). In most cases, the top is placed at the inflection of the gamma-ray curve as it trends from relatively high to low counts across the gradational

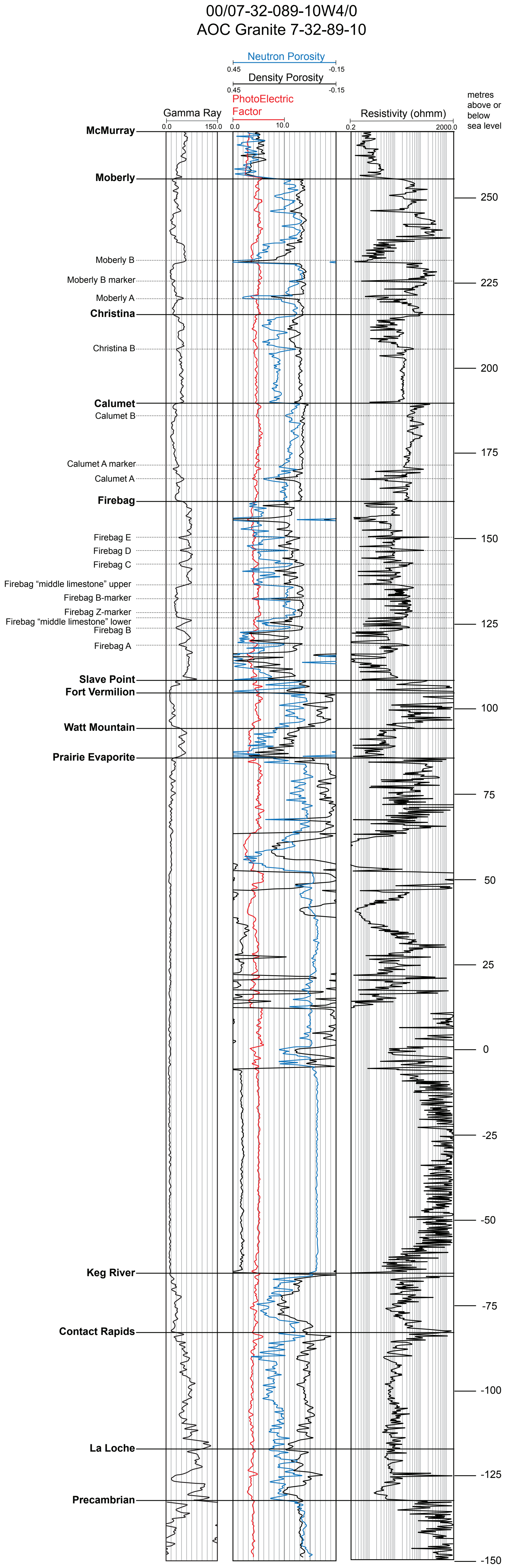

Figure 8. Devonian stratigraphy in well AOC Granite 07-32-089-10 (00/07-32-089-10W4/0).

contact between the sandstones of the La Loche Formation and the silty shale of the Contact Rapids Formation. (Figure 8; note that in this well, the top is placed at the abrupt transition to lower gamma-ray counts).

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, subhorizontal 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 and the degree of filling of basement topography by La Loche Formation sandstone. 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 (Schneider and Grobe, 2013). In all but one core in this study that penetrated below the Keg River Formation, the Contact Rapids Formation is present. In the present study, thickness of the Contact Rapids Formation varies between 13.4 and 71 m.

In well logs, the Contact Rapids Formation generally decreases in radioactivity upsection. The base of the formation is often arbitrarily placed where the decrease in gamma-ray counts is most steep (Figure 8). In contrast, the top pick is less arbitrary and is placed at the top of a distinctive and consistent radioactive spike, which occurs at an approximately 0.3 m thick green shale that underlies the Keg River Formation dolostone (Figure 8).

3.3 Keg River Formation (Methy Formation, Winnipegosis Formation)

Throughout the study area, the Keg River Formation is a beige to brown limestone or dolostone. The Keg River Formation varies greatly in thickness, ranging between 17.5 and 102 m in wells of the present study. Thicker Keg River sections likely indicate the presence of stromatoporoid-coral 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 upwards into tidal-flat facies containing oncoids, subaerial exposure surfaces, caliche deposits, and domal stromatolites. This tidal-flat facies occurs in all examined cores of the upper portion of the Keg River Formation and overlies both reef and inter-reef facies.

Porosity types in the Keg River dolostone range from large moulds of reef builders, to smaller dissolutional vugs of unknown origin 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 outcrops along the Clearwater River.

The Keg River Formation is mostly nonargillaceous limestone and dolostone. In most wells, the lowermost few metres of the Keg River Formation are more radioactive than the rest of the formation and often have not been completely dolomitized. In the upper tidal-flat facies, minor anhydrite beds can be recognized on the photoelectric effect (PE) and density-neutron logs of individual wells, but cannot be correlated.

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 (Figure 8). The top is also sharp, picked at the first several-metre-thick bed of anhydrite or halite above the dolostone, or where the dolostone abuts a continuous succession of evaporite minerals (Figure 8). Where the Keg River Formation underlies the insoluble residue of the dissolved Prairie Evaporite Formation, the Keg River Formation is picked where the dolostone transitions abruptly into argillaceous breccia with a highly variable gamma-ray log.

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 (Schneider and Grobe, 2013). This northward increase in anhydrite arises from the proximity of the study area to the lateral 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 00/11-26-091-13W4/0 (11-26 well). In general, the Prairie Evaporite Formation thins gradually eastwards until it disappears into an interval of brecciated, insoluble residue.

Evaporite dissolution frequently resulted in brecciation of nonhalite interbeds and, locally, the brecciation and mixing of overlying strata. Brecciation is most common east of the Athabasca River where halite in the Prairie Evaporite Formation is either greatly reduced or is missing. However, in places where dissolution did not result in brecciation, thin, compacted beds of shale and other insoluble residue 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. It is unknown whether the thickened Prairie Evaporite section in the 11-26 well is the result of halite migration.

Where intact, the contacts of Prairie Evaporite Formation with the underlying Keg River Formation and overlying Watt Mountain Formation 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 (Figure 8). 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, as well as a sharp decrease in resistivity (Figure 8 and Figure 9).

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

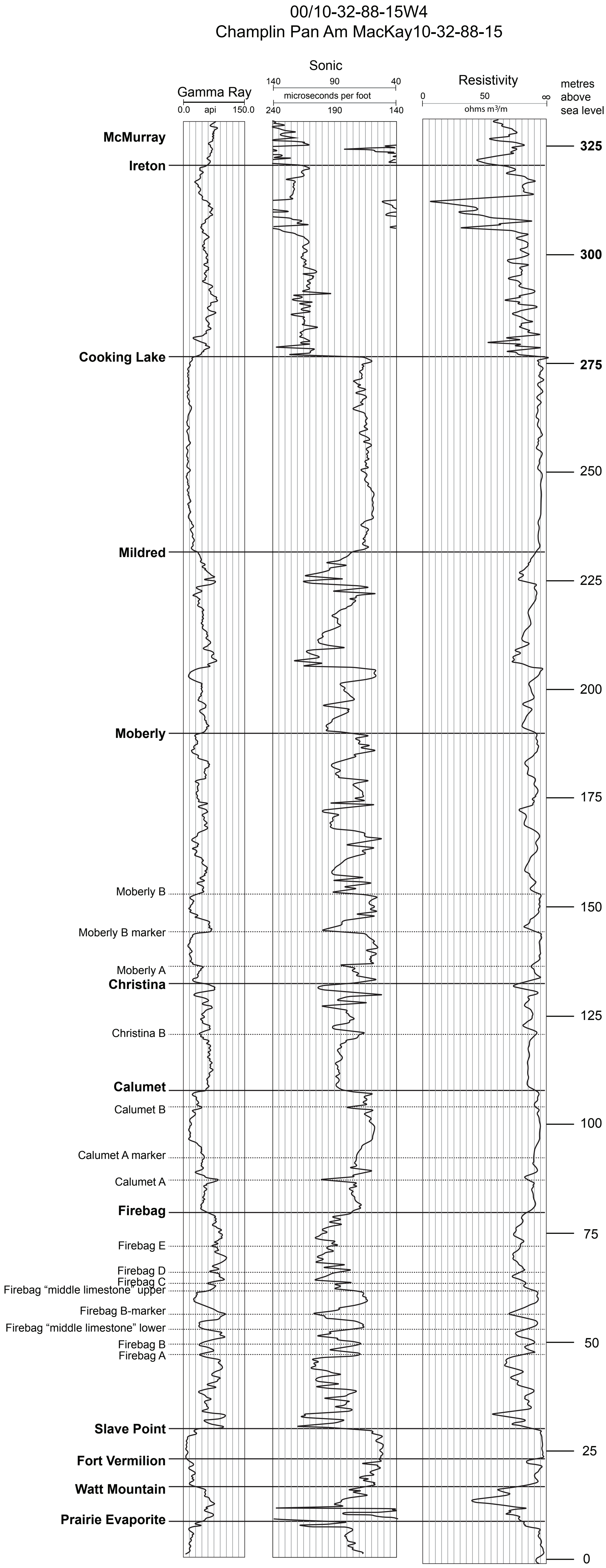

Figure 9. Devonian stratigraphy in well Champlin Pan Am MacKay 10-32-088-15 (00/10-32-088-15W4/0).

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, interpreted by Meijer Drees (1988) in northern Alberta and representing a widespread regression at the boundary between transgressive-regressive sequences If and IIa of Johnson et al. (1985), 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 (Figure 8 and Figure 9), but where the Prairie Evaporite 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 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 deflection in the gamma-ray and PE curves at the base of the Fort Vermilion Formation (Figure 8 and Figure 9) 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 eastwards. In most cores, the Fort Vermilion Formation is dominantly laminated brown shale and anhydrite with lesser intertidal dolostones of mudstone to cryptalgal bindstone textures.

In well logs, the transition from the Watt Mountain Formation into 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 (Figure 8 and Figure 9). The base can be sharp or gradational with the Watt Mountain Formation, as discussed above. The Fort Vermilion Formation top is placed at the top of a thin interval of slightly increased gamma-ray values, coincident with a metre-thick shale to argillaceous carbonate in core (Figure 9). The transition into the limestone of the overlying Slave Point Formation, particularly seen in the shift from an argillaceous anhydrite PE to one of nonargillaceous limestone and in the loss of anhydrite in the density-neutron log, also supports the top pick (Figure 8).

Where Prairie Evaporite Formation dissolution resulted in brecciation of the Fort Vermilion Formation, the top could not 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 common in the Slave Point Formation and in the basal few metres of the overlying Firebag Member of the Waterways Formation. Other fossils in the Slave Point Formation within the study area include other brachiopods, crinoid columnals, and gastropods, many of which are broken and abraded.

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 (Figure 8 and Figure 9).

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 most logs (Figure 8 and Figure 9).

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

3.8 Waterways Formation

In the study area, the Waterways Formation is a 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, so 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 has distinct lithological characteristics and well-log signatures.

3.8.1 Firebag Member

The Firebag Member is dominantly green-grey shale with minor argillaceous limestone. Most of the shale is unfossiliferous, but some of the argillaceous limestone beds contain abundant brachiopods and occasional crinoid columnals. Thickness of the Firebag Member 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 (Figure 8 and Figure 9), 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 one or more thin, very calcareous shale beds, which can be recognized as a sharp increase (e.g., ‘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 (Figure 8 and Figure 9).

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 increased gamma-ray counts (Figure 8 and Figure 9) and are regionally correlatable. 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 McMurray Formation, 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 limestone bed of the Calumet Member (Figure 8 and Figure 9). Like the top of the Firebag Member, the top of the Calumet Member is easily picked on gamma-ray logs because of an abrupt lithological change to shale of the Christina Member (Figure 8 and Figure 9). In core, the Calumet Member contains at its top a hardground with a thin, overlying, and boring-infilling grainstone of fossil fragments and millimetre-scale phosphate nodules.

3.8.3 Christina Member

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 upwards into interbedded argillaceous lime mudstone and shale. The unit is largely unfossiliferous and not bioturbated. Hardgrounds are common in this member, particularly in the centimetre-scale lime mudstone beds of the upper portion of the unit. In the shalier lower portion of the member, hardgrounds are typically associated with 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, phosphatized limestone 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 parts of the study area, creating good marker beds for portions of the study area (Figure 8 and Figure 9).

The base of the Christina Member is placed at the top of the clean limestone of the Calumet Member (Figure 8 and Figure 9), which in core is marked by a hardground. The Christina Member top is easily picked in well logs where the shale rapidly or abruptly 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 8 and Figure 9). In core, the top of the Christina Member is placed just below a lowermost hardground of a hardground couplet that occurs in the basal 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. Within the present study, the Moberly Member is present in its entirety within only the westernmost two cores of the southern cross-section. 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 nonargillaceous limestone. The limestone ranges from nodular, *Thalassinoides*-bioturbated wackestones to brachiopod-rich and stromatoporoid-coral rudstones to stromatoporoid bindstone. Tempestite coquinas of shingled brachiopod shells are common in the lower beds of the member.

A stromatoporoid biostrome more than 2 m thick can be traced throughout the study area and provides a good stratigraphic marker bed for correlation from core to core and between outcrops. Branching, bulbous, tabular, and massive stromatoporoids are common, particularly in the northern portions of the study area, forming rudstones to bindstones with a packstone to grainstone matrix. Bitumen commonly fills the pores in the fossils and the matrix.

Several shale and argillaceous limestone beds in the Moberly Member are good markers throughout the region (Figure 8 and Figure 9). In the area of densest well coverage and where the Moberly Member subcrops beneath the McMurray Formation oil sand, the upper Moberly Member has been eroded; thus, only marker beds in the lower Moberly Member were identified for the study area.

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 (Figure 8 and Figure 9). In core, this change is easily recognized in two ways: the Christina Member is green-grey, nonfossiliferous, centimetre-scale interbedded calcareous shale and argillaceous lime mudstone, whereas the Moberly Member is beige, bioturbated, fossiliferous argillaceous limestone. Also, 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 and can contain evidence of other intervening hardgrounds in some cores.

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 (Figure 9). This pick is different from 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, following Crickmay's original base of the Mildred Member.

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 rudstones dominated by brachiopods. Most limestone beds are nodular- to wavy-bedded. The limestone of the upper couplet grades upwards into the cleaner carbonate of the overlying Cooking Lake Formation.

The base of the Mildred Member is placed at the base of the upper two shale-limestone couplets, which is the boundary between the Moberly and Mildred members in the Bear Biltmore no. 1 (00/07-11-087-17W4/0) defined by Crickmay (1957) (Figure 9). The top argillaceous limestone has a rapid transition into the nonargillaceous Cooking Lake Formation and is picked at the inflection point of decreasing gamma-ray counts, which usually is near the onset of 'clean' carbonate (Figure 9).

4 Methods

The study area encompasses townships 87 to 99, ranges 1to 13, west of the Fourth Meridian (Figure 1). The majority of data were collected from well logs, supplemented and verified by core and outcrop data.

4.1 Well-Log Picks

All wells found to have been drilled into Devonian strata within the study area and that were available at the time of investigation were used in the study. Depending on available logs, gamma-ray, photoelectric, density-neutron, spontaneous potential, and resistivity well logs were used to pick stratigraphic tops.

Wells were picked using the software IHS AccuMap and Petra using IHS raster and digital well logs. Figure 8 and Figure 9 depict the tops picked, although the upper Moberly Member and later strata have been eroded from most of the study area.

The boundary between Devonian and Cretaceous strata is easily recognizable in a sharp decrease in both neutron and density porosity and a decrease in photoelectric effect. In some wells, the base of the Cretaceous and the top of the Devonian cannot be differentiated in gamma-ray or resistivity curves, such as a pure sandstone overlying a clean carbonate or a basal McMurray Formation shale overlying the calcareous shale of the Christina or Firebag Member; thus, the density-neutron and, when available, PE curves were most helpful.

Karstification or brecciation in Devonian strata often led to an inconsistent gamma-ray signature for Devonian strata, but the density-neutron and PE curves still contained the increase typical of a switch from McMurray Formation sandstone and shale to Devonian carbonate and calcareous shale.

The vast majority of wells penetrated only a few metres into Devonian strata. Thus, in order to maintain a high degree of certainty of Devonian picks, we undertook the following quality control measures:

- Marker beds: Correlations between logs with thicker Devonian intervals allowed the recognition of township- to study-area-wide marker beds within each Waterways member. Most marker beds were traceable throughout the entire study area, although a few markers were only useful over a smaller subregion. These marker beds were often the sharp boundary between a shale (high gamma ray) and a carbonate (low gamma ray) member or unit or a bed of different lithology within a dominant lithological trend. Marker beds often have unique well-log signatures. Most were easily recognized in 5 m or more of Devonian strata within a well, and sometimes within a shorter interval. Marker beds were confirmed in core for lithological continuity.
- Simultaneous mapping: Concurrent with picking the well logs, we recorded by hand the topmost member or marker within each well on a map of the wells in the area. This method was applied as a logical check for picks (e.g., the Calumet Member would subcrop next to a Firebag Member subcrop, which is more logical than neighbouring Moberly Member and Firebag Member picks).
- Recheck and repicking: In townships with high degrees of lateral and vertical variability (e.g., much of the area to the east of the Athabasca River), each picked well was double-checked at a later date for stratigraphic precision. In some cases, an area was repicked and compared against earlier picks for quality control.

In some instances, the well-log signature of Devonian strata was stratigraphically unidentifiable, either because too short of a Devonian interval was penetrated by the well or recorded by a well log or because of karst effects, brecciation, or collapse of Devonian strata. In these wells, Devonian strata were identified to the most precise stratum possible: Beaverhill Lake Group, Waterways Formation, or specific Waterways Formation member. Rarely were there any instances where the Devonian stratum could not be identified to group level or lower.

4.2 Surface Modelling

Surface models were constructed for the sub-Cretaceous unconformity surface for townships 87 through 99, ranges 1 through 13, west of the Fourth Meridian. A slightly larger Devonian subcrop model was created for townships 86 through 100, ranges 1 through 14, west of the Fourth Meridian.

4.2.1 Sub-Cretaceous Unconformity

The picks used for generating the sub-Cretaceous unconformity surface include those made by C.L. Schneider, P. Greene, and other AER staff (Alberta Energy and Utilities Board, 2003; Hein et al., 2006, 2007) using geophysical logs. Additional infilling and refined picks were added by S. Mei during geostatistical analysis and geological modelling. In generating the pre-Cretaceous unconformity surface, the first step was to perform quality control of the picks; primarily, this means identifying outliers. In this study, the method described in Mei (2009) for quality control was used, which includes the following steps:

1) A local trend surface was generated around each data point using the surrounding data points; then, the deviation of the data point from the local trend was calculated.
2) The histogram of deviations was examined and the data points with deviations larger than an initially determined threshold (e.g., two or three standard deviations away from the mean deviation) were identified as outliers.
3) The outliers were visually examined againfist the structure map and grouped into two categories based on their distribution patterns. One category contained outliers that are clustered in a linear or circular pattern, potentially indicating local structural features. The other category contained outliers that are randomly distributed across the study area, likely representing erroneous picks.
4) The outliers were then examined against well logs to confirm the existence of local structures or to correct other errors. Data points identified with kelly bushing errors were corrected or refined with available digital elevation model (DEM) data (e.g., light detection and ranging or Shuttle Radar Topography Mission DEM), or using offset well KBs in a flat area. The data points associated with picking errors were reassessed. Wells with errors that were undetermined or could not be corrected (e.g., lack of good quality logs for repicking) were removed from the analysis.
5) The above-mentioned steps were repeated until a minimized and acceptable degree of uncertainty was reached.

The data points remaining after quality control (18 109 Devonian picks in total) were then used to generate the sub-Cretaceous unconformity (Figure 10) through kriging, using the Geostatistical Analyst extension of ArcGIS.

4.2.2 Subcrop Extents of Devonian Stratigraphic Units

Subcrop extents of the Devonian stratigraphic units were constructed by finding the intersections of their uneroded stratigraphic top surfaces with the sub-Cretaceous unconformity surface. However, the resultant intersections of the Devonian formation and member subcrop and the sub-Cretaceous unconformity surface generated in this study did not always coincide with the well locations. This can be attributed to the uncertainty associated with the data and the smoothing effect applied in the interpolation process (described below).

Interpolation is the process of using original data points (observations) to generate calculated data points at unsampled locations. When these data points are presented as a raster surface, the interpolated value is assigned to the pixel at the grid node. Kriging was used to construct an interpolated surface of the Devonian subcrop. Like most of the interpolation algorithms, kriging is a weighted average interpolation. Thus, the interpolated surface is smoother than the actual subcrop surface. This results in the simplification of the modelled subcrop edges. In areas where formation-top picks are not available, such as along the subcrop edge of a stratigraphic unit or in areas that contain no original data, kriging estimates approach the mean of the data when distances from data points are larger than the range of the variogram model. This effect increases inaccuracy along the subcrop edges.

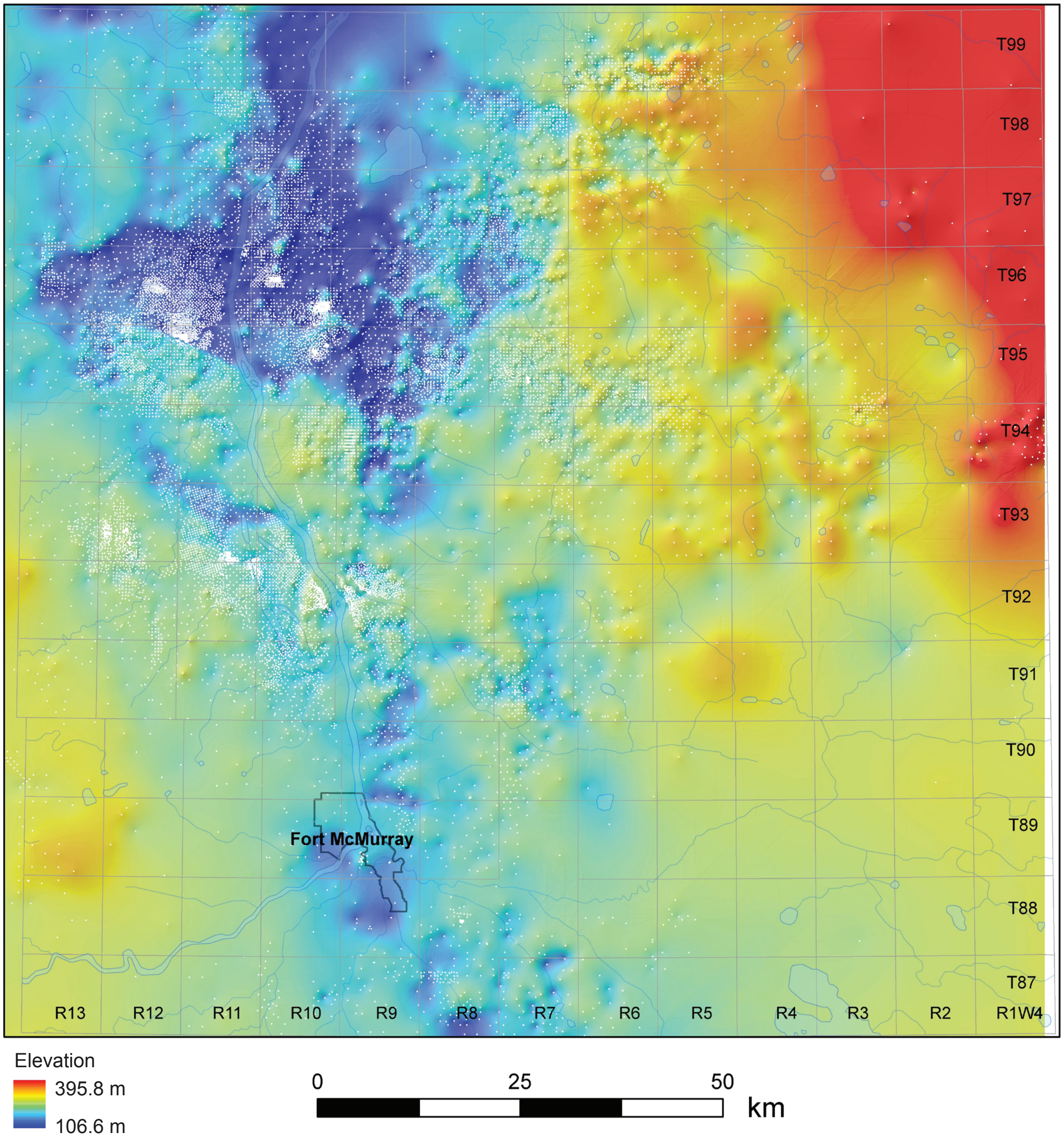

Figure 10. Topography of the sub-Cretaceous unconformity in the study area. White dots are the location of wells used in the study.

The intersection of a Devonian subcropping formation-top surface and the sub-Cretaceous unconformity surface was first generated; this intersection line was only used for approximating a zone in which the subcrop edge may be located. Next, actual data points (well locations, formation-top depths) of the subcropping Devonian formation in this zone were identified as those with a zero isopach of the overlying (younger) formation. The data points that contain the same, but uneroded, formation top are also identified in this zone and are those with the minimal isopach (compared to neighbouring data points and well locations) of the overlying formation in the zone. The location of the subcrop edge is then estimated at a point between the data point of the subcropping formation and the nearest data point of the same, but uneroded, formation top. Finally, the geological map was completed by connecting these estimated subcrop edge points in a smooth and continuous curve guided by both the paleotopographic contour and the trend of the intersection with the pre-Cretaceous unconformity surface.

5 Results

The level of resolution in the Devonian subcrop (Figure 11) and sub-Cretaceous unconformity surface (Figure 10) models was highly influenced by well density. Areas with a dense well distribution resulted in a high degree of topographic variability and complexity in stratigraphic boundaries. Conversely, areas with sparse wells could only be modelled at coarse resolution, with gently undulatory surfaces and straight-line stratigraphic boundaries. The discussion below will focus on areas of high well density and thus corresponding areas of high resolution within the surface models.

5.1 Subcrop Extents of Devonian Stratigraphic Units

Like previous studies, our model of subcropping Devonian units shows that Devonian strata generally strike southeast at the sub-Cretaceous unconformity and become progressively older to the east (Figure 11). When compared with previous maps of subcropping Devonian strata (e.g., Figure 7; Cotterill and Hamilton, 1995), the present model contains a significant increase in resolution of stratigraphic boundary complexity within areas of dense well distribution (compare with Figure 1).

5.2 Sub-Cretaceous Unconformity Surface

Subtraction of the regional dip from the Devonian subcrop resulted in a model of topography on the sub-Cretaceous unconformity relative to a horizontal surface (Figure 10). The model contains topographically high areas to the east and southwest within the study area, each containing nearly flat-lying to gently rolling topography resulting from sparse well control. These topographic highs constrain a trough of connected small basins through the central portion of the model that follow a south-southeast trend. At the northern extent of this trend, the trough expands and deepens into the Bitumount Basin. The north-south trough on the sub-Cretaceous unconformity surface, including the Bitumount Basin, roughly corresponds to the zones of halite and anhydrite dissolution of Schneider and Grobe (2013; Figure 12).

South of the Bitumount Basin, the deepest portions of the trough do not correspond to the modern Athabasca River. Rather, the deepest basins are to the east of the river, except for the Bitumount Basin and several topographic lows on the sub-Cretaceous unconformity surface beneath Fort McMurray.

5.3 Integration and Interpretation

The sub-Cretaceous unconformity surface is a product of hypogenic karst in the Prairie Evaporite Formation and post-Devonian through pre-Cretaceous surficial weathering. Devonian strata within the zones of evaporite dissolution (Schneider and Grobe, 2013; Figure 12) experienced hypogenic karst processes in which dissolution of evaporite minerals at depth affected the relatively stable overlying

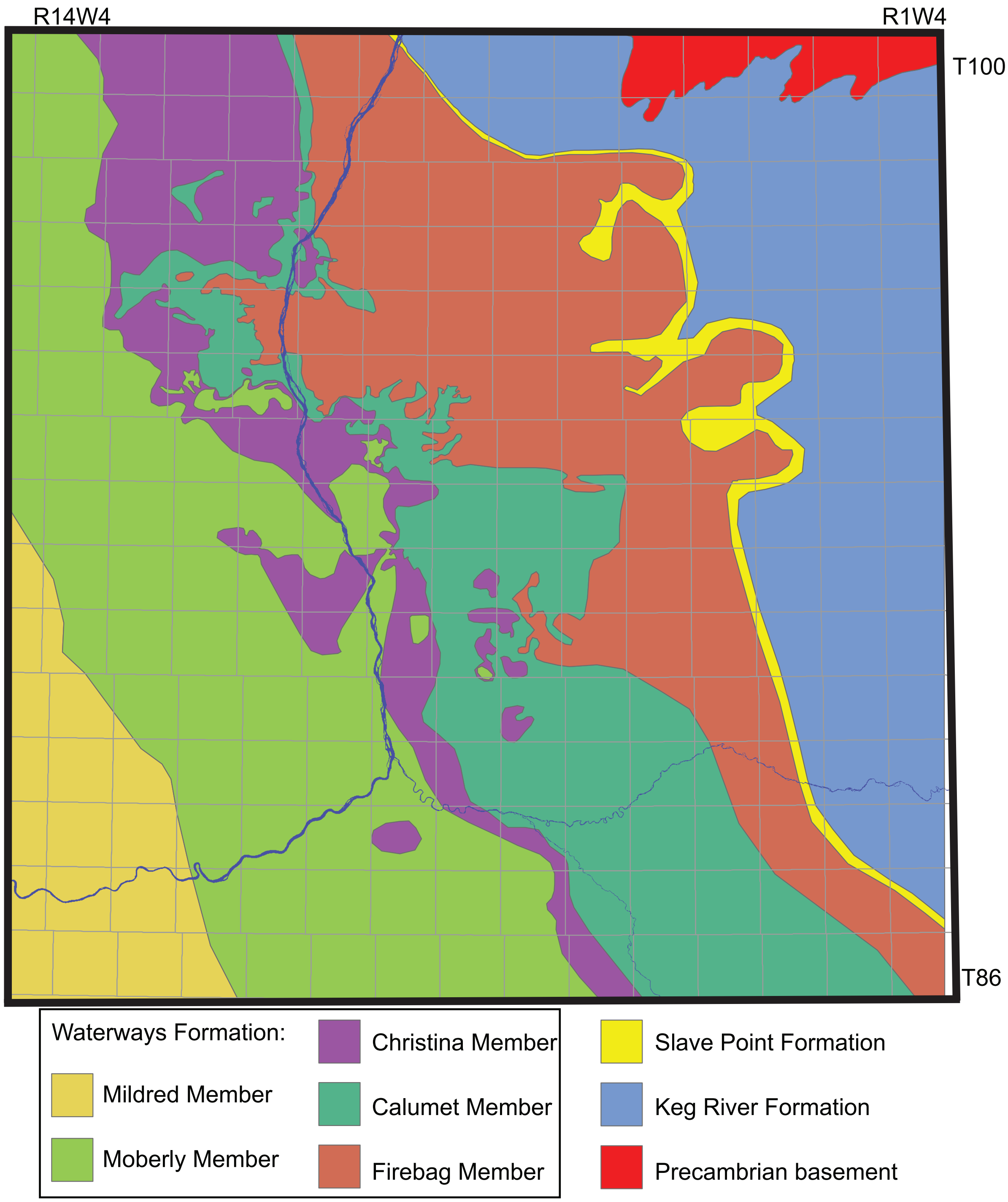

Figure 11. Devonian subcrop model for townships 86–100, ranges 4–14, west of the Fourth Meridian.

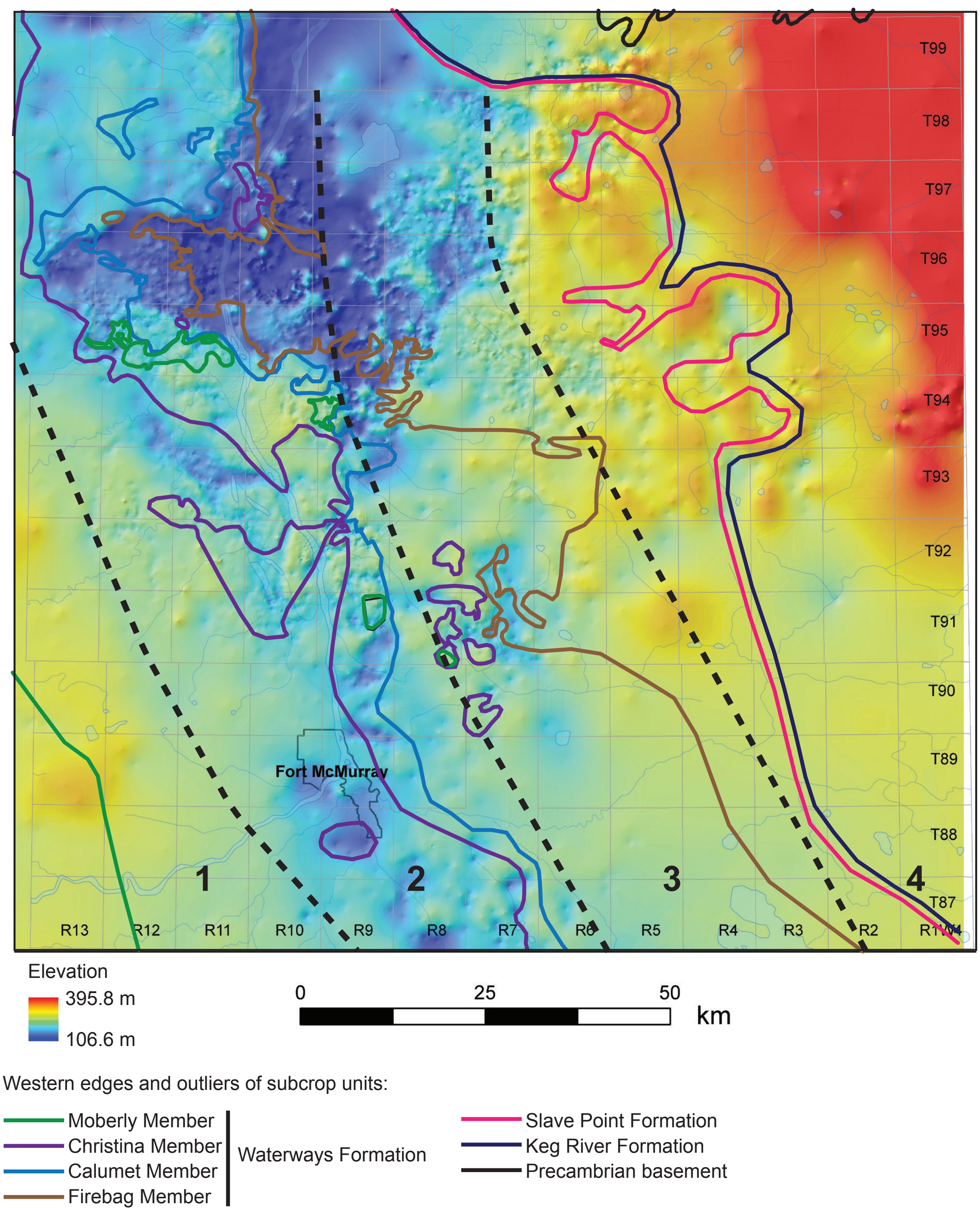

Figure 12. An overlay of the Devonian subcrop on the sub-Cretaceous unconformity surface. The Mildred Member is not depicted in the map lines but exists in the southwestern corner, southwest of the Moberly Member western limit. Numbers refer to Prairie Evaporite Formation dissolution zones of Figure 3 and Schneider and Grobe (2013). Zone 1 shows little to no halite dissolution; zone 2 shows halite dissolution; zone 3 shows anhydrite hydration and gypsum dissolution (halite totally dissolved, except for localized remnants); and zone 4 shows total halite and gypsum dissolution, in which only a residuum of collapse breccia, siliciclastics, dolostone, and limestone is present in the Prairie Evaporite Formation.

strata. Evaporite dissolution within the >200 m thick Prairie Evaporite Formation resulted in minor subsidence (in western areas affected by minimal halite loss) to complete collapse of post–Prairie Evaporite Formation Devonian strata (in areas with little or no halite and anhydrite strata remaining in the Prairie Evaporite Formation). A comparison between the pre-Cretaceous unconformity and Devonian subcrop models is generally too coarse in resolution to interpret the proportions of karst processes and surface erosion in shaping topographic features, but a few general observations are possible.

Previous work suggested that topography of the sub-Cretaceous unconformity was influenced by the lithology of Devonian strata (i.e., more resistant limestone, more easily eroded shale) and that resistant strata formed ‘ridges’ in the topography of the sub-Cretaceous surface (e.g., Martin and Jamin, 1963). In our model, topography does not necessarily follow the recessiveness or resistance of lithological units. Rather, the pattern of subcropping Devonian strata at the sub-Cretaceous unconformity surface is complicated by dissolution of evaporite strata at depth and the subsidence or collapse of post–Prairie Evaporite Formation Devonian strata.

A primary example of the discrepancy between lithology and surficial topography is the south-southeast-trending trough made up of the Bitumount Basin in the north and smaller basins in the central and southern portions of the study area. The area covered by the trough south of the Bitumount Basin cuts equally through resistant- (Moberly and Calumet members) and recessive-weathering (Christina and Firebag members) lithologies, rather than cutting more deeply through the ‘softer’ rocks of more argillaceous units. This lack of expected, predictable erosional patterns emphasizes the strong influence of hypogenic karst in addition to subaerial weathering processes.

The Bitumount Basin itself is a long-recognized feature in the sub-Cretaceous unconformity surface. In the present study, both paleo-subaerial erosion and hypogenic karst are interpreted as forming the basin. Around the basin edges, a comparison of topography with stratigraphic boundaries suggests that erosional downcutting through Devonian strata had significant influence on basin formation, especially along the south and west borders of the basin (Figure 12). Evidence of karst in many cores within the basin also indicates the high impact of evaporite dissolution at depth on Devonian in the basin (Hein et al., 2000; Broughton, 2013).

Most high-resolution features that might be of interest to mining operations are beyond the resolution of this study, such as paleosinkholes, small faults, and dissolutionally enlarged joints. However, paleosinkholes are evident in outcrops (e.g., Fustic et al., 2014), as are dissolutionally enlarged joints up to several metres in diameter (observed by the authors).

One topographic low was investigated for evidence of karst-related collapse versus erosional downcutting. In a small depression on the sub-Cretaceous unconformity surface, a cross-section portrays Firebag Member strata as conformable with the topography of the depression (Figure 13). Subsidence resulting from evaporite dissolution at depth played a greater role in originating this topographic low than the process of subaerial erosional downcutting before the deposition of the McMurray Formation. Similar topographic lows on the sub-Cretaceous unconformity surface that fall within the zones of halite and anhydrite dissolution would likely have similar patterns in cross-sections, illustrating localized subsidence or collapse of Waterways Formation strata.

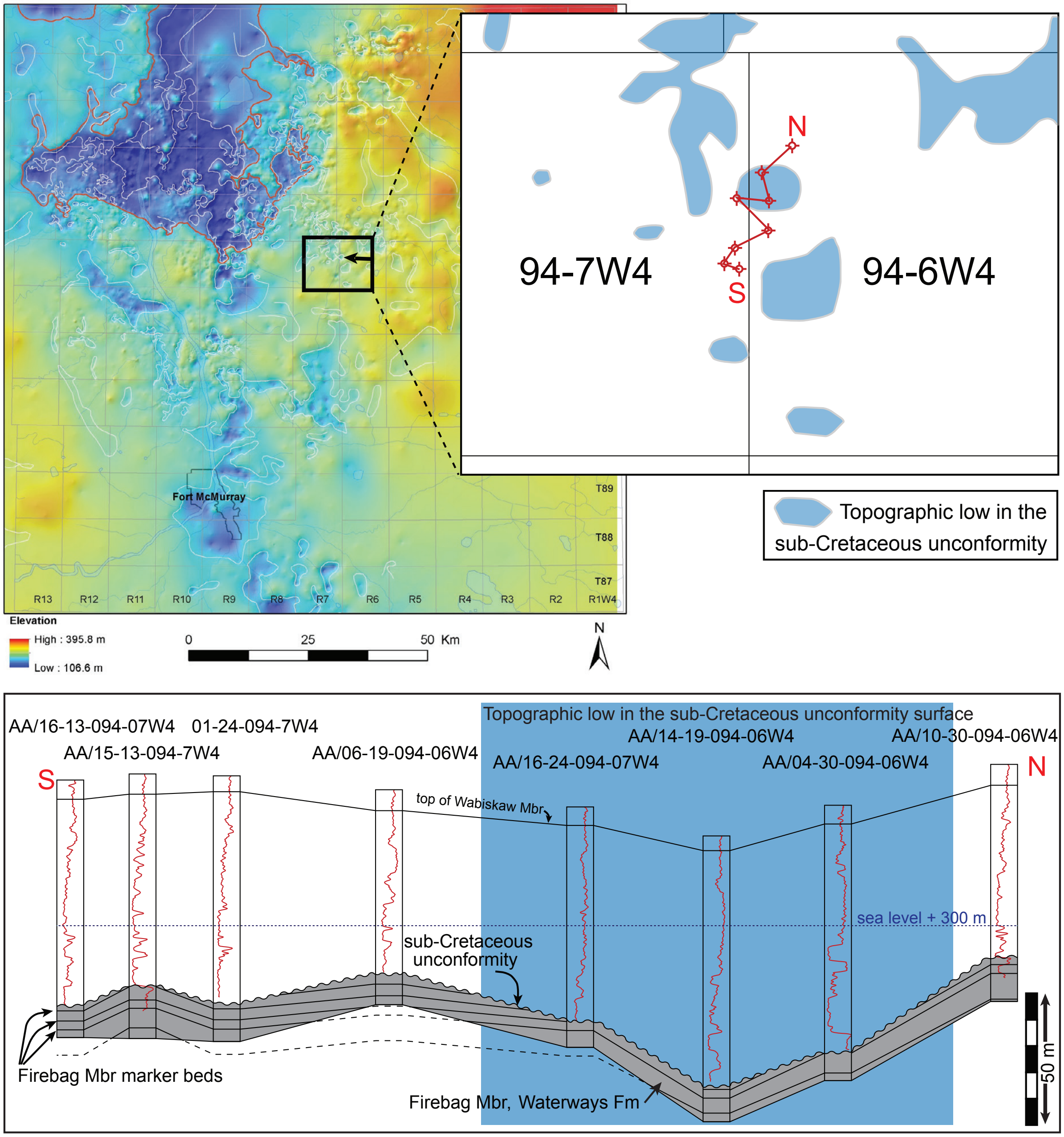

Figure 13. A cross-section through a depression on the surface of the sub-Cretaceous unconformity. Logs shown are gamma ray; however, stratigraphic interpretation and correlation is based on a suite of logs, hence strata are mapped beyond the lowest elevation of the gamma-ray log. Subsided Firebag Member strata and the top of the Wabiskaw Member within the depression, highlighted by the blue box, may indicate a paleosinkhole. Greater subsidence occurred prior to the deposition of the top of the Cretaceous Wabiskaw Member, seen in the thickened section between the sub-Cretaceous unconformity surface and the top of the Wabiskaw Member.

6 Conclusions

Our study resulted in a Devonian subcrop model for townships 86 through 100, ranges 1 through 14, west of the Fourth Meridian, and a sub-Cretaceous unconformity surface model for townships 87 through 99, ranges 1 through 13, west of the Fourth Meridian. Model resolution varies throughout the study area, dependent on the density of available well data.

Boundaries of Devonian strata in our subcrop model have a higher degree of complexity than previous models. Likewise, the complexity of topography on the sub-Cretaceous unconformity (relative to an originally horizontal surface) is high, at least within areas of dense well control.

Our models capture a north-northwest-trending trough that cuts through the sub-Cretaceous unconformity surface that ends in the Bitumont Basin in the north and northwestern portion of the study area. Topography shows features arising from both erosional downcutting prior to Cretaceous deposition and hypogenic karst processes from dissolution of Prairie Evaporite Formation evaporites at depth.

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