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Alberta Energy Regulator

The Elk Point Group of Alberta: Insights into Paleogeography, Evaporite Karstification, and Salt Cavern Potential based on Net-Evaporite Mapping

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Alberta Geological Survey

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Abstract

Lithostratigraphic correlation and mapping of formations and units within the Elk Point Group aims to provide updated information on their extent and distribution within the province of Alberta. Together with detailed net-evaporite mapping of three evaporite minerals, halite, anhydrite, and gypsum, within evaporitic successions, these data provide new representations of the paleogeography of these units across the province. Paleogeographic maps of the Keg River and Prairie Evaporite and Muskeg formations provide new details on the location of the La Crete sub-basin in northern Alberta, and the distribution and nature of Keg River Formation buildups and the overlying evaporite strata within this depositional realm. The net-evaporite mapping provides a robust picture of the distribution of evaporites within the province, and allows for a detailed characterization of heterogeneities within halite-bearing successions, such as interbeds comprising anhydrite, carbonate, and shale. Understanding the degree of nonhalite interbedding has implications for the placement of future caverns within halite successions of the Elk Point Group. Additionally, net-evaporite mapping reveals a number of local-scale zones of evaporite karstification that differ in age from the regional, basin-margin, Prairie Evaporite halite dissolution scarp. Evidence is provided for a top-down advancement of evaporite karstification within all but one recognized zone of karstification.

1 Introduction

This report details the lithostratigraphic correlation and mapping of Elk Point Group strata across the province of Alberta. Lithostratigraphic mapping supports the production of a high-resolution, three-dimensional (3D) model of the Phanerozoic sedimentary strata of Alberta, part of the Geological Framework program at the Alberta Geological Survey (Alberta Geological Survey, 2019). The Elk Point Group was included in previous Paleozoic mapping undertaken by the author in the Lower Athabasca Regional Plan (LARP) area of northeastern Alberta, which forms part of a submodel for that economically important part of the province, known for the extraction of bitumen from oil sands deposits (Figure 1; Hauck et al., 2017, 2018b). This current study is a province-wide extension of the LARP area mapping, and represents the most comprehensive set of regional lithostratigraphic data for the Elk Point Group to date. It includes 24 701 stratigraphic picks made on geophysical logs from 4644 wells (Figure 1; see Digital Data 2020-0008 accompanying this report). The results of this work include regional extents of formations within the Elk Point Group supported by a series of cross-sections, and new isopach maps of the Keg River and Prairie Evaporite formations (and equivalent/correlative strata), illustrating the paleogeography at the time. These new paleogeographic maps represent a more complete picture of this important stratigraphic interval in the Alberta Basin.

Evaporite deposits in the Elk Point Group were assessed in detail to better define their extent and degree of lithological heterogeneity. The presence of three evaporite minerals, halite, anhydrite, and gypsum, was manually determined on wireline raster logs from more than 740 wells within the evaporite-bearing Lotsberg, Cold Lake, and Prairie Evaporite and Muskeg formations, employing a 'net-evaporite' methodology. This effort is also a province-wide extension of mapping done in the LARP area, originally completed to aid in delineating the location of the Prairie Evaporite Formation halite dissolution scarp (Hauck et al., 2017, 2018b). Net-evaporite mapping includes more than 23 600 intervals, defined on wireline logs by the top and base of halite, anhydrite, or gypsum beds (see Digital Data 2020-0008 accompanying this report). Mapping of individual evaporite beds within each formation allows for an appraisal of the degree of interbedding of halite and nonhalite lithologies, which reflects the purity of halite deposits and has implications for the potential placement of salt caverns for various usages. Regional cross-sections display net-evaporite intervals and the degree of nonhalite interbedding within the Prairie Evaporite and Muskeg, Cold Lake, and Lotsberg formations. Also included are maps of net-halite for these formations, and maximum halite bed thickness within the Prairie Evaporite and Muskeg and upper Lotsberg formations. Additionally, areas of evaporite karst are discussed, including the well-known Prairie Evaporite halite dissolution scarp and lesser known areas of pre-Cordilleran karst on the eastern flank of the Peace River Arch (PRA).

The base of the Elk Point Group succession in the Alberta Basin is a major unconformity, known as the sub-Devonian unconformity, which is underlain by subcropping Cambrian, Ordovician, and Silurian strata in southern Alberta, and the Precambrian basement in central and northern Alberta. In addition to the sub-Devonian unconformity, mapped lithostratigraphic units include, in ascending stratigraphic order: 1) La Loche Formation, 2) Lotsberg Formation, including the basal and middle red beds units, and the lower and upper Lotsberg halite units, 3) Ernestina Lake Formation, 4) Cold Lake Formation, 5) Contact Rapids and Chinchaga formations, 6) Keg River and Winnipegosis formations, 7) Prairie Evaporite, Muskeg, and Eyot formations, including the Whitkow and Telegraph, Aurora, Shell Lake, Black Creek, lower and upper anhydrite (Hay River Bank sub-basins), Zama, and Leofnard members, including the White Bear and Conklin marker beds, 8) Sulphur Point Formation, and 9) Watt Mountain Formation, including the Dawson Bay Formation in eastern Alberta.

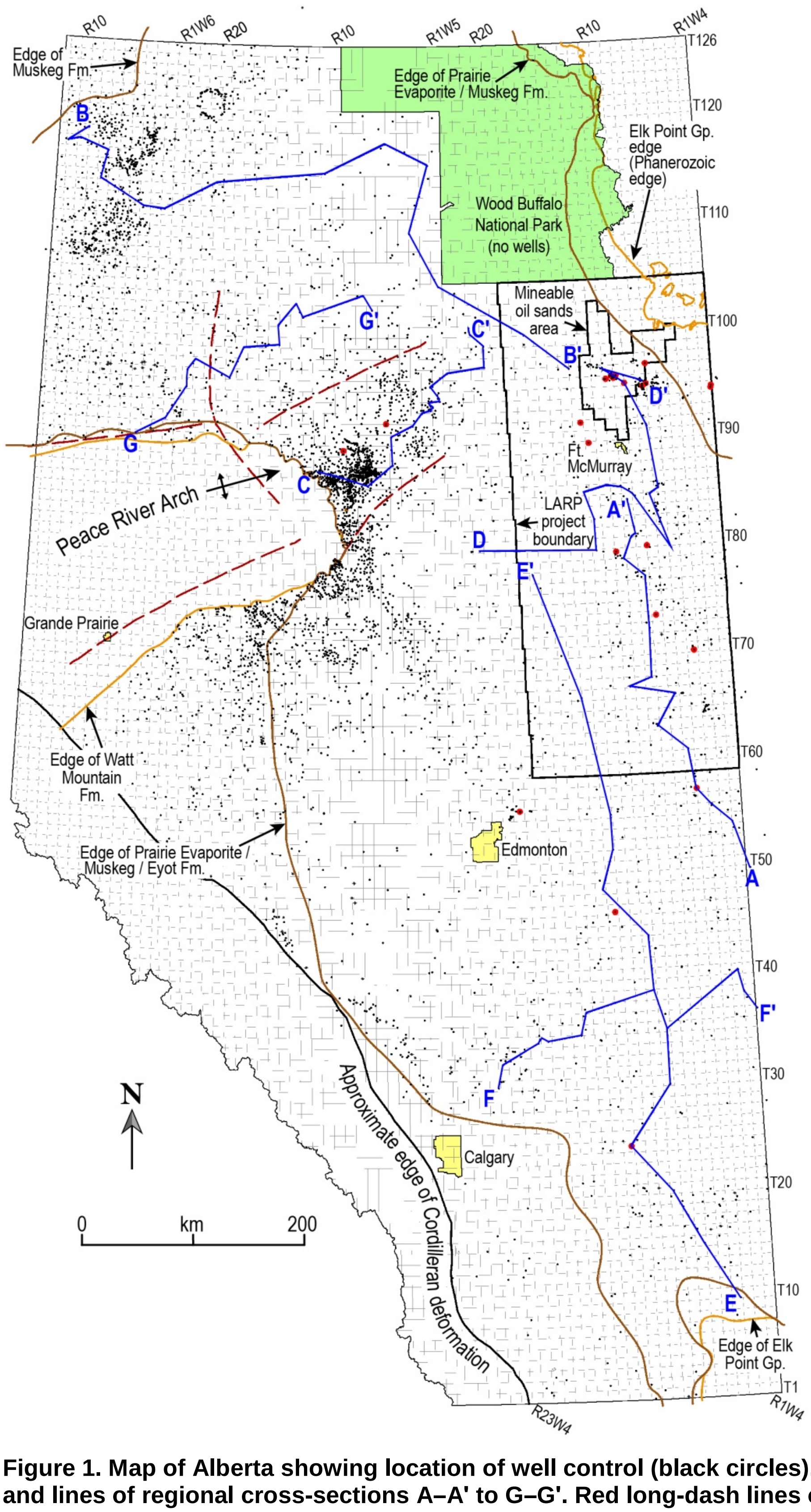


Figure 1. Map of Alberta showing location of well control (black circles), core control (red circles), and lines of regional cross-sections A–A' to G–G'. Red long-dash lines outline the Peace River Arch (from O'Connell, 1994). Abbreviations: Ft., Fort; LARP, Lower Athabasca Regional Plan.

2 Previous Work

2.1 Elk Point Group Stratigraphy

This account of previous work on the Elk Point Group is by no means exhaustive. The publications detailed here provided the author with some guidance or direct data during the course of mapping Elk Point Group strata within the Alberta Basin. Many of the earliest publications listed here were informed by much earlier pioneering work (see Schneider and Grobe, 2017).

McGehee (1949) originally introduced the name Elk Point Formation for a series of Devonian rocks, recognized in wells from the subsurface of Alberta and Saskatchewan, that rested on Ordovician, Cambrian, or Precambrian rocks. Recognizing the continuity and extent of these rocks, Belyea (1952) later raised the rank of the Elk Point to group level. Sherwin (1962) introduced a subgroup level distinction, which separated a Lower Elk Point subgroup comprising predominantly evaporites and red beds from an overlying succession of reefal carbonates and evaporites (Figure 2), although the Upper Elk Point subgroup was never formally defined. Sherwin (1962) named and described the formations comprising the Lower Elk Point subgroup in central to northern Alberta, including a lowermost basal red beds unit overlain by the Lotsberg Formation, which he described as almost pure halite. Sherwin (1962) did not distinguish a lower and upper Lotsberg halite. Above this succession are the lower red bed, middle carbonate, and upper anhydrite of the Ernestina Lake Formation, overlain by the red bed and upper halite of the Cold Lake Formation (Figure 2).

In northeastern Alberta, the Elk Point Group includes a basal arkosic sandstone known as the La Loche Formation (Norris, 1963), which was placed in the Elk Point Group by Norris (1973). Notably absent from Figure 2 is the Granite Wash unit located along flanks of the PRA. Because the Granite Wash represents the protracted erosion of the PRA and deposition of arkosic sand during overall transgression of Devonian seas, it is highly time-transgressive and therefore excluded from the Elk Point Group.

Overlying the Cold Lake Formation halite or red beds in northern Alberta (Figure 2) is the anhydrite of the Chinchaga Formation (Law, 1955), which grades southeastwards into argillaceous dolomite and dolomitic shale of the Contact Rapids Formation (Sherwin, 1962). In southeastern Alberta, the Contact Rapids Formation merges with the Ashern Formation of Saskatchewan and Manitoba (Baillie, 1951; Meijer Drees et al., 2002; Figure 2). In the present study, the Ashern is not differentiated from the Contact Rapids.

Work by Reinson and Wardlaw (1972) in Saskatchewan found that the Lower Elk Point subgroup is missing from the Saskatchewan sub-basin of the Williston Basin, whereas the Upper Elk Point subgroup is well developed. Baillie (1953) proposed some of the earliest stratigraphic subdivisions in this upper interval. The work of Van Hees (1956), Grayston et al. (1964), and Holter (1969) aided in elucidating stratigraphic relationships from Saskatchewan into Alberta. These workers defined the potash-bearing members within the Prairie Evaporite Formation that are restricted to Saskatchewan and established the White Bear marker bed as regionally extensive (Figure 2). Reinson and Wardlaw (1972) resolved some stratigraphic complexities associated with the Winnipegosis Formation to Prairie Evaporite Formation transition, and expanded on the Whitkow, Shell Lake, Quill Lake, and Leofnard units, informally introduced by Jordan (1967, 1968). Reinson and Wardlaw (1972) also introduced the Ratner Member (Prairie laminites) for the finely laminated, bituminous carbonate mudstone and anhydrite at the top of the lower Winnipegosis Formation (Figure 2). Many of these units were correlated into east-central Alberta by Meijer Drees (1986a, 1994).

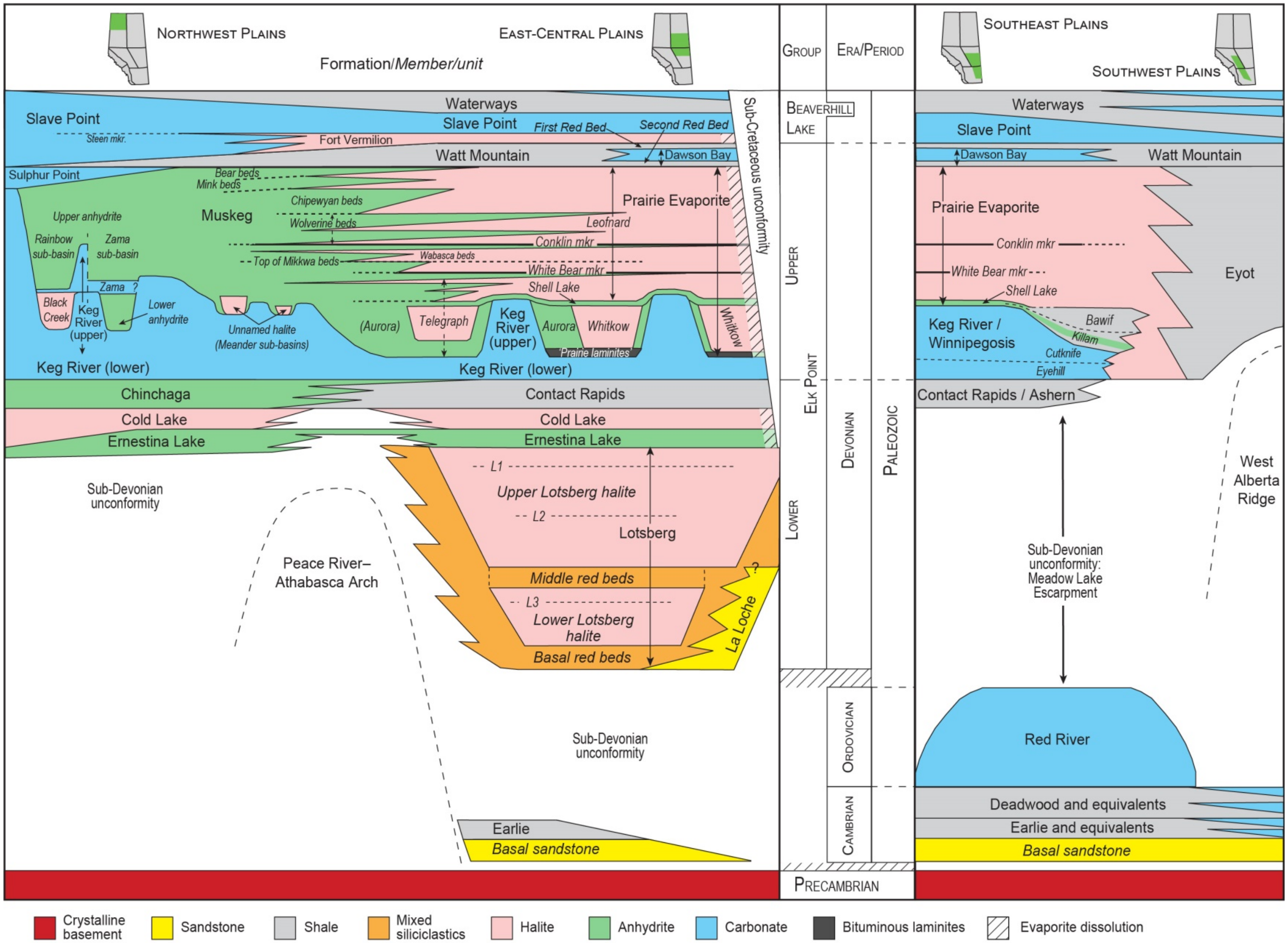


Figure 2. Stratigraphic correlation chart of Elk Point Group strata and adjacent units in the Alberta Basin. Originators of stratigraphic nomenclature are discussed in the text. Within the Lotsberg Formation, marker beds L1–L3 represent mappable 'discontinuities' within the halite succession. Abbreviation: mkr., marker bed.

An anhydrite-dominated evaporitic succession in northwestern Alberta was named the Muskeg Formation by Law (1955). This unit was shown to gradually transition to the southeast into the halite-dominated Prairie Evaporite Formation (Klingspor, 1969). In the transition zone, a number of correlatable 'beds' in the Muskeg Formation were introduced by Klingspor (1969), including the Telegraph, Mikkwa, Wabasca, Wolverine, Chipewyan, Mink, and Bear (Figure 2). The lowermost Telegraph beds (also referred to as the Telegraph Member) are a relatively thick halite succession, which is partly equivalent to the Whitkow Member (Figure 2). Klingspor (1969) also introduced the Muskeg 40 marker bed at the top of the Wabasca beds. In northeastern Alberta, Hauck et al. (2017, 2018a) recognized a regional marker bed of shale, dolomite, and anhydrite within the Prairie Evaporite Formation and named it the Conklin marker bed. Later it was established that the Conklin marker bed is equivalent to Klingspor's Muskeg 40 marker bed (Figure 2). Recent work by Rogers (2017) in northeastern Alberta introduced the Aurora Member for the anhydrite-dominated portions of the lower Prairie Evaporite Formation, which flank upper Keg River Formation buildups (Figure 2).

In west-central and south-central Alberta, Meijer Drees et al. (2002) introduced a number of members for the Winnipegosis Formation, which becomes increasingly silty and shaly westwards and towards the southern flank of the PRA. The members are, in stratigraphically ascending order, the Eyehill, Cutknife, Killam, and Bawif (Figure 2). The lower two members were shown to have correlatives with the Winnipegosis Formation in west-central and southern Saskatchewan. The upper two members are in 'lateral facies contact' with the upper part of the Shell Lake Member of the Prairie Evaporite Formation (Meijer Drees et al., 2002). Meijer Drees et al. (2002) also introduced the Eyot Formation for dolomitic siliciclastic units of the upper part of the Prairie Evaporite Formation, which record a facies change towards the West Alberta Ridge in west-central and southwestern Alberta (Figure 2).

In far northwestern Alberta, the Middle Devonian Presqu'ile Barrier, formed of the Keg River Formation, was described from outcrops and the subsurface in the Northwest Territories by Campbell (1950). The Sulphur Point Formation (Figure 2) was also described from outcrops in the Great Slave Lake region, Northwest Territories (Norris, 1965). Correlation of these units with Elk Point Group carbonates in the subsurface was made by Law (1955). Oil discoveries in Keg River Formation carbonate rocks southeast of the Presqu'ile Barrier in the mid 1960s led to the discovery of the Rainbow and Zama sub-basins. These sub-basins comprise small isolated Keg River Formation buildups with halite (Black Creek Member of the Muskeg Formation) or 'lower Muskeg anhydrite' in interbuildup basinal areas (Figure 2; McCamis and Griffith, 1967, 1968; Barss et al., 1970; Campbell, 1992). Fuller and Porter (1969) discussed deposits in the Elk Point 'basin' within the Western Canada Sedimentary Basin (WCSB) and suggested stratigraphic relationships between the Elk Point Group of northwestern Alberta and southern Saskatchewan.

In Alberta, the Watt Mountain Formation was introduced by Law (1955) for the uppermost siliciclastic rocks of the Elk Point Group (Figure 2). Correlatives in eastern Alberta and Saskatchewan are more complex, with First and Second Red beds separated by carbonate rocks and anhydrite of the Dawson Bay Formation (Dunn, 1982). The Dawson Bay Formation can be correlated into eastern Alberta (Dunn, 1982; Hauck et al., 2018b).

2.2 Elk Point Group Halite and Potash Assessments

Early research on halite as a potential industrial mineral in western Canada include the work of J.A. Allan of the University of Alberta, who logged a series of early 'salt' wells drilled in northeastern Alberta (Allan, 1929, 1943). Crockford (1949) reviewed a number of oil and gas wells drilled into the 'common salt' of the Elk Point Group of eastern Alberta to assess their halite potential. In Saskatchewan, Holter (1969) described in detail the Prairie Evaporite Formation, which includes the economically important potash salts of the Esterhazy, Belle Plaine, and Patience Lake members of the upper Prairie Evaporite Formation. Holter (1969, Figure 6) also made correlations with Elk Point Group strata in Alberta and showed that no similar significant potash deposits are found within Alberta. However, Eccles et al. (2009)

report carnallite- and sylvite-rich intervals in the uppermost Prairie Evaporite Formation in a few cores from east-central and southeastern Alberta. Holter (1969) also described areas of 'salt solutioning', where the dissolution of halite was recognized in localized areas in southern Saskatchewan and in a regional basin-margin trend across central Saskatchewan.

In east-central Alberta, Hamilton (1971) compiled thicknesses of Elk Point Group evaporite deposits, including the Lotsberg, Cold Lake, and Prairie Evaporite formations. Meijer Drees (1986a) comprehensively reviewed Paleozoic evaporitic successions within western Canada, which included evaporites of the Elk Point Group in the WCSB. Meijer Drees (1994) presented an important series of maps for the distribution of Elk Point Group evaporites within the WCSB. This work defined areas of basin-margin halite dissolution in the Lotsberg, Cold Lake, and Prairie Evaporite formations, and it also defined the transition of the Prairie Evaporite Formation to the Muskeg Formation through halite percentages within the Prairie Evaporite Formation (Meijer Drees, 1994, Figure 10.7). Following the work of Meijer Drees (1994), Grobe (2000) generated a series of maps, based on new well data, for the distribution and thickness of halite in the lower and upper Lotsberg, Cold Lake, and Prairie Evaporite formations of the WCSB. Hauck et al. (2017, 2018a, b) mapped the distribution of halite, anhydrite, and gypsum in the Prairie Evaporite Formation of northeastern Alberta to assess basin-margin evaporite karst associated with the Prairie Evaporite halite dissolution scarp.

3 Geological Setting

3.1 Timing and Major Depositional Features

Strata of the Elk Point Group of the WCSB were deposited along the western cratonic margin of the paleocontinent Laurentia, within what is known as the Elk Point Basin (e.g., Moore, 1993). The timing of initial deposition of the lowermost Elk Point Group strata is poorly constrained due to a general lack of fossils (Moore, 1993). Basal siliciclastic rocks (La Loche Formation or basal red beds unit of the Lotsberg Formation) may be as old as Lochkovian (Moore, 1993), or as young as Emsian (Meijer Drees, 1994); however, the Ernestina Lake Formation, which lies above the Lotsberg Formation, contains fauna of Emsian age (Moore, 1993) suggesting Lotsberg Formation strata may be at least older than Emsian. The Keg River Formation contains brachiopod and conodont faunas of late Eifelian (lower Keg River) to early Givetian age (upper Keg River; Norris, 1973). Recent rhenium-osmium isotope geochronology from bituminous laminites of the lower Keg River returned an errorchron of 389 ±15 Ma, which is consistent with a late Eifelian to early Givetian age for the lower Keg River (Pană et al., 2018).

Elk Point Group deposition represents renewed sedimentation after a significant hiatus during the transition from the Ordovician–Silurian Tippecanoe cratonic sequence to the Devonian–Mississippian Kaskaskia sequence. The hiatus is associated with significant erosion of Silurian to Cambrian deposits in the Alberta Basin, which results in a sub-Devonian unconformity surface of significant relief (Bassett and Stout, 1967; Williams, 1984). This relief is evident in the isopach map of the Elk Point Group (Figure 3). There are two major depocentres with thick Elk Point Group strata within Alberta: the central Alberta sub-basin (CAS) and the northern Alberta sub-basin (NAS; Figure 3). The Meadow Lake Escarpment forms the southern boundary of the CAS (Figure 3), and comprises Ordovician carbonate rocks at the subcrop of the sub-Devonian unconformity in southeastern Alberta. To the southeast of the Meadow Lake Escarpment, Elk Point strata thin before thickening again in a third depocentre within the Williston Basin of Saskatchewan and North Dakota, known as the Saskatchewan sub-basin (Holter, 1969).

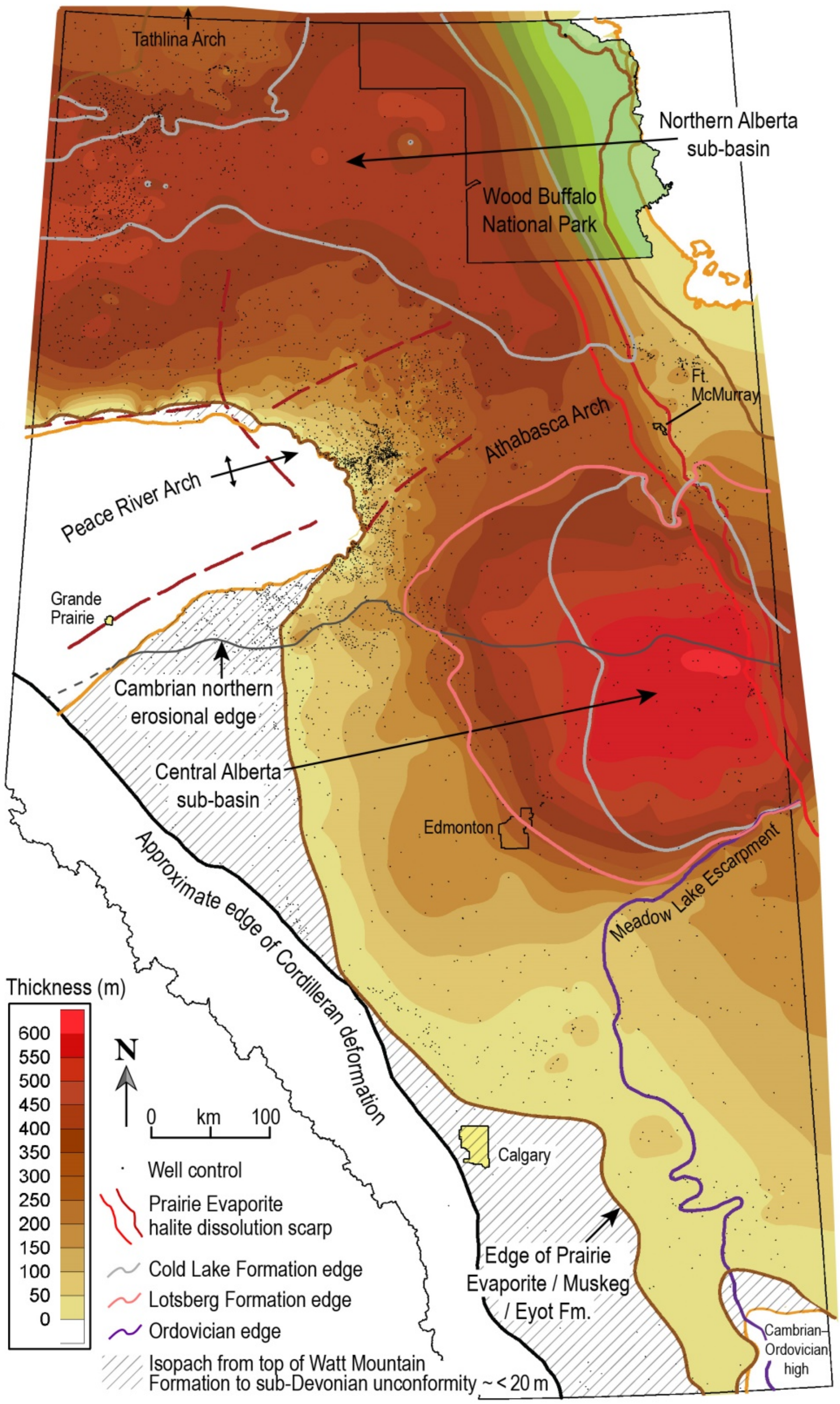


Figure 3. Isopach map of the Elk Point Group in Alberta, which approximates the paleotopographic relief on the sub-Devonian unconformity. Two major depocentres are the central and northern Alberta sub-basins, which are the locations of predominantly evaporite deposition during Lower Elk Point subgroup time. Two paleohighs include the Peace River–Athabasca Arch and the West Alberta Ridge, the latter approximated by the present-day location of the Cordilleran deformation front. The Tathlina Arch is located in southwestern Northwest Territories, and affects the isopach of the Elk Point Group in northwestern Alberta. Red long-dash lines outline the Peace River Arch (from O'Connell, 1994). Lotsberg Formation edge shown represents the maximum extent of halite in the Lotsberg Formation. Abbreviation: Ft., Fort.

Elk Point Group deposits thin westwards of the CAS towards two paleotopographic highs known as the West Alberta Ridge (WAR) and the PRA (Figure 2). The WAR is approximated by the present-day Cordilleran deformation front (Figure 3), where it comprises Cambrian strata, but its genesis is poorly understood. Approaching these highs, deposits of the Watt Mountain Formation rest unconformably on Cambrian strata at the sub-Devonian unconformity, the Granite Wash, or Precambrian basement rock of the PRA (Figure 3). The Athabasca Arch, which is an eastwards extension of the more prominent PRA, forms the northern boundary of the CAS. The evaporite deposits of the Lotsberg and Cold Lake formations are missing over the Athabasca Arch (Figure 3). The NAS is located north of the Peace River–Athabasca Arch (Figure 3). This depocentre was not as deep as its southern counterpart, and as a consequence evaporites and red beds of the Lotsberg Formation are missing (Figure 2).

Two other paleohighs affected Elk Point Group sediment distribution within Alberta. In the southeast, Elk Point strata onlap, but do not overlie, a subtle high comprising Ordovician carbonates and Cambrian siliciclastics at the sub-Devonian unconformity (Figure 3). The high is roughly coincident, but slightly east of the Sweetgrass–Bow Island Arch (Kent and Christopher, 1994). In northwesternmost Alberta, there is a thinning of Elk Point strata onto the southern flank of the Tathlina Arch (Figure 3), which is centred in southwestern Northwest Territories (Belyea, 1971; Meijer Drees, 1994).

Elk Point Group strata thin towards northeastern Alberta, coincident with the tapering edge of the Phanerozoic sedimentary succession. The past distribution of Elk Point strata likely extended much farther to the east (Williams, 1984), but they were subjected to multiple episodes of erosion. Another prominent feature in this location is the Prairie Evaporite halite dissolution scarp (Meijer Drees, 1994; Hauck et al., 2017). Here, evaporite karstification associated with the influx of undersaturated basin-margin water has had a pronounced effect on the thickness of Elk Point strata (Figure 3). Deposits of the Prairie Evaporite Formation are the principal strata that have been affected by this evaporite karstification, although the halite of the underlying Cold Lake Formation has also experienced dissolution along its eastern extent (see Cold Lake edge on Figure 3). The lowermost halite succession, the Lotsberg Formation, has not experienced dissolution within Alberta; basin-margin dissolution of this unit occurs farther east in west-central Saskatchewan (Meijer Drees, 1994).

4 Methods

4.1 Stratigraphic Correlation and Mapping

The lithostratigraphic units within the Elk Point Group were correlated and mapped using IHS Markit's Petra™ software. Where possible, correlation was done with a full suite of wireline logs within stratigraphic cross-sections with different datums, depending on the location within the province. Depending on data availability, wireline logs run after 1980 were preferred because modern density log suites include photoelectric effect and have enhanced vertical resolution. Contour maps, comprising structural elevations and isopachs, were employed to assess the consistency of stratigraphic picks and to identify potentially anomalous data. Well data distribution for the Elk Point Group is irregular across the province, with locally high concentrations of data associated with prospective hydrocarbons in Elk Point Group strata, in areas such as near the PRA and within northwestern Alberta (Figure 1). Away from these locations, data is mostly widely distributed. Wood Buffalo National Park in northeastern Alberta contains no wells, and as such is an area where geological knowledge stems from outcrop study alone (Figure 1).

The province-wide extent of mapping in this study required the use of numerous studies of Elk Point Group strata, especially those that provided indications of picks on logs. The following studies were used to aid in the correlation of lithostratigraphic units: McCamis and Griffith (1967), Klingspor (1969), Geldsetzer and Meijer Drees (1984), Meijer Drees (1986a, 1994), Chow et al. (1995), Cotteril and Hamilton (1995), Hoffman and Kimball (2006), Balshaw (2010), Cotteril (2011), Wiebe et al. (2013), and Rogers (2017). For the base of the Elk Point succession, numerous other studies were used to aid in the picking of units comprising the sub-Devonian unconformity, including the top of the Cambrian and

Ordovician successions and the Precambrian basement, or the top of the Granite Wash lithosome (Hamilton, 1971; Pugh, 1971, 1973; Dunham et al., 1983; Anderson et al., 1988; Trotter and Hein, 1988; Slind et al., 1994; Hein et al., 1995a, b; Dec et al., 1996; Meijer Drees et al., 2002; Balshaw, 2010).

Given the contrast in lithologies (e.g., shale, carbonates, halite, anhydrite, etc.) and resulting log responses across lithostratigraphic units in the Elk Point Group, many of the correlations at the formation level were straightforward. However, in areas of subtle facies changes (e.g., towards depositional edges) or complex lithological changes associated with the halite dissolution scarp, a number of cores were reviewed to calibrate picks on wireline logs (Figure 1).

Contouring for isopach maps was done in Petra using the Kingdom Flex Gridding method. Isopach maps for a given formation are constrained to a series of zero-edges that informed the gridding algorithm. These hand-drawn zero edges are based on all available well control. Extensive use of hand-drawn contours within Petra was also employed to inform the gridding algorithm and add conceptual geological understanding of the distribution and thickness of strata, especially where data is sparse within the lowermost stratigraphic units (e.g., Lotsberg Formation).

4.2 Net-Evaporite Mapping from Raster Logs

The presence and abundance of three evaporite minerals, halite, anhydrite, and gypsum, were assessed with a net-evaporite methodology using raster wireline logs in Petra. In areas where modern well log suites were not available, additional data for halite and anhydrite, derived from the interpretation of electric well logs supplemented with observations from core and drill cuttings, were used. These data were transcribed from archival field notes taken by W.N. Hamilton and coworkers for the study of Elk Point Group salt deposits in east-central Alberta (Hamilton, 1971).

Based on the petrophysical properties of evaporite minerals, a top and base for individual beds of the respective minerals were picked on the raster logs (Table 1). Halite, anhydrite, and gypsum all have distinct petrophysical properties when compared with each other and with the carbonate and siliciclastic rocks they are associated with (Figure 4). Gypsum is only present in a very limited area east of the Prairie Evaporite halite dissolution scarp (Hauck et al., 2018a). Additionally, potassium-bearing potash salts do not form a significant component of the evaporite succession in Alberta (Holter, 1969), with the exception of the Prairie Evaporite Formation in southeastern Alberta (Eccles et al., 2009; Lopez et al., 2020). As such, over most of the areal extent of Elk Point Group evaporites, the successions have a basic tripartite division of mineralogies/lithologies: halite, anhydrite, and ‘insolubles’—the latter comprising carbonate and shale. Therefore, by mapping halite and anhydrite, an assessment of nonevaporite lithologies can be made as well. A number of parameters were derived from these data, including 1) cumulative halite, anhydrite, and gypsum thicknesses, 2) halite percentage within a respective formation, 3) minimum, maximum, and average thickness of individual halite beds, 4) minimum, maximum, and average number of nonhalite interbeds, and 5) total volume of evaporite minerals within the province of Alberta.

Table 1. Petrophysical criteria used for net-evaporite mineral mapping.

Evaporite Mineral	Gamma-Ray Count	Photoelectric Effect (barns/electron)	Bulk Density (g/cm^3)	Limestone Density Porosity (pu)	Limestone Neutron Porosity (pu)
Halite	Low	4.7	≤2.2	≥30	~–3
Anhydrite	Low	5.1	≥2.8	≤–6	~–2
Gypsum	Low	4.0	≥2.4	~21	≥45

Based on Ellis and Singer (2008); some thresholds and ranges have been changed to account for interbedded lithologies (e.g., anhydrite interbedded with shale). Abbreviation: pu, porosity units.

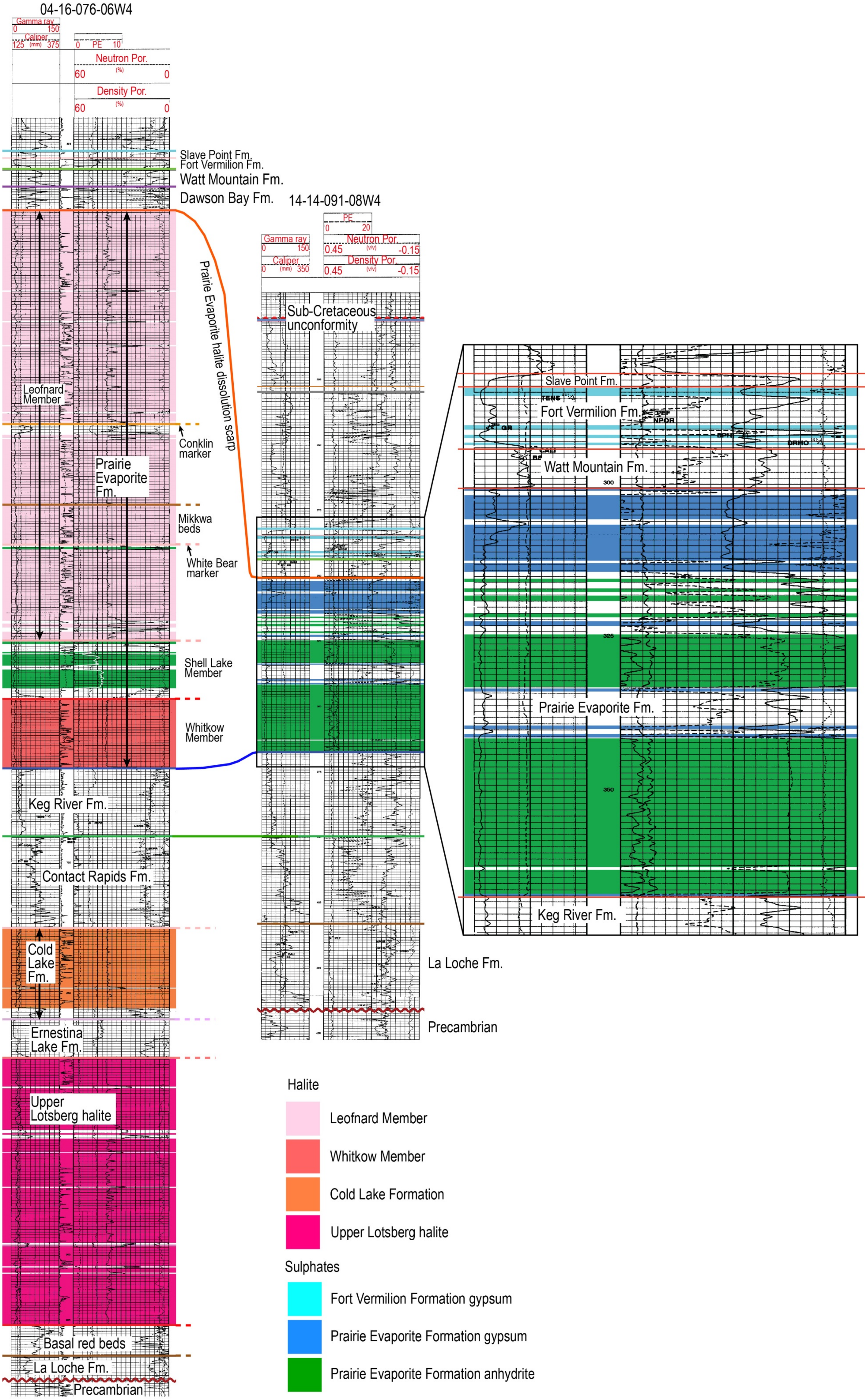


Figure 4. Two well logs from northeastern Alberta demonstrating log responses to various evaporite lithologies in the Elk Point Group. Well 04-16-076-06W4 is located west of the Prairie Evaporite halite dissolution scarp, whereas well 14-14-091-08W4 falls east of the scarp where less-soluble sulphates still remain. Abbreviations: PE, photoelectric effect; Por., porosity; v/v, volume/volume.

In order to verify the accuracy of the net-evaporite mapping on wireline logs, a core that recovered the Prairie Evaporite Formation and upper Lotsberg halite was reviewed. This well was chosen because of the significant nonhalite interbedding within the Prairie Evaporite Formation (Figure 5). Thickness of halite and nonhalite interbeds were measured and compared with the log-based net-evaporite mapping results. In the Prairie Evaporite, the cumulative halite thicknesses from the two methods were within 5 m; however, the number of measured nonhalite interbeds was considerably larger from measurements of the core. This is likely due to the resolution of the logging tools. In the upper Lotsberg halite, the log measurements slightly overestimated the number of nonhalite interbeds (Figure 5). This may be due to the nature of some of the nonhalite interbeds in the upper Lotsberg, which are often mixtures of halite and shale in convoluted bedding textures (Figure 5).

Cumulative thickness of individual beds of halite, anhydrite, and gypsum were contoured in Petra. In addition, the maximum halite bed thickness was mapped as an evaluation of thick, noninterrupted, potentially contiguous halite beds within the upper Lotsberg halite and Prairie Evaporite and Muskeg formations.

5 Results

5.1 Lithostratigraphic Mapping

5.1.1 Lower Elk Point Subgroup

5.1.1.1 La Loche Formation

The La Loche Formation comprises lower regolithic beds, with overlying arkosic sandstone and conglomerate, resting unconformably on Precambrian crystalline basement (Schneider et al., 2013). The La Loche is compositionally indistinct from other basal sandy clastic units that formed from the weathering and erosion of the Precambrian basement, such as the Granite Wash on the Peace River Arch (PRA). The boundary between arkosic sandstone units of the La Loche and those of Granite Wash affinity is arbitrary, the latter associated with highly diachronous and continuous deposition along the PRA from at least the Early Devonian through to the Late Devonian (Famennian).

There can be some difficulty in separating thinly developed La Loche Formation units from likewise thinly developed basal red beds of the Lotsberg Formation in the CAS (Figure 2). There are locations within the CAS where the La Loche is relatively thick and can be easily differentiated from the basal red beds (Figure 6, well 16-10-077-08W4). In particular, thick deposits of La Loche sandstone occur within the CAS in and around basement highs on the southern flank of the Athabasca Arch. This suggests that these highs were potential sources for the La Loche as the margins of the CAS were transgressed. To the north and east of the CAS, the basal siliciclastics comprise only the La Loche (Figure 6); however, the Ernestina Lake or Cold Lake formations may rest directly on the Precambrian basement along the Athabasca Arch where the La Loche is missing.

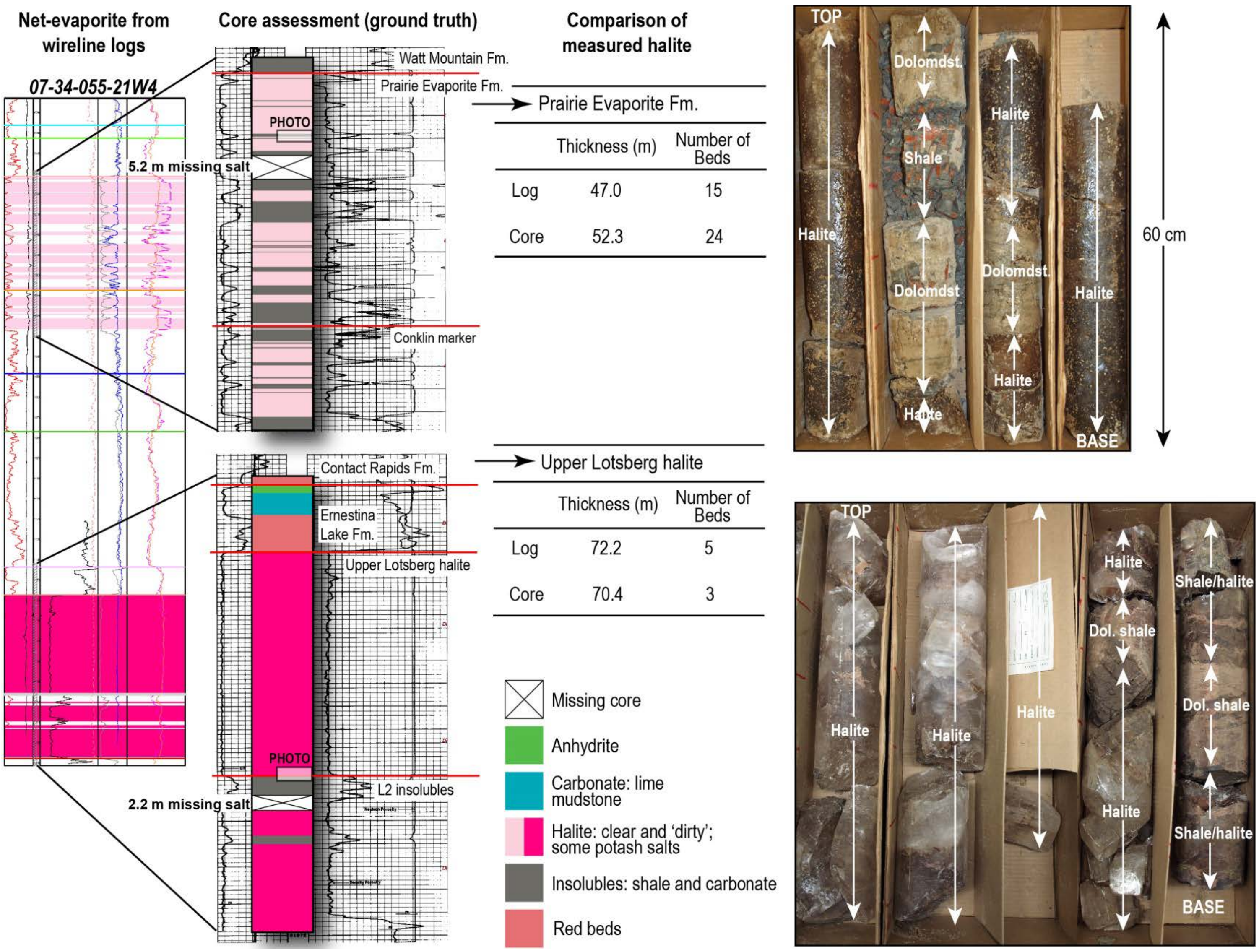


Figure 5. A comparison of net-evaporite mapping of evaporite minerals from logs and an assessment from a core from the same well (7-34-055-21W4), central Alberta. The locations of the photographed core are highlighted on the raster logs in the core assessment column. Core sleeve length is 60 cm for both photos. Abbreviations: Dolomdst., dolomudstone; Dol., dolomitic.

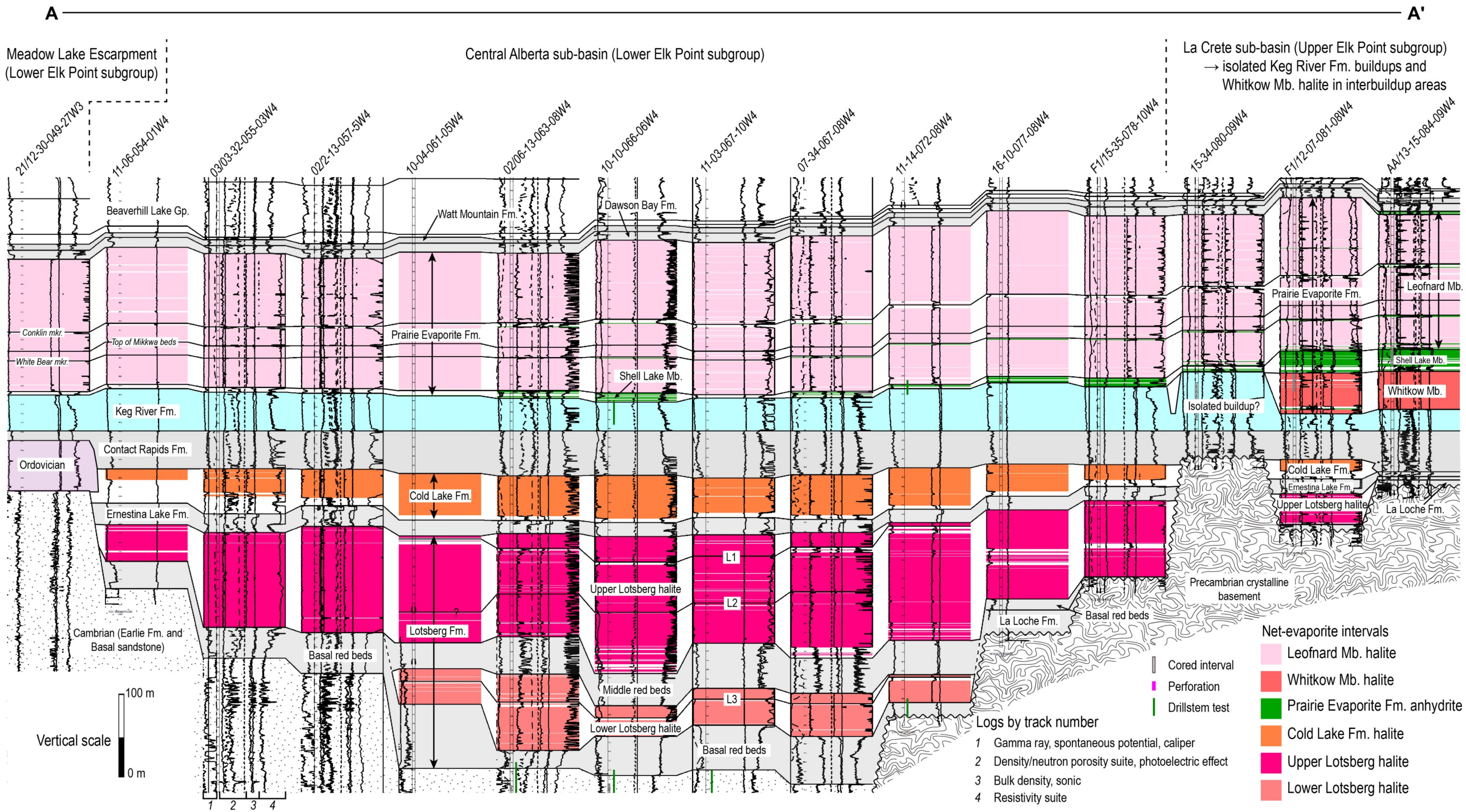


Figure 6. Stratigraphic cross-section A–A'. The cross-section runs north–south across the central Alberta sub-basin in east-central Alberta (Figure 1), from the Meadow Lake Escarpment in the south to the La Crete sub-basin in the north. Net-evaporite intervals are colour-coded according to the legend. The Keg River Formation is highlighted in light blue. The remaining Elk Point Group nonevaporite strata are coloured light grey. Abbreviation: mkr., marker bed.

5.1.1.2 Lotsberg Formation

The Lotsberg Formation comprises two major red bed–halite successions. The lower succession includes the basal red beds overlain by the lower Lotsberg halite. The second succession includes the middle red beds and the overlying upper Lotsberg halite (Figure 2). There are a number of other red bed successions throughout the Lower Elk Point subgroup, all associated with the lower parts of evaporitic successions. Generally speaking, the basal red beds of the Lotsberg Formation are the oldest red beds, having formed in the lowest paleotopography associated with the CAS. Within the CAS, the basal red beds were deposited on either the Cambrian subcrop at the sub-Devonian unconformity, or the Precambrian basement to the north. The basal red beds are more extensive than the Lotsberg Formation halite, as the red beds form a fringe laterally around the halite. However, in areas where the basal red beds are not overlain by either the lower or upper Lotsberg halite, they are hard to distinguish from younger red bed deposits. Therefore, only the mapped extents of lower and upper Lotsberg halite units are shown on map figures in this report (Figure 7).

The lower Lotsberg halite is less extensive than that of the upper Lotsberg halite, being the first halite deposit to fill the bowl-shaped depression of the CAS (Figure 7). However, along the western margin of the CAS, the lower Lotsberg halite extends beyond the limit of the upper Lotsberg halite (Figure 7). In this area, the southern edge of the lower Lotsberg halite aligns with the interpreted erosional limit of underlying Cambrian strata, suggesting the location of the latter played a role in the distribution of lower Lotsberg halite (Figure 7). Where present, the lower Lotsberg halite overlies the basal red beds and is overlain by the middle red beds (Figures 6, 8). Where fully developed in the central portions of the CAS, the lower Lotsberg halite is roughly half as thick as the upper Lotsberg halite (Figure 6).

Nonhalite interbedding within the lower Lotsberg halite is difficult to correlate across its distribution because of 1) poor well control, 2) a significant number of old logs, and 3) an apparent lack of consistency in traceable beds in evaporitic sequences. An attempt was made to correlate one particular nonhalite interbed, L3, in the upper half of the lower Lotsberg halite (Figures 2, 6, 8). Log signatures suggest it comprises mostly shale with some halite. Whereas nonhalite interbedding in the lower Lotsberg halite varies significantly from well to well, this marker bed can be consistently identified (Figures 6, 8).

The upper Lotsberg halite, which defines the outline of the CAS, is considerably more extensive than the lower Lotsberg halite (Figure 7). The upper Lotsberg halite is underlain by the middle red beds where the lower Lotsberg halite is present, or by the basal red beds (Figures 2, 6, 8). The southern limit of the upper Lotsberg halite is abruptly constrained by the Meadow Lake Escarpment, which is the erosional edge of Ordovician carbonate rocks at the sub-Devonian unconformity (Figures 6–8). Upper Lotsberg strata thin more gradually along the western margin of their extent. The northern limit of the upper Lotsberg halite onlaps the Athabasca Arch, which is the eastern extension of the PRA (Figure 2). Coincident with the southern margin of the Athabasca Arch, a pronounced Precambrian basement high occurs, over which all but the Contact Rapids Formation strata of the Lower Elk Point subgroup are missing (Figure 6, well 15-34-080-09W4; also see Hauck et al., 2017, Figure 8).

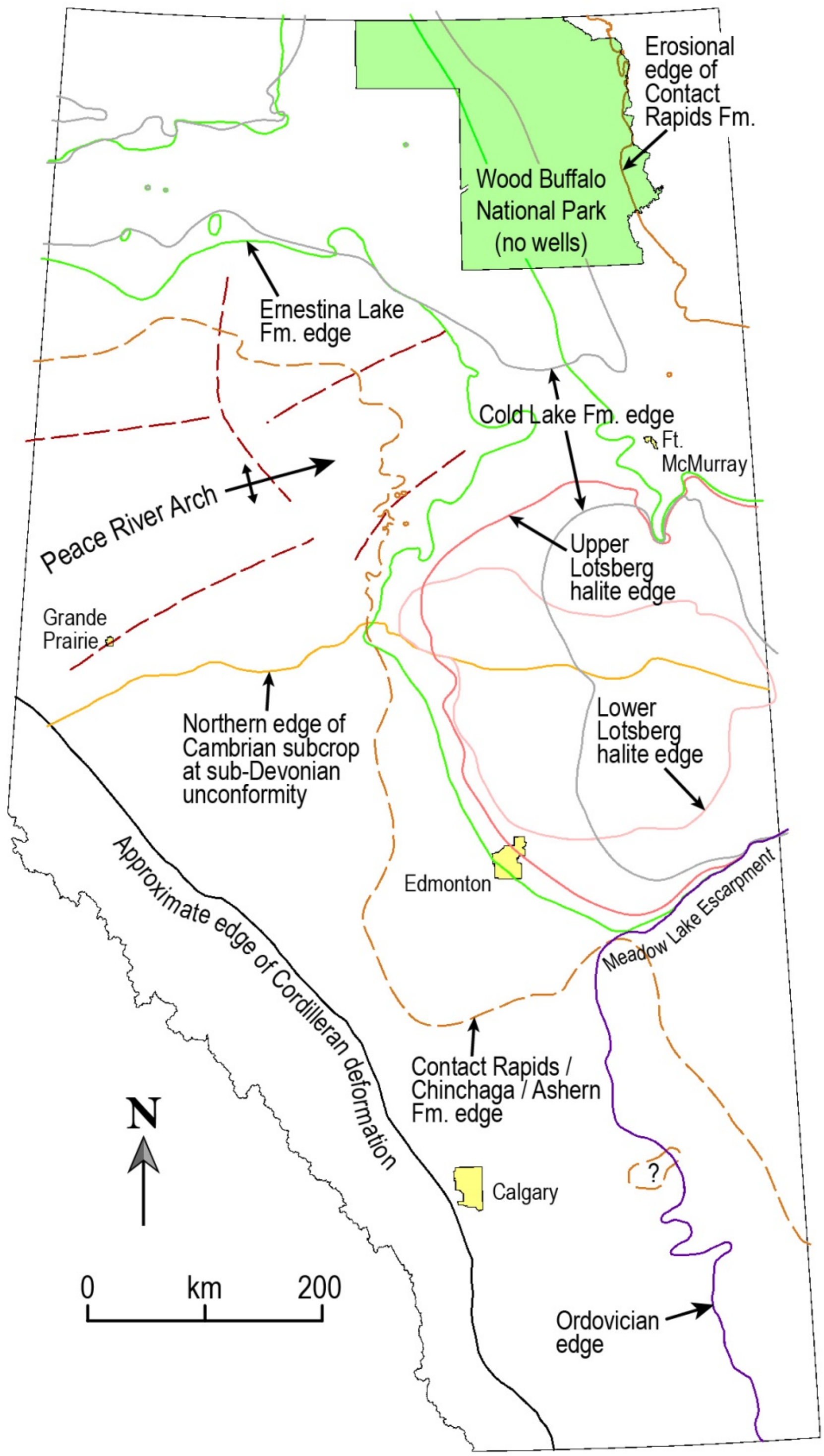


Figure 7. Depositional and erosional edges of Lower Elk Point subgroup strata in the Alberta Basin. The Cambrian and Ordovician erosional edges at the sub-Devonian unconformity are also included. The erosional edge of the Contact Rapids Formation in northeastern Alberta coincides with the erosional edge of the Elk Point Group. Dashed lines show approximate location of formation edge. Red long-dash lines outline the Peace River Arch (from O'Connell, 1994). Abbreviation: Ft., Fort.

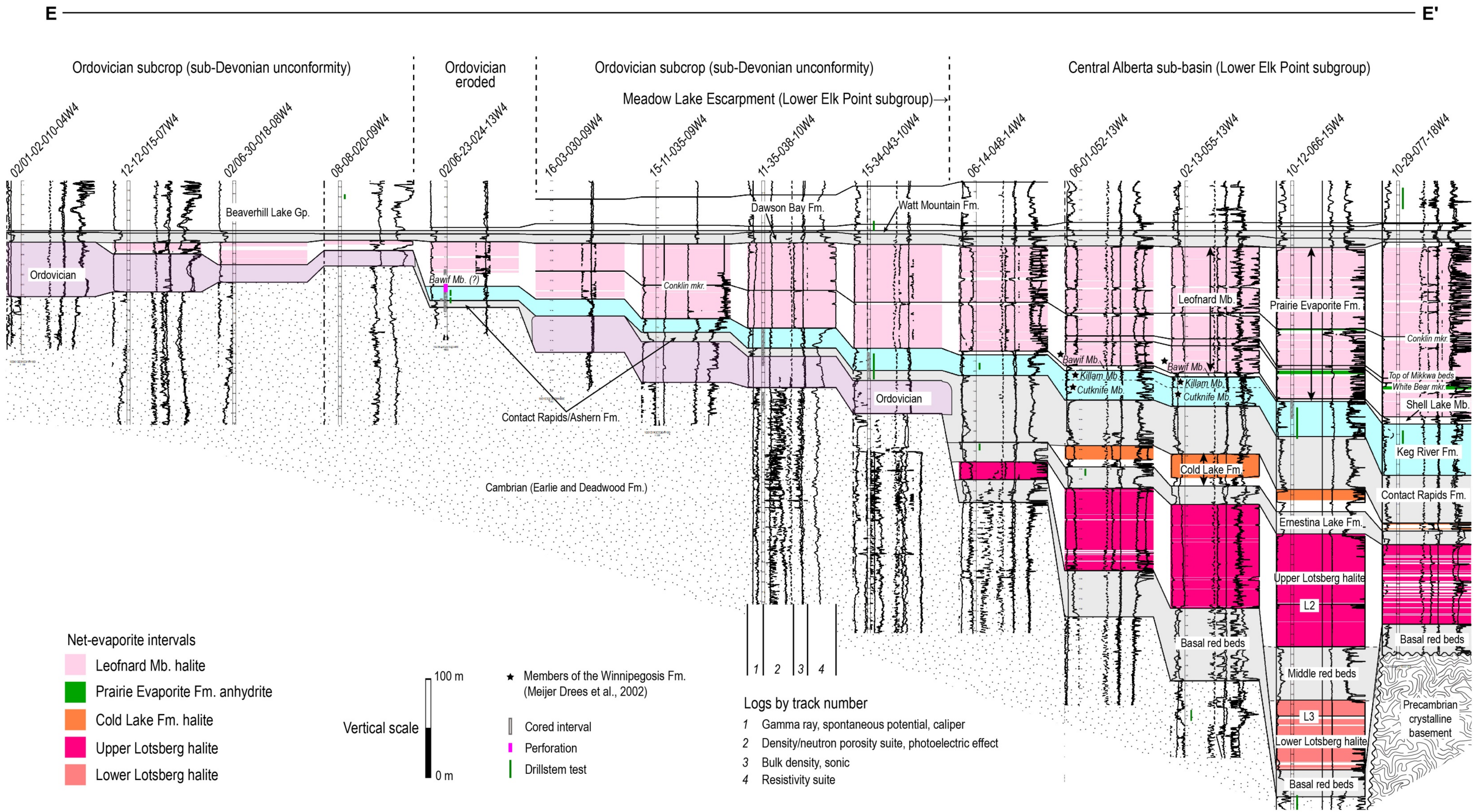


Figure 8. Stratigraphic cross-section E–E'. The cross-section runs south–north from southern Alberta into the central Alberta sub-basin (Figure 1). Net-evaporite intervals are colour-coded according to the legend. The Keg River Formation is highlighted in light blue and Ordovician carbonate rocks in purple. The remaining Elk Point Group nonevaporite strata are coloured light grey. The location of stratigraphic picks from Meijer Drees et al. (2002) are highlighted. Abbreviation: mkr., marker bed.

Nonhalite interbeds within the upper Lotsberg halite are difficult to correlate from well to well for similar reasons listed above for the lower Lotsberg halite. There appears to be a lack of continuity in halite beds from well to well. In general, the lower part of the upper Lotsberg halite can display significant interbedding with nonhalite beds (Figure 6, well 10-10-066-06W4). Two prominent nonhalite interbeds (L1, L2) are correlated within the upper Lotsberg halite (Figure 2). From logs, these markers appear to be shale and/or minor carbonate rocks. The L1 marker bed near the top of the upper Lotsberg halite mirrors the general bowl-shape of the CAS, suggesting it forms the base of a final phase of deposition, or redeposition, of halite within the basin centre (Figure 6). The L1 marker bed could only be correlated with some confidence in the east-central part of the CAS, where the Lotsberg Formation deposits are thickest (Figure 6). The L2 marker bed can be correlated within roughly the midway point in the upper Lotsberg halite (Figure 6). It has been correlated farther westwards than the overlying L1 marker bed, although this correlation is tentative (Figure 8).

5.1.1.3 Ernestina Lake Formation

The Ernestina Lake Formation comprises a lower dolomitic red bed, a middle anhydritic limestone, and an upper anhydrite (Sherwin, 1962; Meijer Drees, 1986a). The log response of the anhydrite in the upper part of the formation makes it readily distinguishable from adjacent formations. The Ernestina Lake is present in both the CAS and NAS, and is only thinly developed over the Athabasca Arch between the two sub-basins (Figures 7, 9). The limits of the Ernestina Lake in the CAS mirror those of the underlying Lotsberg Formation, yet are somewhat more laterally extensive. Like the Lotsberg, the southern extent of the Ernestina Lake is abruptly constrained by the Meadow Lake Escarpment (Figures 6, 7, well 21/12-30-049-27W3). Beyond the limit of the Lotsberg Formation halite, the lower red bed of the Ernestina Lake is indistinguishable from, and mapped with, the basal red beds of the Lotsberg Formation (e.g., Meijer Drees, 1986a).

The distribution of the Ernestina Lake Formation in the NAS is roughly coincident with that of the overlying Cold Lake Formation (Figure 7). It is missing in a number of wells over local Precambrian basement highs in the NAS (e.g., Figure 9, wells 06-28-011-04W6, 08-24-111-03W6).

5.1.1.4 Cold Lake Formation

The Cold Lake Formation comprises two broad lithologies across the province, a lower red bed and an upper halite. Where the halite is not present, possible equivalent siliciclastic strata, including the lower red bed, are mapped with the overlying Contact Rapids or Chinchaga formations. The Cold Lake Formation is present in both the CAS and the NAS (Figure 7). The eastern margin of the formation in the CAS and NAS is a dissolution edge, whereas the rest of the edge is depositional. Within the CAS, the Cold Lake Formation has a smaller areal extent than the underlying evaporitic deposits. Like the underlying units, the southern boundary is constrained by the Meadow Lake Escarpment (Figures 6, 7). In the NAS, the extent of the Cold Lake Formation more or less coincides with that of the underlying Ernestina Lake Formation. Three wells penetrate Precambrian basement highs over which the Cold Lake Formation is missing (Figure 9, wells 02-25-116-08W6, 06-28-111-04W6, 08-24-111-03W6).

There is a small depositional outlier of the Cold Lake Formation in the far northwestern part of the province, which trends into northeastern British Columbia (Figures 2, 9, wells 12-17-117-11W6, 01-29-117-10W6).

Nonhalite interbeds were not correlated within the Cold Lake Formation as they lack continuity from well to well, similar to the underlying Lotsberg Formation. Above the red bed, Cold Lake halite is often uninterrupted by nonhalite beds, especially in the CAS (Figure 6). There tends to be more interbedding within the NAS (Figure 9).

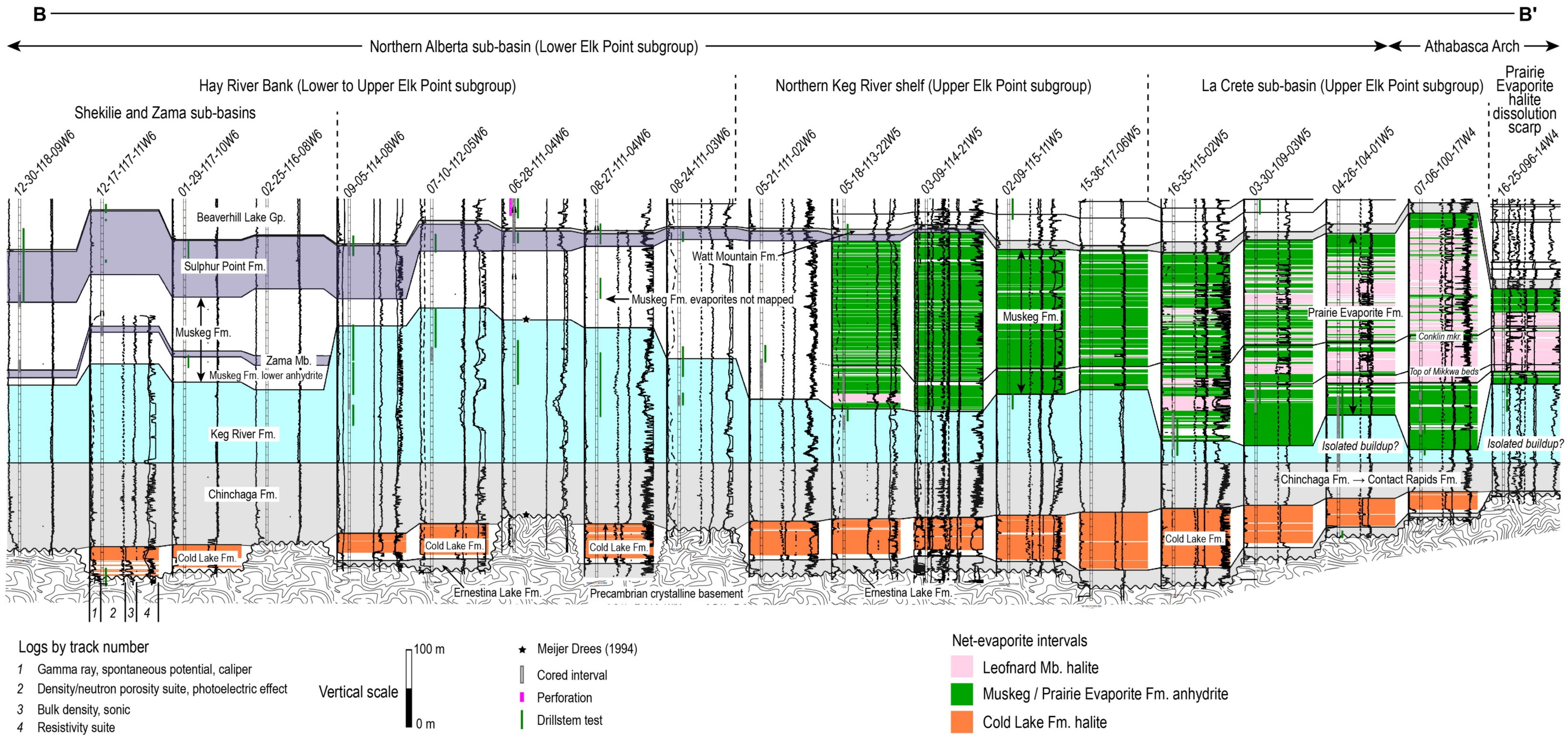


Figure 9. Stratigraphic cross-section B–B'. The cross-section runs northwest–southeast across the northern Alberta sub-basin, from the Presqu'ile Barrier in the far northwest to Prairie Evaporite halite dissolution scarp in the northeast (Figure 1). Net-evaporite intervals are colour-coded according to the legend. The Keg River Formation is highlighted in light blue, and the Sulphur Point Formation in purple. The remaining Elk Point Group nonevaporite strata are coloured light grey. The location of stratigraphic picks from Meijer Drees (1994) are highlighted. Abbreviation: mkr., marker bed.

5.1.1.5 Contact Rapids and Chinchaga Formations

The Contact Rapids and Chinchaga formations occupy the same stratigraphic level, but vary lithologically. The Contact Rapids Formation comprises dolomitic shale and argillaceous dolomite and is present over east-central and southeastern Alberta (Figure 7). These facies interfinger gradually with the predominantly anhydritic Chinchaga Formation in the northern part of the province (Figure 2). The transition occurs north of the Peace River–Athabasca Arch in the NAS. The boundary roughly approximates a west-trending paleoshoreline (Meijer Drees, 1986a). The Chinchaga Formation comprises interbedded dolomitic anhydrite and anhydritic dolomite (Meijer Drees, 1986a). The anhydrite of the Chinchaga Formation persists for a considerable distance southeastwards, and forms a relatively thin facies above the dolomitic shales of the Contact Rapids Formation (Figure 9). This relationship records the transgression within the basin, a transition into a marine environment where the overlying carbonate rocks of the Keg River Formation were deposited (Figure 2).

Strata of the Contact Rapids Formation thin over the Meadow Lake Escarpment in southern Alberta where they merge with the Ashern Formation (Meijer Drees et al., 2002). Due to similarity in log signatures, the Contact Rapids and Ashern formations are not mapped separately (Figures 6–8). Northwest of the Meadow Lake Escarpment and outside of the CAS (Figure 7), correlation of Contact Rapids Formation strata is difficult because the overlying carbonate rocks of the Keg River Formation transition to increasingly siliciclastic facies along the margins of the WAR. Additionally, it is difficult to pick the contact between shaly strata of the Contact Rapids Formation and the underlying shaly strata of the Cambrian succession (Figure 8, well 02/06-23-024-13W4).

Dolomitic shale of the Contact Rapids Formation interfingers with arkosic sandstone of the Granite Wash near the PRA. The thickness of the Granite Wash sandstone increases westwards along the flank of the arch, where modern log suites are needed to accurately differentiate the sandstone from the Contact Rapids shale, which is possible due to the shale’s high gamma-ray response (Figure 10). North of the arch, strata of the Chinchaga Formation interfinger with the Granite Wash in a similar manner; however, a lowermost sandy facies mapped as the Granite Wash can be distinguished for some distance away from the PRA (Figure 11).

5.1.2 Upper Elk Point Subgroup

5.1.2.1 Keg River and Winnipegosis Formations

The Keg River Formation and stratigraphically equivalent Winnipegosis Formation, which are the lowermost units of the upper Elk Point subgroup (Figure 2), mark a significant change in the Elk Point Basin. Underlying strata were predominantly deposited in evaporitic settings, with carbonate rocks being devoid of significant faunal diversity, indicating restricted conditions. The carbonates of the Keg River and Winnipegosis formations are of the open-marine variety, and record a significant transgression of Middle Devonian seas onto the cratonic margin of Laurentia. The Keg River and Winnipegosis formations are commonly subdivided into informal lower and upper members in Alberta and Saskatchewan (Campbell, 1992). The first carbonate deposition during initial relative sea-level rise was surprisingly uniform across the Elk Point Basin of Alberta. A consistent lower Keg River ramp blankets the Contact Rapids and Chinchaga formations. Across much of Alberta this ramp records two shoaling-upwards phases (Chow et al., 1995). A lowermost shoaling-upwards phase is overlain by a second shoaling-upwards phase, which includes a basal succession of thin bituminous laminites (laminated lime mudstones) with abundant styliolinids, called the ‘bituminous marker’ by Chow et al. (1995) on account of its consistent, correlatable log signature. The laminites grade upwards into nonbituminous, fossil-rich carbonates (Chow et al., 1995). Together these units comprise the lower Keg River member (Figure 2). The bituminous laminites persist at least as far south as well 16-10-046-13W4 in southern Alberta, where they are recognized in core between 1612.3 and 1614.1 m. Meijer Drees et al. (2002) include this unit within the Cutknife Member (Figure 2), which is discussed below. The bituminous laminites vary in thickness, degree of interbedding with carbonates, and proportion of terrigenous clastics, the latter associated with the PRA (Chow et al., 1995).

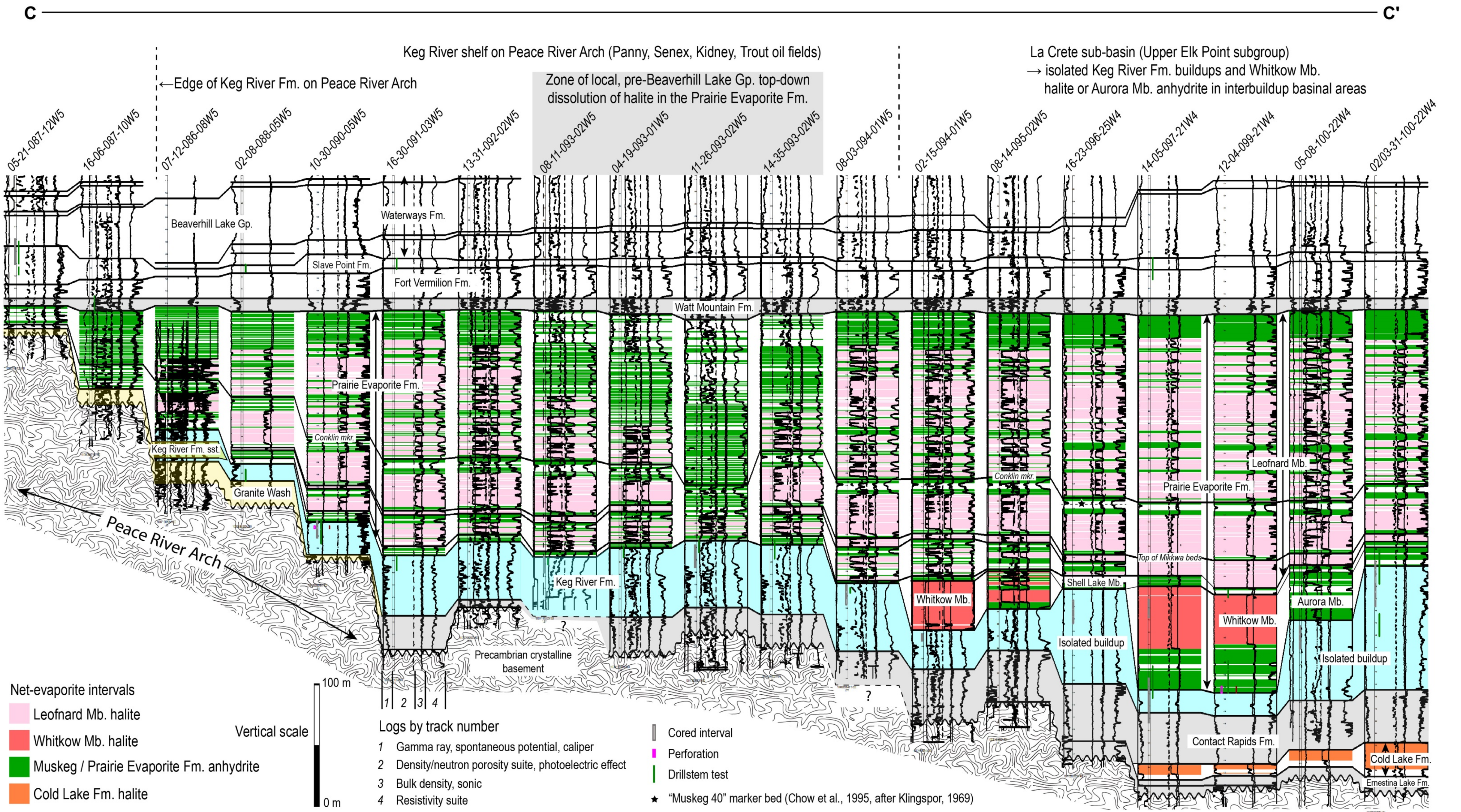


Figure 10. Stratigraphic cross-section C–C'. The cross-section runs southwest–northeast across the eastern flank of the Peace River Arch in north-central Alberta (Figure 1), highlighting an area of local top-down dissolution of halite in the Prairie Evaporite Formation. Net-evaporite intervals are colour-coded according to the legend. The Keg River Formation is highlighted in light blue. The remaining Elk Point Group nonevaporite strata are coloured light grey. The location of stratigraphic picks from Chow et al. (1995) are highlighted. Abbreviation: mkr., marker bed; sst., sandstone.

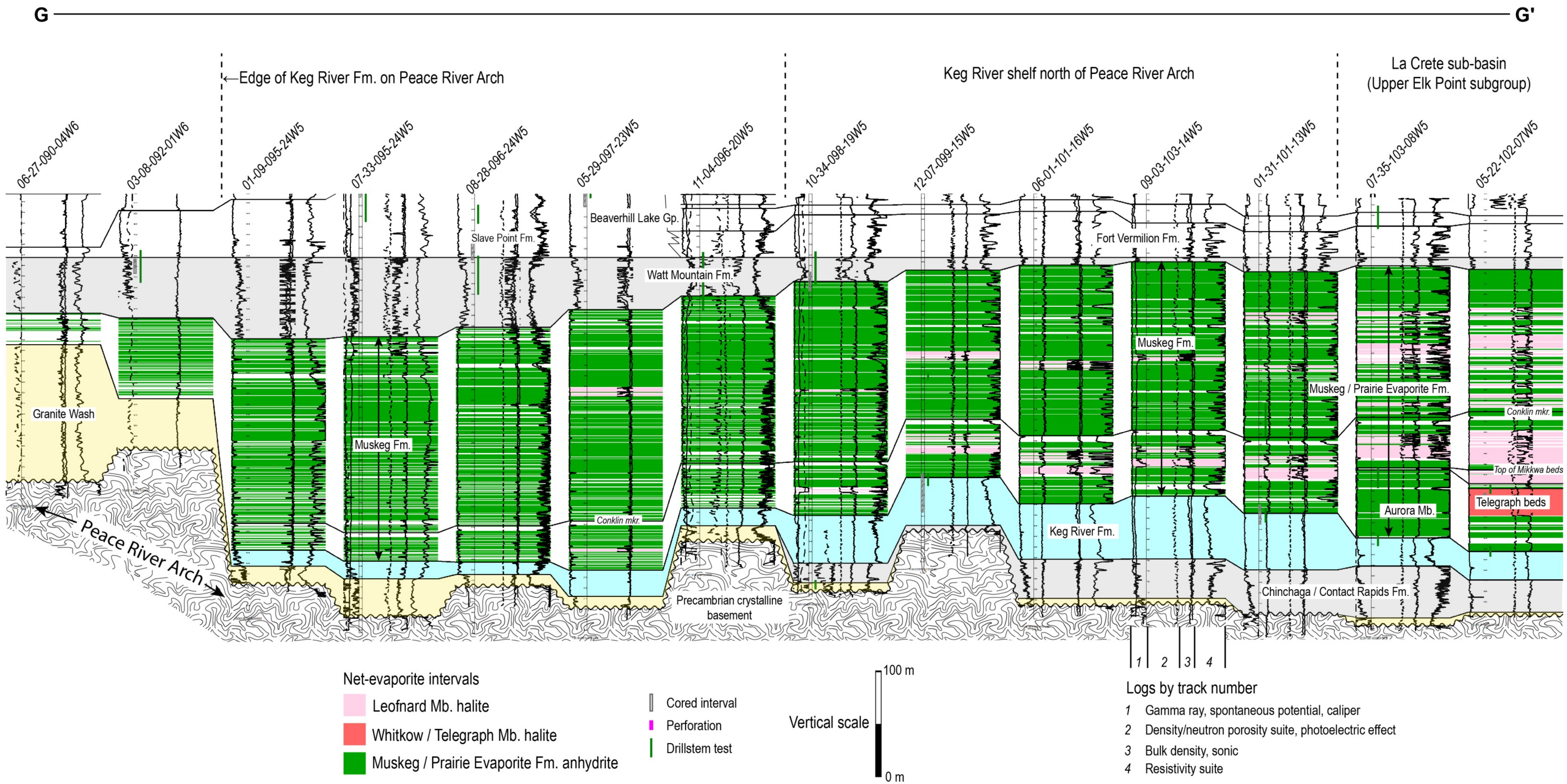


Figure 11. Stratigraphic cross-section G–G'. The cross-section runs southwest–northeast from the northern flank of the Peace River Arch to the northern part of the La Crete sub-basin in north-central Alberta (Figure 1). Net-evaporite intervals are colour-coded according to the legend. The Keg River Formation is highlighted in light blue. The remaining Elk Point Group nonevaporite strata are coloured light grey.

Deposition of the upper Keg River Formation member was mostly constrained to basement highs, such as the shelf margin flanking the La Crete sub-basin on the eastern flank of the PRA (Chow et al., 1995, Figure 13) and along the Presqu'ile Barrier, or to a series of sub-basins, where it was deposited as isolated buildups. The sub-basins include the well-known Zama, Rainbow, and Shekilie sub-basins southeast of the Presqu'ile Barrier on the Hay River Bank (Moore, 1993), where the Keg River hosts hydrocarbons (Figure 12), and the less-well defined La Crete sub-basin in northeastern Alberta (e.g., Bebout and Maiklem, 1973, Figure 29). The La Crete sub-basin is much more extensive than the smaller sub-basins on the Hay River Bank and contains a large number of isolated buildups, commonly referred to as mounds, owing to abundant algae and apparent lack of framework builders. The work of Rogers (2017) shows that upper Keg River buildups in the La Crete sub-basin include both linear banks and pinnacle-like buildups, with true framework components consisting in part of solenoporoid chaetetid sponges along the margins of the banks and the isolated buildups. The location and morphology of isolated buildups in the La Crete sub-basin are mostly poorly constrained due to a general lack of well control, although a number of wells penetrate thick upper Keg River buildups (Figures 6, 9, 10, 13). Figure 14 shows the known distribution of buildups within the La Crete sub-basin based on current well control (bull's-eye patterns). From these data alone it cannot be determined whether the buildups comprise bank-like or pinnacle-like features. Rogers (2017, Figure 28) has shown that three-dimensional seismic can greatly enhance the understanding of the location and morphology of upper Keg River buildups.

The Keg River Formation is much more consistent in thickness outside of the sub-basins, lacking isolated buildups and interbuildup basinal areas (Figure 14). North of the La Crete sub-basin and the PRA, the Keg River isopach gradually thickens towards the northwest, where the carbonate succession bordered the open ocean. Carbonate units of the Keg River eventually coalesced to form the Presqu'ile Barrier, creating restricted conditions in the Elk Point Basin within the cratonic interior. The transition from open-marine conditions to restricted, evaporitic conditions (Prairie Evaporite and Muskeg formations succession) is recorded in a complex series of deposits above the Keg River southeast of the Presqu'ile Barrier (e.g., Rogers, 2017). The uniform thickness of the shelflike deposits of the Keg River persists towards the steeper, northern flank of the PRA (Figure 11).

Consistency in Keg River Formation thickness changes significantly as the formation onlaps the eastern flank of the PRA. The thickness of the Keg River is affected by paleotopography on the PRA; the unit thins near to, and is missing over, a few basement highs (Figures 12, 14). In general, paleotopography on the basement is most conspicuous along the Peace River–Athabasca Arch, and likely affects the distribution and type of Keg River buildups as far east as the border with Saskatchewan. Near the maximum onlap edge on the PRA, Keg River strata include a sandstone unit known as the Keg River sandstone, which records a pulse of siliciclastic input from the PRA (Figure 10, well 07-12-086-08W5).

Outside of the La Crete sub-basin and south of the PRA, the Keg River Formation is more uniform in thickness, but gradually thins towards southern Alberta where it overlies a thin Contact Rapids Formation and eventually rests directly on Ordovician carbonate rocks (Figures 8, 15). One local anomaly occurs on the shelf in central Alberta where Keg River strata are missing in one well near Twp. 62, Rge. 11, W 4th Mer. (Figure 14). The anomaly is accompanied by facies variations in the Ernestina Lake Formation, and thickness irregularities in the Lower Elk Point subgroup evaporite successions (Hauck et al., 2018b).

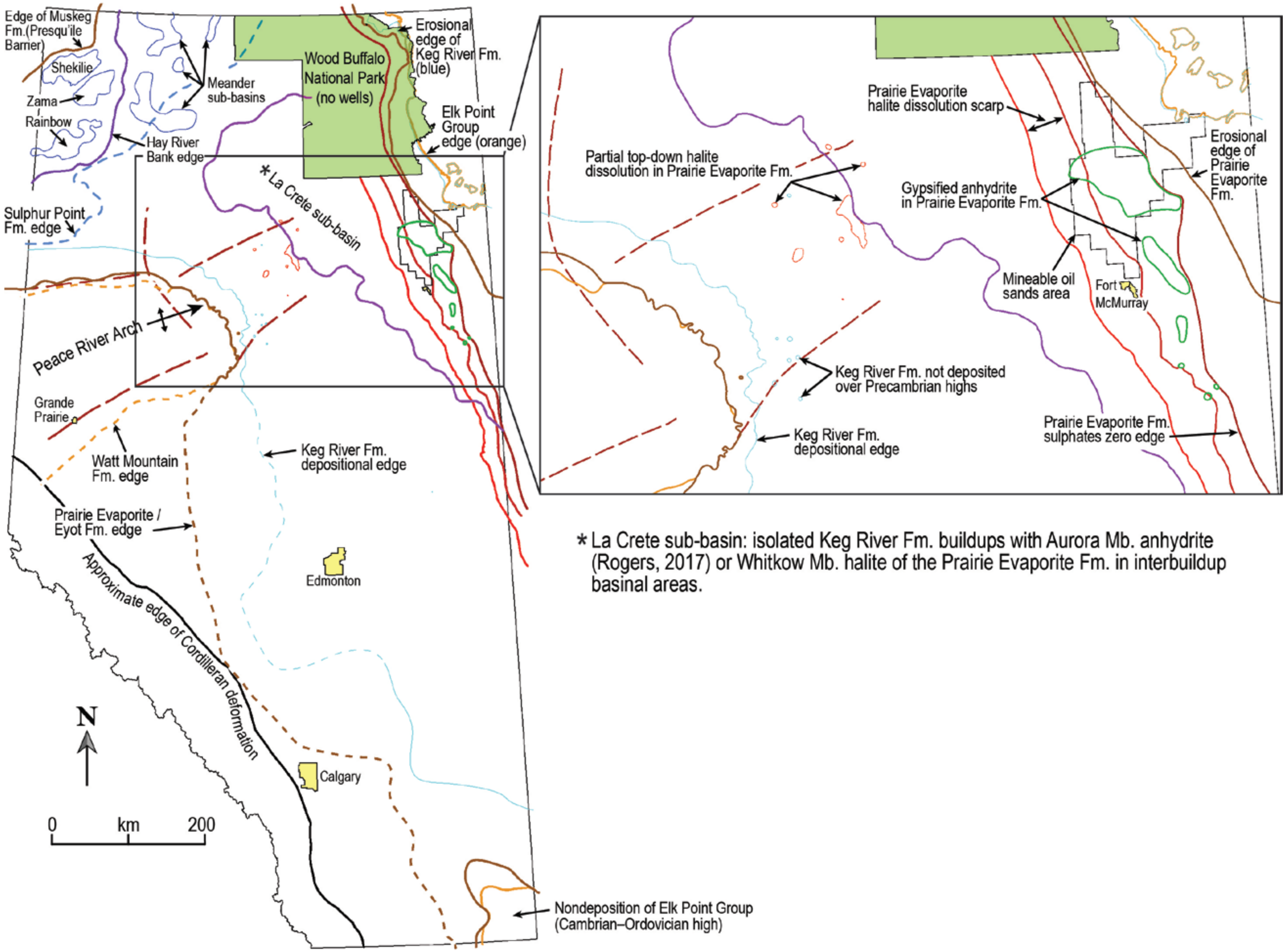


Figure 12. Depositional and erosional edges for upper Elk Point Group strata in the Alberta Basin. Edges include the location of the La Crete sub-basin, a feature of the Keg River to Prairie Evaporite formations succession. The Shekilie, Zama, and Rainbow sub-basins located on the Hay River Bank are from Davies and Smith (2006). The inset details areas of regional evaporite karst (Prairie Evaporite halite dissolution scarp), local-scale evaporite karst on the eastern flank of the Peace River Arch, and gypsum deposits associated with hydration of anhydrite (gypsified anhydrite) along the basin margin. The inset also highlights areas of Keg River Formation nondeposition over Precambrian basement highs associated with the Peace River Arch. Dashed lines show approximate location of formation edge. Red long-dash lines outline the Peace River Arch (from O'Connell, 1994).

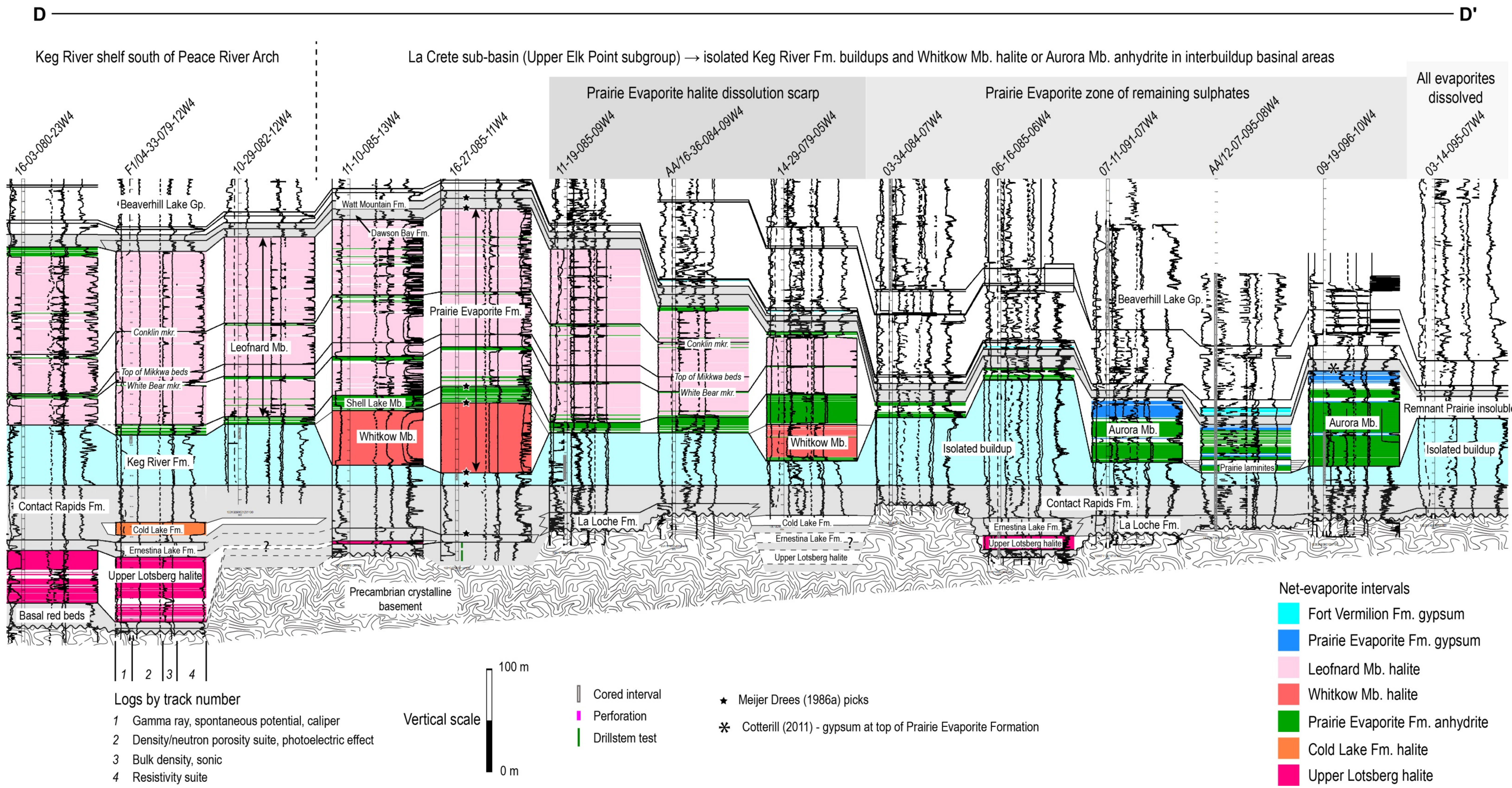


Figure 13. Local stratigraphic cross-section D–D'. The cross-section runs southwest–northeast across the Prairie Evaporite halite dissolution scarp in northeastern Alberta (Figure 1). Net-evaporite intervals are colour-coded according to the legend. The Keg River Formation is highlighted in light blue. The remaining Elk Point Group nonevaporite strata are coloured light grey. The location of stratigraphic picks from Meijer Drees (1986a), and gypsum occurrence from Cotterill (2011) are highlighted.

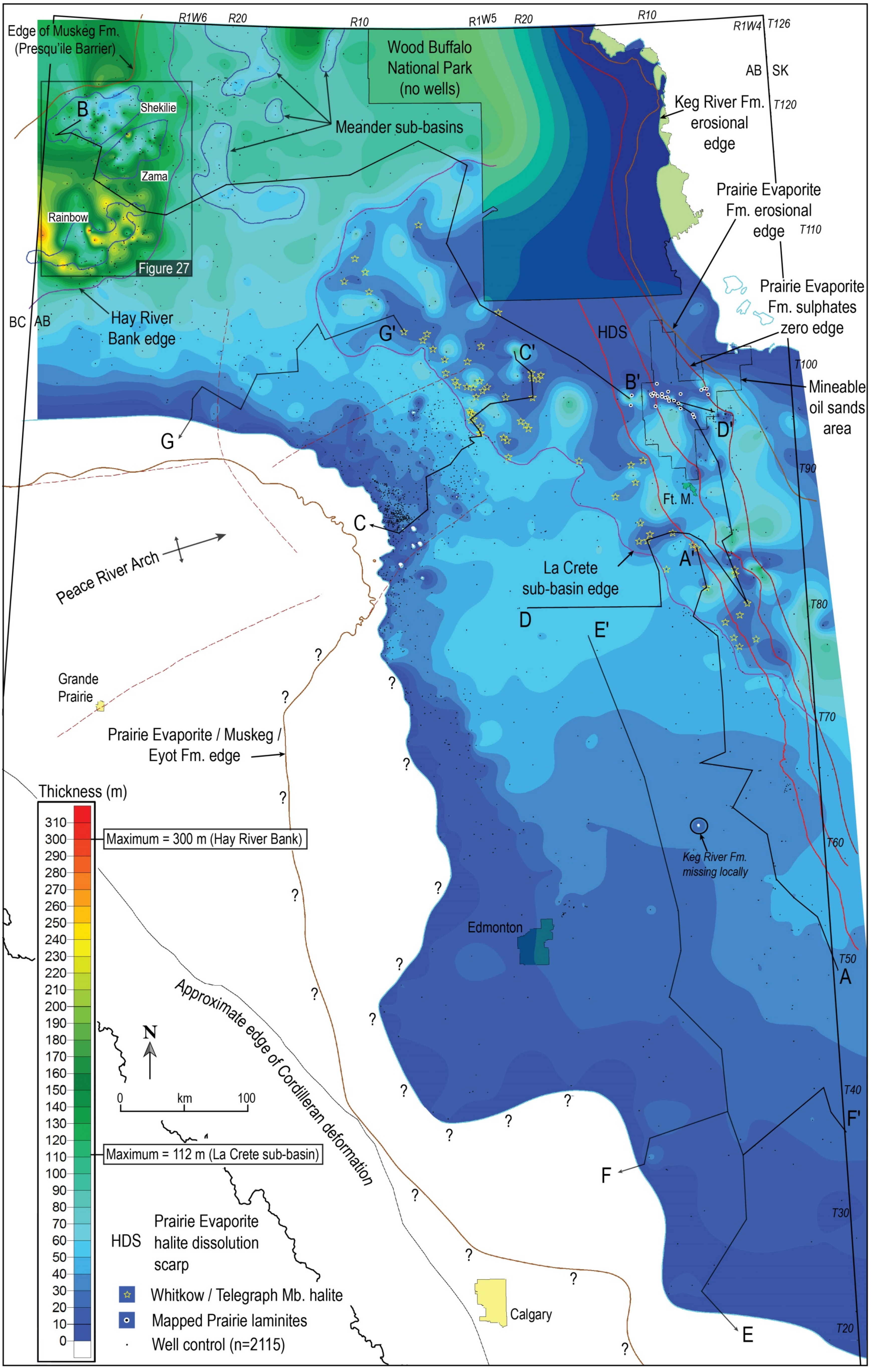


Figure 14. Isopach map of the Keg River Formation with paleogeographic elements and lines of cross-section, Alberta. Reddish purple short-dash lines outline the Peace River Arch (from O'Connell, 1994). The Shekilie, Zama, and Rainbow sub-basins located on the Hay River Bank are from Davies and Smith (2006). Abbreviation: Ft. M., Fort McMurray.

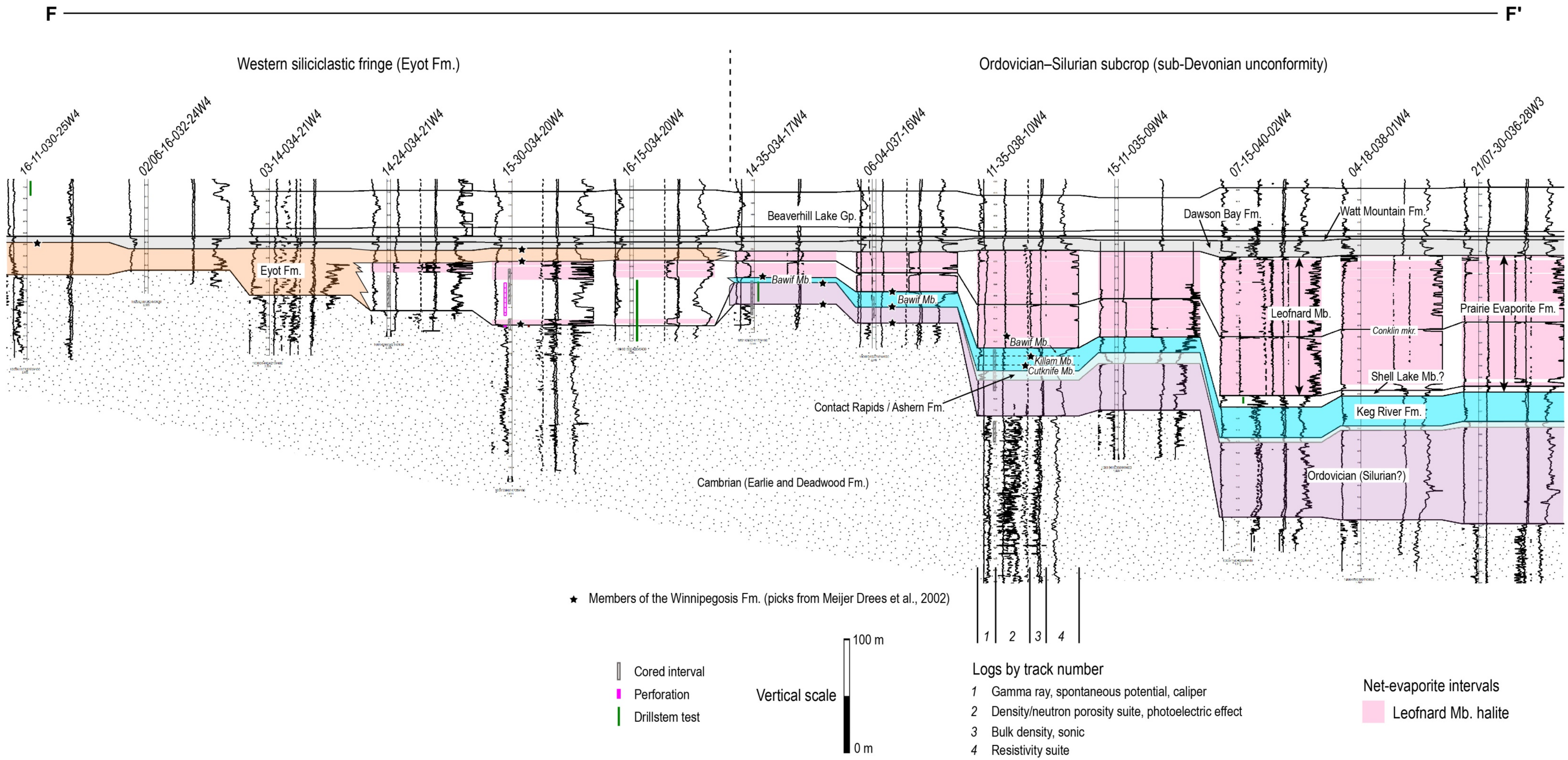


Figure 15. Stratigraphic cross-section F–F'. The cross-section runs west–east in southern Alberta (Figure 1), from Cambrian siliciclastics to Ordovician carbonates at the sub-Devonian unconformity. Net-evaporite intervals are colour-coded according to the legend. The Keg River Formation is highlighted in light blue, and the mixed siliciclastic rocks and anhydrite of the Eyot Formation in orange. The remaining Elk Point Group nonevaporite strata are coloured light grey. The location of stratigraphic picks from Meijer Drees et al. (2002) are highlighted.

South of the PRA and west of the La Crete sub-basin, the Keg River shelf gradually transitions to clastic- and anhydrite-dominated facies towards the WAR. Meijer Drees et al. (2002) introduced a number of members of the Winnipegosis Formation to capture these changes. In ascending stratigraphic order, these are the Eyehill, Cutknife, Killam and Bawif members (Figures 2, 8, 15). According to Meijer Drees et al. (2002), the lowermost Eyehill Member is equivalent to the lower Keg River Formation in northeastern Alberta and the lower Winnipegosis Formation in Saskatchewan. The Cutknife Member is equivalent to the upper Winnipegosis and Keg River formations. The Killam and Bawif members are correlative with the Shell Lake Member of the Prairie Evaporite Formation yet, somewhat problematically, Meijer Drees et al. (2002) assigned them to the Winnipegosis Formation. Whereas the lower two members are carbonate rocks, the upper two members comprise anhydritic dolostone (Killam) and dolomitic shale, siltstone, and anhydrite (Bawif), which are similar to facies found in the Shell Lake Member of the Prairie Evaporite Formation.

5.1.2.2 Prairie Evaporite, Muskeg, and Eyot Formations

Keg River Formation carbonates along the Presqu'ile Barrier eventually built up to a point that they significantly impeded the flow of open-marine waters onto the cratonic margin to the southeast. The open-ocean connection in west-central Alberta was impeded by the PRA, and by the WAR in southwestern Alberta. This restriction led to the shutdown of Keg River growth within the Elk Point Basin, and a transition to evaporitic conditions across much of western Laurentia. Evaporite strata in the Alberta portion of the Elk Point Basin include the anhydrite-dominated Muskeg Formation bordering and southeast of the Presqu'ile Barrier, the halite-dominated Prairie Evaporite Formation farther to the southeast, and anhydrite- and siliciclastic-dominated strata of the Eyot Formation south of the PRA bordering the WAR (Figure 2).

Figure 16 shows the thickness of the Prairie Evaporite Formation and equivalent strata within Alberta. Unlike the underlying evaporitic successions that are confined to paleotopography on the sub-Devonian unconformity, these strata are extensive across the province. Gross facies changes reflect the influence of distance to the open-ocean connection (Muskeg Formation), and siliciclastic inputs (Eyot Formation). The thickest portions of the Prairie Evaporite and/or Muskeg formations succession occur within northern Alberta south of the Hay River Bank and north of the PRA, and more markedly within the La Crete sub-basin (Figure 16). Thick deposits southeast of the Hay River Bank comprise predominantly anhydrite of the Muskeg Formation (Figure 9). The gradual transition between Muskeg anhydrite and Prairie Evaporite halite is recorded within the northwestern part of the La Crete sub-basin (Figure 9).

Upper Keg River buildups within the La Crete sub-basin strongly influence the thickness of the Prairie Evaporite and/or Muskeg formations succession, with thickening occurring within interbuildup basinal areas (compare Figures 14, 16). Within the interbuildup basinal areas, lower Prairie Evaporite Formation strata include basin-centred halite deposits of the Whitkow Member (Figure 2). Whitkow Member halite is partly equivalent to the Telegraph Member halite of Klingspor (1969), with the latter being partly equivalent to the lower part of the Leofnard Member (Figure 2). Whitkow Member halite is relatively pure, lacking significant nonhalite interbeds (Figures 6, 10, 11, 13). The Whitkow Member is in lateral facies contact with anhydrite of the Aurora Member within the interbuildup basinal areas (Rogers, 2017). The Aurora anhydrite appears to flank upper Keg River buildups, with the Whitkow halite forming predominantly within the centre of the interbuildup basinal areas (Rogers, 2017). In northeastern Alberta, the Whitkow halite may overlie a finely laminated bituminous, organic-rich carbonate and anhydrite called the Prairie laminites of the Prairie Evaporite Formation. The Prairie laminites are restricted to the deepest portions of the interbuildup basinal areas, where the lower Keg River is thinly developed. In Saskatchewan, similar laminate facies at the base of interbuildup basinal areas are known as the Ratner Member of the Winnipegosis Formation (Reinson and Wardlaw, 1972; Davies and Ludlam, 1973). However, the name Prairie laminites (Figure 2) is used in this study as, despite the similarity in stratigraphic position within the interbuildup basinal areas and general facies, the stratigraphic relationship with the Ratner Member of Saskatchewan is poorly understood (Rogers, 2017).

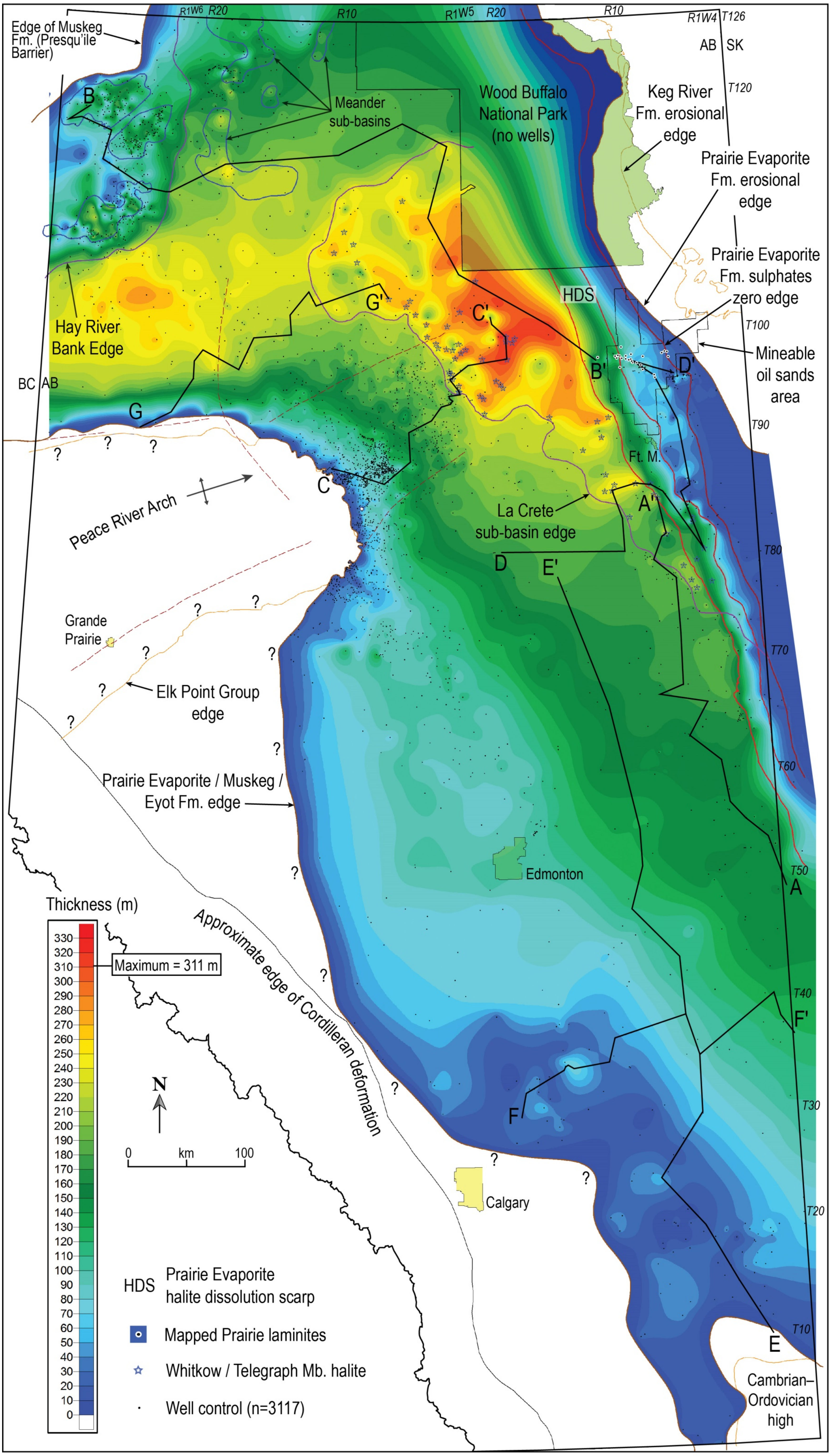


Figure 16. Isopach map of the Prairie Evaporite, Muskeg, and Eyot formations with paleogeographic elements and lines of cross-section, Alberta. Reddish purple short-dash lines outline the Peace River Arch (from O'Connell, 1994). Abbreviation: Ft. M., Fort McMurray.

Within the La Crete sub-basin in northeastern Alberta, the top of the upper Keg River Formation buildups and the interbuildup evaporites are overlain by the Shell Lake Member of the Prairie Evaporite Formation (Figures 2, 13). The Shell Lake comprises anhydrite, carbonate, and shale that record a pause in evaporitic drawdown within the Elk Point Basin—a significant incursion of marine waters. In Saskatchewan, the pause in evaporitic drawdown is accompanied by deposition of the carbonate Quill Lake marker beds within the Shell Lake, which extend outwards from the upper Keg River buildups (Reinson and Wardlaw, 1972). The Quill Lake marker beds are less well-developed in Alberta and are difficult to correlate. The Shell Lake is difficult to correlate northwestwards because of the overall increase in anhydrite within the interbuildup basinal areas of the La Crete sub-basin.

The upper Prairie Evaporite Formation interval comprises the laterally extensive Leofnard Member (Figure 2). The Leofnard comprises halite with minor anhydrite, carbonate, and shale interbeds within much of the southern portion of the La Crete sub-basin and within southern Alberta (Figures 6, 8, 13). Leofnard halite becomes markedly interbedded with anhydrite and clastics towards the eastern flank of the PRA (Figure 10), and highly interbedded with anhydrite and carbonates towards the transition with the Muskeg Formation in the northern part of the La Crete sub-basin (Figure 9). The halite gradually gives way to interbedded anhydrite and carbonates of the Muskeg towards the Presqu'ile Barrier (Figures 9, 11). In western Alberta, south of the PRA, the Prairie Evaporite transitions gradually to interbedded anhydrite, carbonate, and shale of the Eyot Formation (Figure 15). In southern Alberta, outside of the La Crete sub-basin, the Prairie Evaporite interval is made up predominantly of the Leofnard Member, which rests directly on Shell Lake Member or Keg River (Winnipegosis) strata, and eventually directly on Ordovician carbonates (Figures 6, 8) or Cambrian clastics (Figure 15). In southeasternmost Alberta, the Prairie Evaporite is missing over a paleotopographic high that comprises both Ordovician carbonates and Cambrian clastics at the sub-Devonian unconformity (Figures 8, 16).

Given the large areal extent of the Leofnard Member and its equivalents within the Muskeg Formation, a number of regional marker beds have been correlated within the unit over a large part of the province (e.g., Meijer Drees, 1994; Hauck et al., 2017). Additionally, a number of 'beds' have been used to parse the interval within the transition zone between the Prairie Evaporite and Muskeg formations (Klingspor, 1969; Figure 2). Within the Leofnard Member, the two most well-developed marker beds have been mapped extensively: the White Bear (Holter, 1969) and Conklin (Hauck et al., 2017; equivalent to the Muskeg 40 marker bed of Klingspor, 1969). The Conklin marker bed is the most widespread, with correlations suggesting it can be mapped from southern Alberta northwards well into the northern Keg River shelf behind the Hay River Bank (Figures 6, 8–11, 13, 15). These regional marker beds record significant pauses in evaporitic drawdown within the Alberta portion of the Elk Point Basin.

In addition to the regionally extensive, basin-margin Prairie Evaporite halite dissolution scarp (Figure 16), other areas with more local-scale patterns of dissolution are noted (Figures 12, 16). Dissolution occurs within halite of the Leofnard Member along the eastern flank of the PRA. Minor dissolution occurs within the western part of the La Crete sub-basin, whereas more marked dissolution occurs above the Keg River shelf immediately west of the La Crete sub-basin (Figure 12).

5.1.2.3 Sulphur Point Formation

The Sulphur Point Formation is mapped as a carbonate that rests above, and is laterally gradational with, anhydrite of the Muskeg Formation near the Presqu'ile Barrier and generally overlying the Hay River Bank (Figures 9, 12). Facies are dominated by peritidal deposits, which have been variably overprinted by multiple stages of dolomitization (Lonnee and Al-Aasm, 2000). The Sulphur Point forms a carbonate wedge that thins southeastwards to a zero edge that is slightly more extensive than the Hay River Bank (Figure 9). The carbonate rocks are unconformably overlain by siliciclastic rocks of the Watt Mountain Formation (Figure 2).

5.1.2.4 Watt Mountain and Dawson Bay Formations

Deposits of the Watt Mountain Formation rest unconformably on the Prairie Evaporite, Muskeg, and Eyot formations across much of the province (Figure 2). The interval is relatively thin and uniform in thickness, comprising argillaceous shale and siltstone, with some dolomite and limestone (Law, 1955). The Gilwood Member of the Watt Mountain Formation is a clastic wedge comprising interbedded sandstone, shale, and conglomerate that fringe the PRA, representing marginal-marine deposition (Jansa and Fischbuch, 1974). The Gilwood Member was not mapped for this study (see Jansa and Fischbuch [1974] for detailed information on the unit).

The Dawson Bay Formation of Saskatchewan can be correlated into eastern Alberta as a distinct carbonate and anhydrite unit within shale of the Watt Mountain Formation (Figure 2). The shales above and below the Dawson Bay Formation are known as the First and Second red beds, respectively, within Saskatchewan (Dunn, 1982). The maximum depositional extent of these strata is difficult to delineate in Alberta; however, the top of the Dawson Bay Formation was mapped as a distinct surface within the Watt Mountain Formation (Figures 6, 8, 13, 15).

The Watt Mountain Formation becomes very thin over the Presqu'ile Barrier in northwestern Alberta, and can be difficult to correlate in this area (Figure 9). Where the anhydrite of the Fort Vermilion Formation of the overlying Beaverhill Lake Group was not deposited on the barrier, correlation of the Watt Mountain is aided by the location of the Steen marker bed within the Slave Point Formation of the Beaverhill Lake Group (Meijer Drees, 1994).

Deposits of the Watt Mountain Formation onlap the PRA in west-central Alberta and can be mapped beyond the extents of the underlying strata of the Prairie Evaporite and Muskeg formations, especially along the PRA's southern margin (Figure 12). In southeastern Alberta, the Watt Mountain Formation is missing over a Cambrian-Ordovician high, where deposits of the overlying Beaverhill Lake Group rest on the sub-Devonian unconformity (Figure 12).

5.2 Mapping of Evaporite Minerals

5.2.1 Lotsberg Formation

The distribution of halite deposits of the Lotsberg Formation mimics the bowl-shape of the CAS (Figure 3). The thickness of halite within the lower Lotsberg halite is presented in Figure 17. The isopach map represents the cumulative thickness of individual halite beds within the lower Lotsberg halite delineated through the net-evaporite method (see Section 4.2). Cumulative halite thickness is greatest in the centre of the CAS (75 m), gradually decreasing to a zero edge that falls almost entirely within Alberta. The proportion of halite within the lower Lotsberg ranges from a minimum of 36% to a maximum of 100%, averaging 87% (Table 2). The number of nonhalite interbeds is variable (Figure 6), with a measured maximum of 11 halite beds within a well (Table 2). The thickest recorded individual halite bed is just over 40 m.

Table 2. Measured halite parameters from evaporite successions in the Elk Point Group.

Formation	Halite Proportion (%)			Halite Bed Thickness (m)			Number of Halite Beds		
	Min.	Max.	Avg.	Min.	Max.	Avg. Max.	Min.	Max.	Avg. Max.
Prairie Evaporite and Muskeg (498 wells)	0.7	97.4	55.2	1.4	93.0	21.2	1	58	16
Cold Lake (244 wells)	13.9	96.6	73.9	0.6	58.4	23.3	1	17	4
Upper Lotsberg (133 wells)	61.8	100.0	88.9	1.6	82.4 (106.1)*	34.2	1	36	11
Lower Lotsberg (59 wells)	36.0	100.0	87.1	0.9	40.1	18.1	1	11	3

*Local anomaly; see text and Figures 18 and 19.

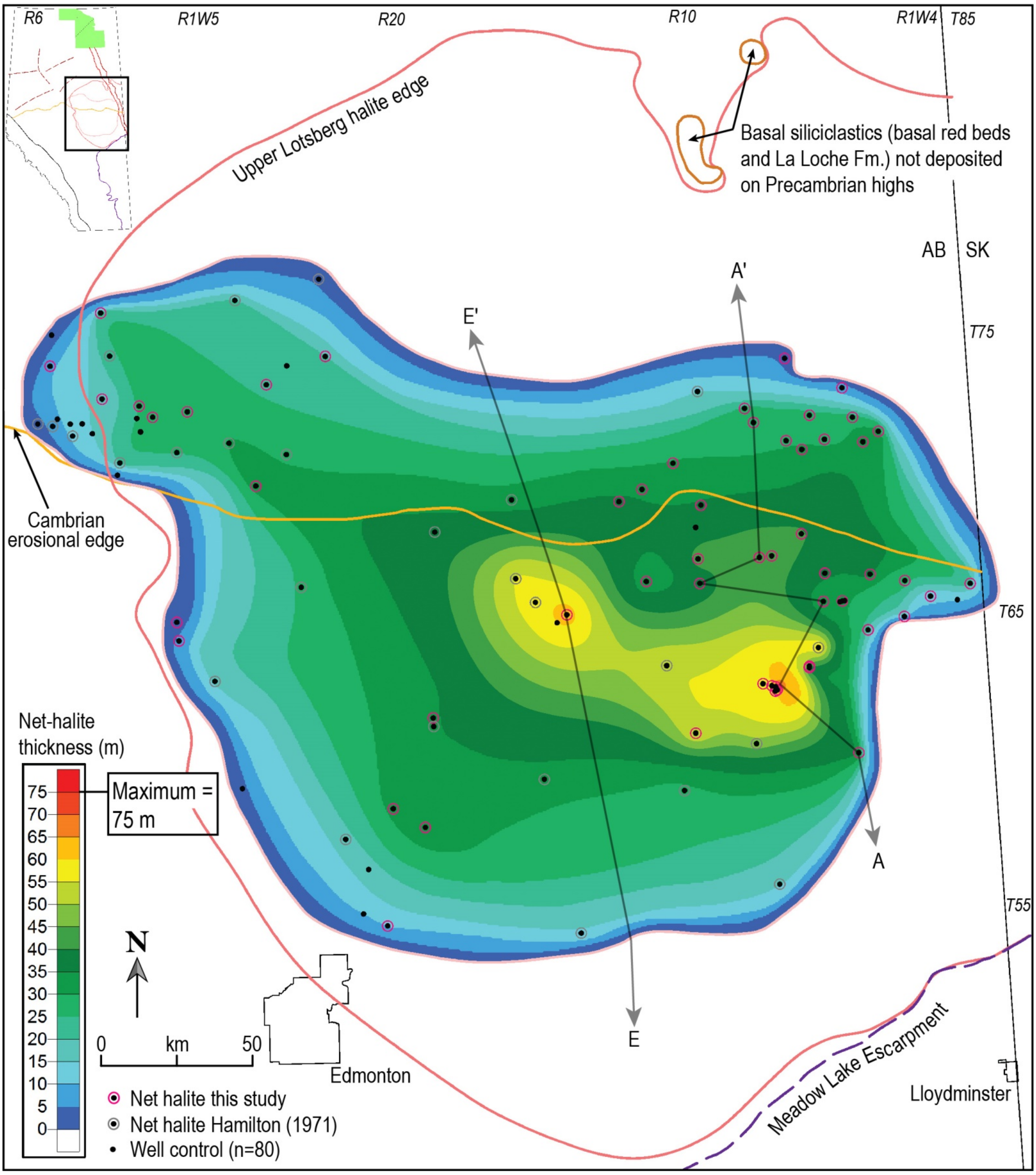


Figure 17. Cumulative halite thickness in the lower Lotsberg halite in the central Alberta sub-basin, east-central Alberta. Relevant lines of cross-section are shown.

The cumulative thickness of halite beds within the upper Lotsberg halite is greatest within the centre of the CAS (165 m, Figure 18). The deposits continue eastwards into Saskatchewan where they are partially dissolved near the basin margin (see Moore, 1993, Figure 4D.2). In addition to greater thickness, the upper Lotsberg has a higher minimum proportion of halite (61.8%) than the lower Lotsberg. Although the unit contains a larger number of nonhalite interbeds, the maximum individual halite bed thickness is considerable at 106.1 m (Table 2). However, this thick bed corresponds to a local anomaly that occurs in Twp. 62, Rge. 11, W 4th Mer. (Figures 18, 19), which is documented in Hauck et al. (2018b). Outside of this local anomaly, the maximum individual halite bed thickness is double that of the underlying lower Lotsberg halite at 82.4 m (Table 2). Nonhalite interbedding within the upper Lotsberg varies and individual interbeds are difficult to correlate (Figures 6, 8, 13).

An isopach map of maximum individual halite bed thickness for the upper Lotsberg halite is presented in Figure 19. This map represents the location of potentially contiguous, thick halite beds. These beds occur preferentially within the central part of the CAS. The average maximum halite bed thickness is 34.2 m (Table 2).

5.2.2 Cold Lake Formation

Halite of the Cold Lake Formation is present in the NAS and the CAS (Figure 20). The greatest cumulative thickness of halite (81.6 m) occurs in the NAS near the western border of Wood Buffalo National Park (Figures 20, 21). Thickness in the NAS gradually decreases away from this main depocentre; the eastern edge is a halite dissolution front. Strata of the Cold Lake Formation are missing in at least three locations penetrated by four wells in the NAS (Figure 21). These areas correspond to Precambrian basement highs (Figure 9, wells 06-28-111-04W6, 08-24-111-03W6).

In the CAS, the greatest cumulative halite thickness in the Cold Lake Formation occurs in easternmost central Alberta around Twp. 64, Rge. 2, W 4th Mer., which is east of the main depocentre for the underlying Lotsberg Formation (Figure 20). Cumulative halite thickness gradually decreases away from this depocentre; the eastern edge is a halite dissolution front paralleling the Prairie Evaporite halite dissolution front. The southern edge of Cold Lake halite strata corresponds to the location of the Meadow Lake Escarpment (Figure 20). The average proportion of halite in the Cold Lake Formation is 73.9% (Table 2). The maximum individual halite bed thickness is 58.4 m, which occurs in the NAS near the main depocentre.

5.2.3 Prairie Evaporite and Muskeg Formations

Halite deposits within the Prairie Evaporite and Muskeg formations form a southeast-trending fairway across the province of Alberta (Figure 22). These strata continue into southern Saskatchewan, where they form a sub-circular outline associated with the intracratonic Williston Basin (Meijer Drees, 1994, Figure 10.7). Within Alberta, the eastern edge of the halite deposits is abrupt at the regional scale, and is the result of halite dissolution (karstification) along the edge of the Phanerozoic sedimentary succession. This Prairie Evaporite halite dissolution scarp continues northwards into Wood Buffalo National Park—although the absence of well data means it cannot be accurately delineated there—and southwards into central Saskatchewan.

Patterns of cumulative halite thickness are strongly linked to the paleogeography of the underlying Keg River Formation. Cumulative halite thickness is greatest within the La Crete sub-basin and is associated with basinal areas surrounding upper Keg River buildups (Figure 22). Within the La Crete sub-basin, cumulative halite thickness reaches a maximum of 213 m (Figure 22). The high halite thickness in this area is associated with Whitkow Member halite within interbuildup basinal areas (Figures 13 [wells 11-10-085-13W4, 16-27-085-11W4], 23). Similar, but less thick halite accumulations occur throughout the La Crete sub-basin and all are associated with halite deposits of the Whitkow and Telegraph members in interbuildup basinal areas (Figures 22, 23). However, the thickness of these halite deposits decreases gradually to the northwest within the La Crete sub-basin.

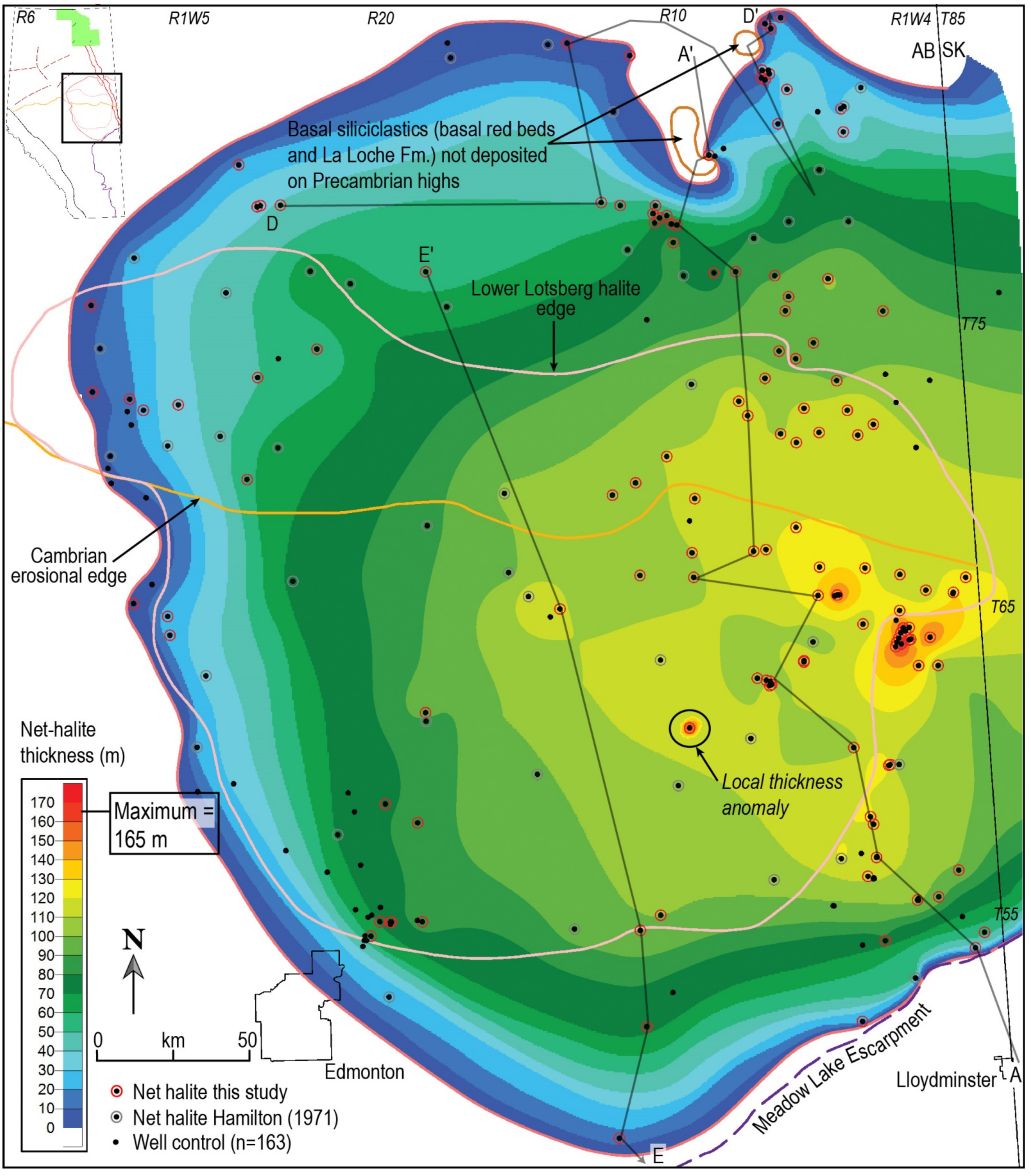


Figure 18. Cumulative halite thickness in the upper Lotsberg halite in the central Alberta sub-basin, east-central Alberta. Relevant lines of cross-section are shown.

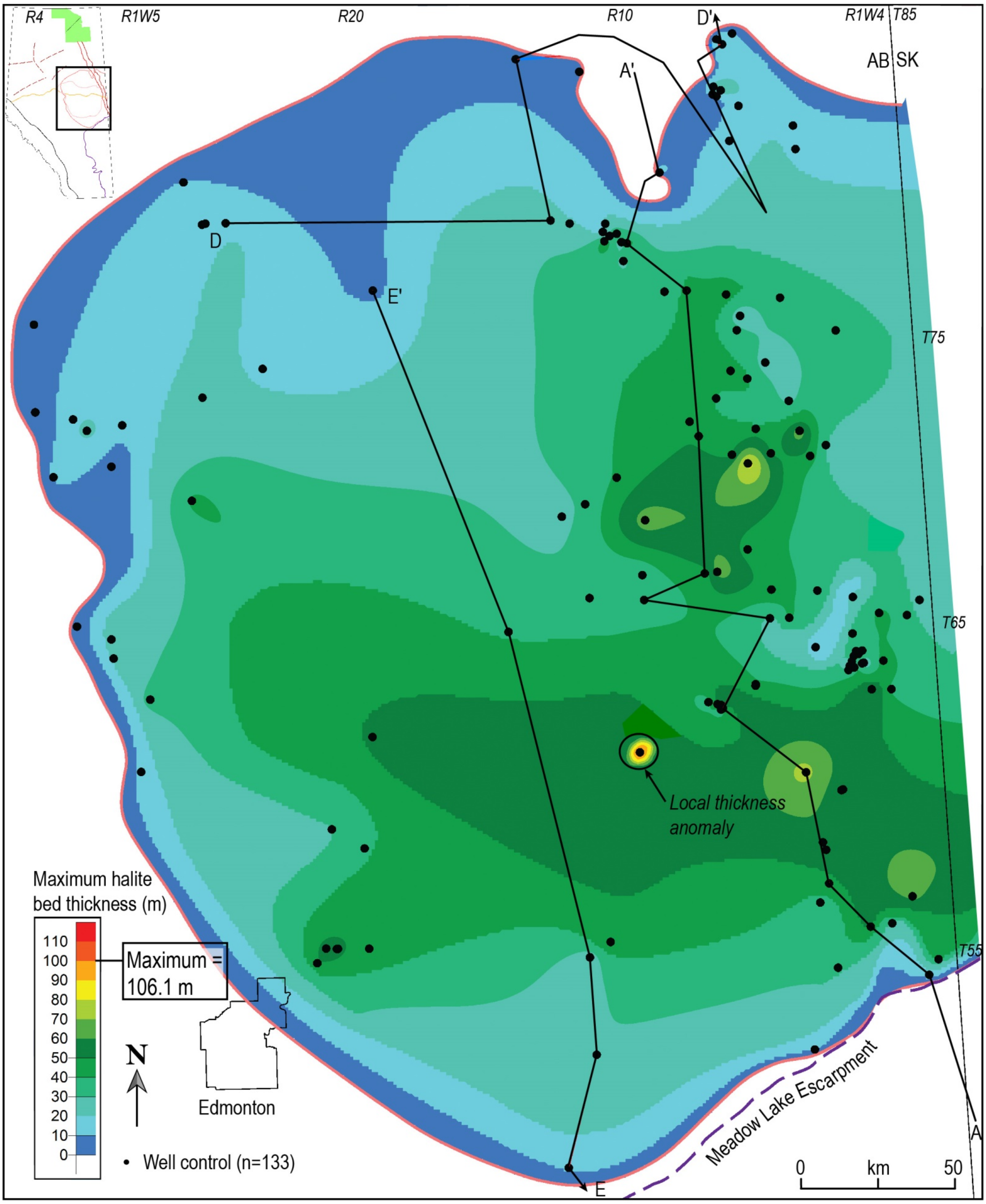


Figure 19. Maximum halite bed thickness in the upper Lotsberg halite in the central Alberta sub-basin, east-central Alberta. Relevant lines of cross-section are shown.

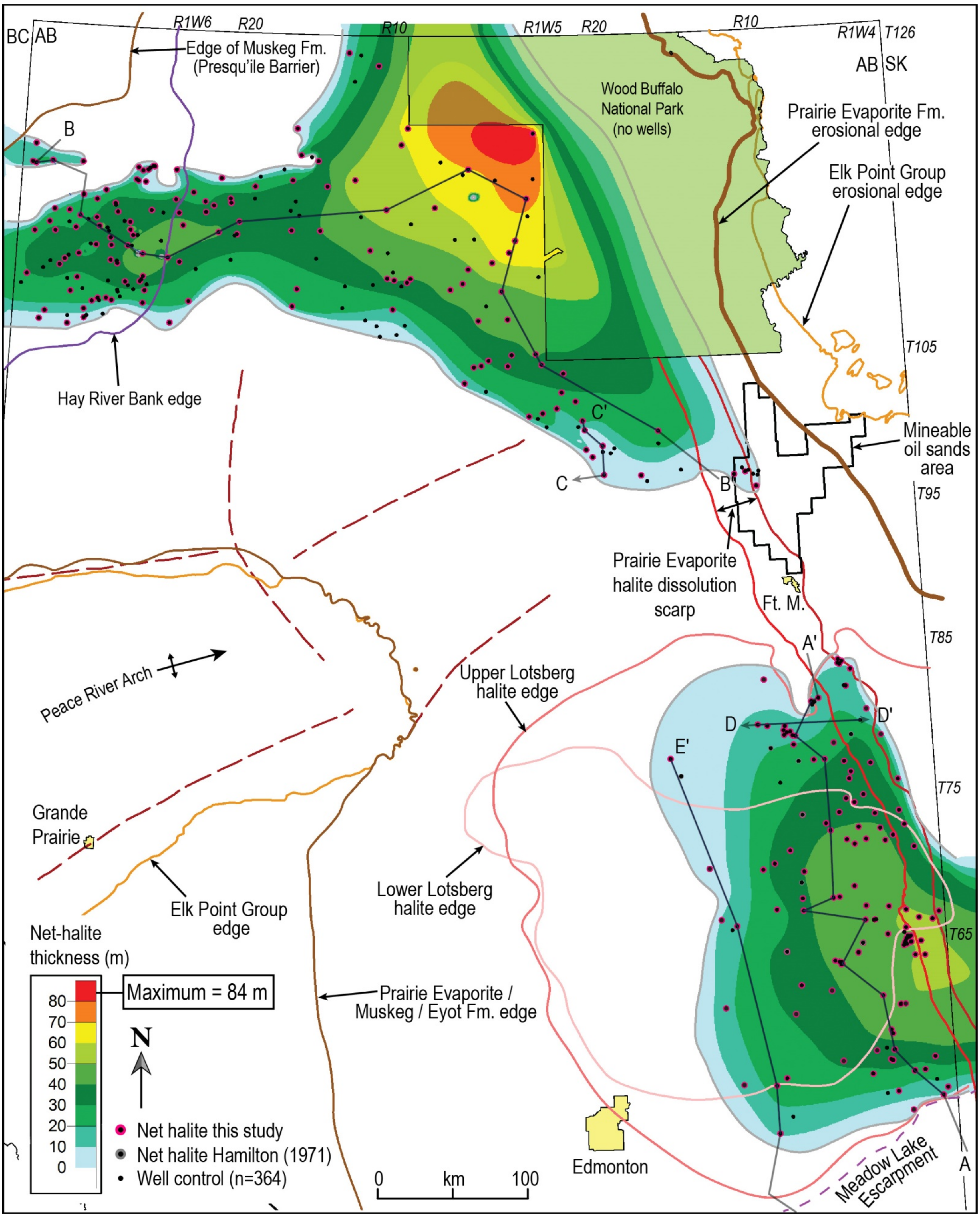


Figure 20. Cumulative halite thickness in the Cold Lake Formation in the central and northern Alberta sub-basins. Relevant lines of cross-section and paleographic elements are shown. Red long-dash lines outline the Peace River Arch (from O'Connell, 1994). Abbreviation: Ft. M., Fort McMurray.

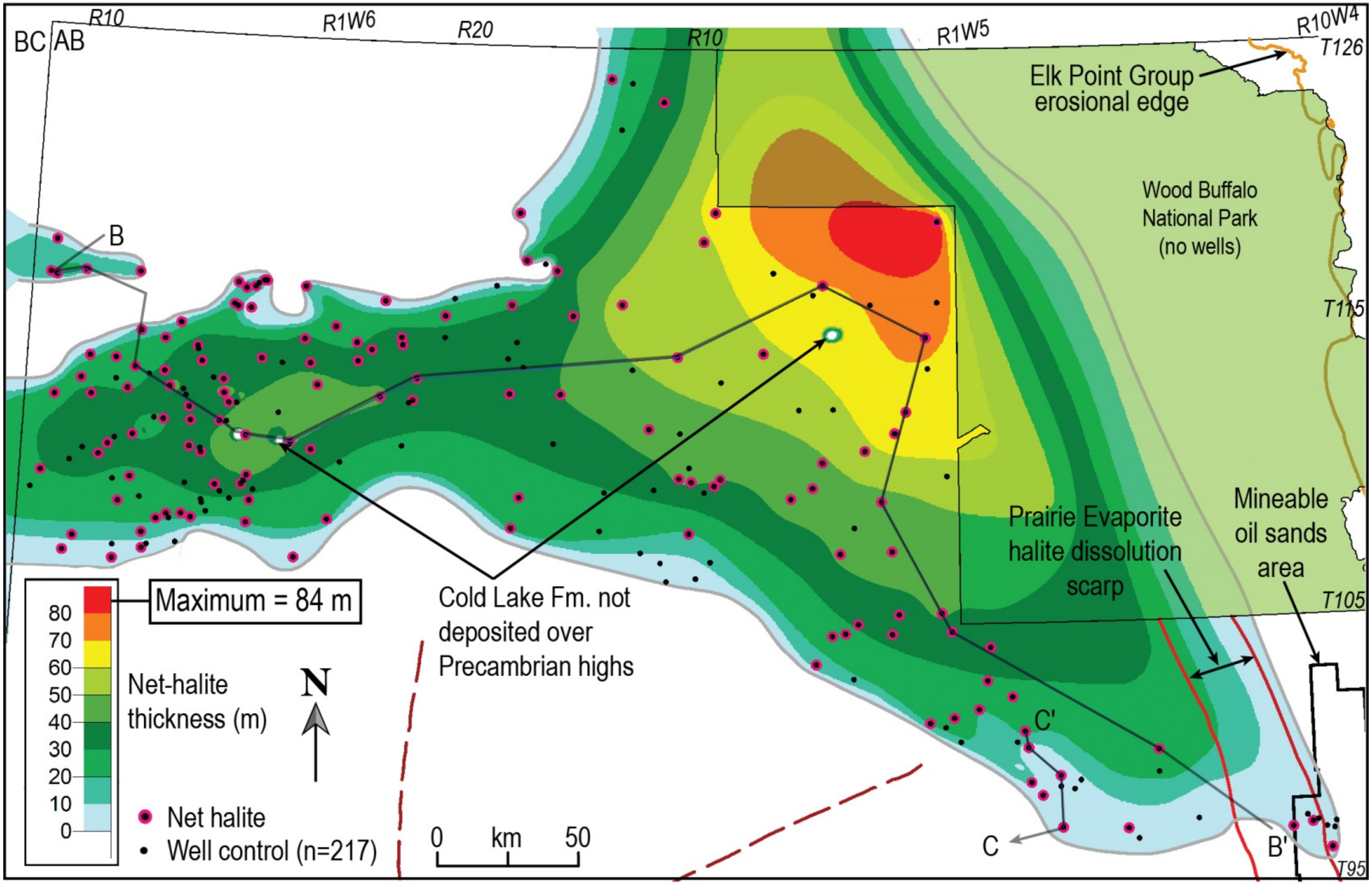


Figure 21. Cumulative halite thickness in the Cold Lake Formation in the northern Alberta sub-basin, highlighting areas of nondeposition of Cold Lake Formation over Precambrian basement highs. Relevant lines of cross-section are shown. Red long-dash lines outline the Peace River Arch (from O'Connell, 1994).

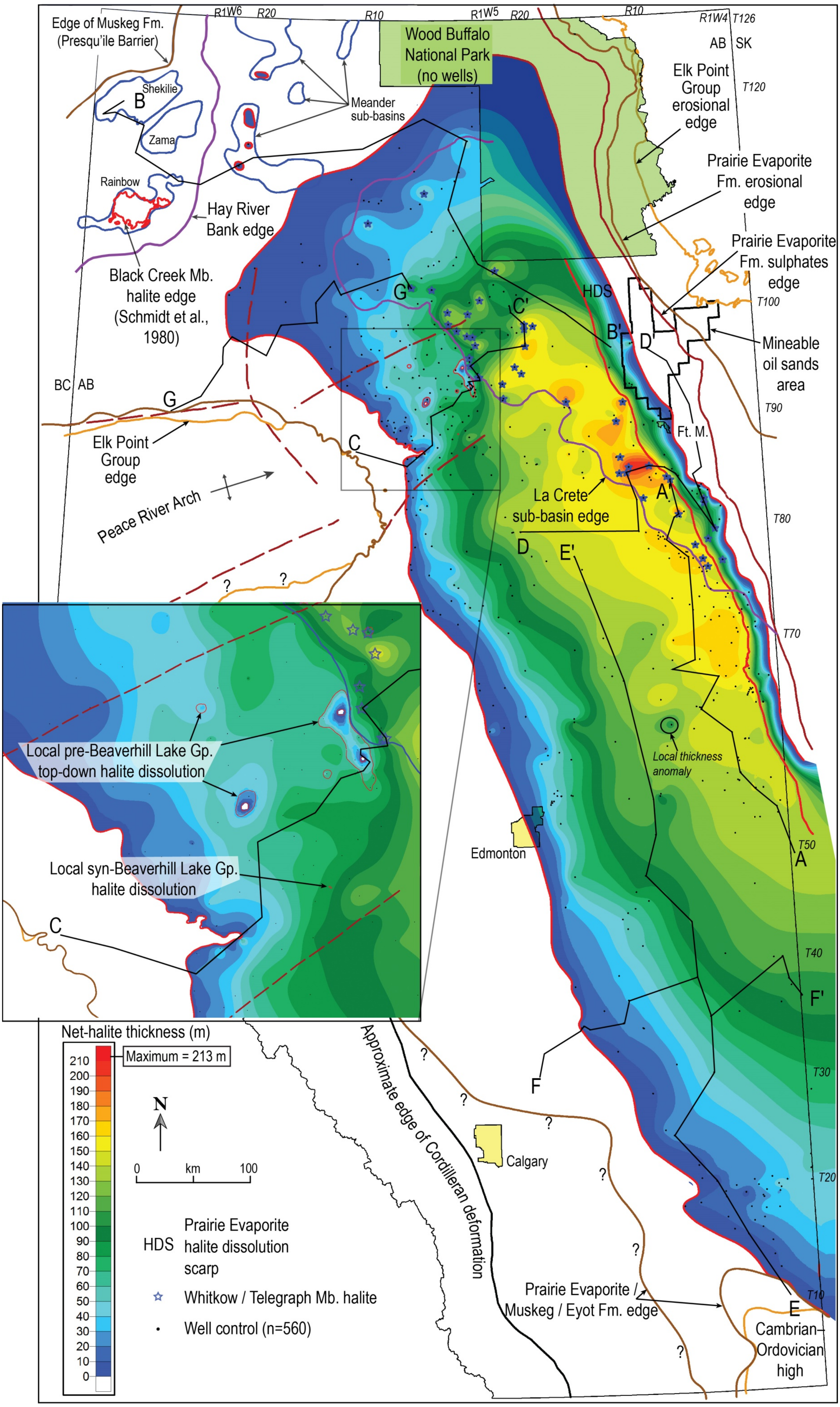


Figure 22. Cumulative halite thickness in the Prairie Evaporite and Muskeg formations, Alberta. Relevant lines of cross-section are shown. The Shekilie, Zama, and Rainbow sub-basins located on the Hay River Bank are from Davies and Smith (2006). Red long-dash lines outline the Peace River Arch (from O'Connell, 1994). Abbreviation: Ft. M., Fort McMurray.

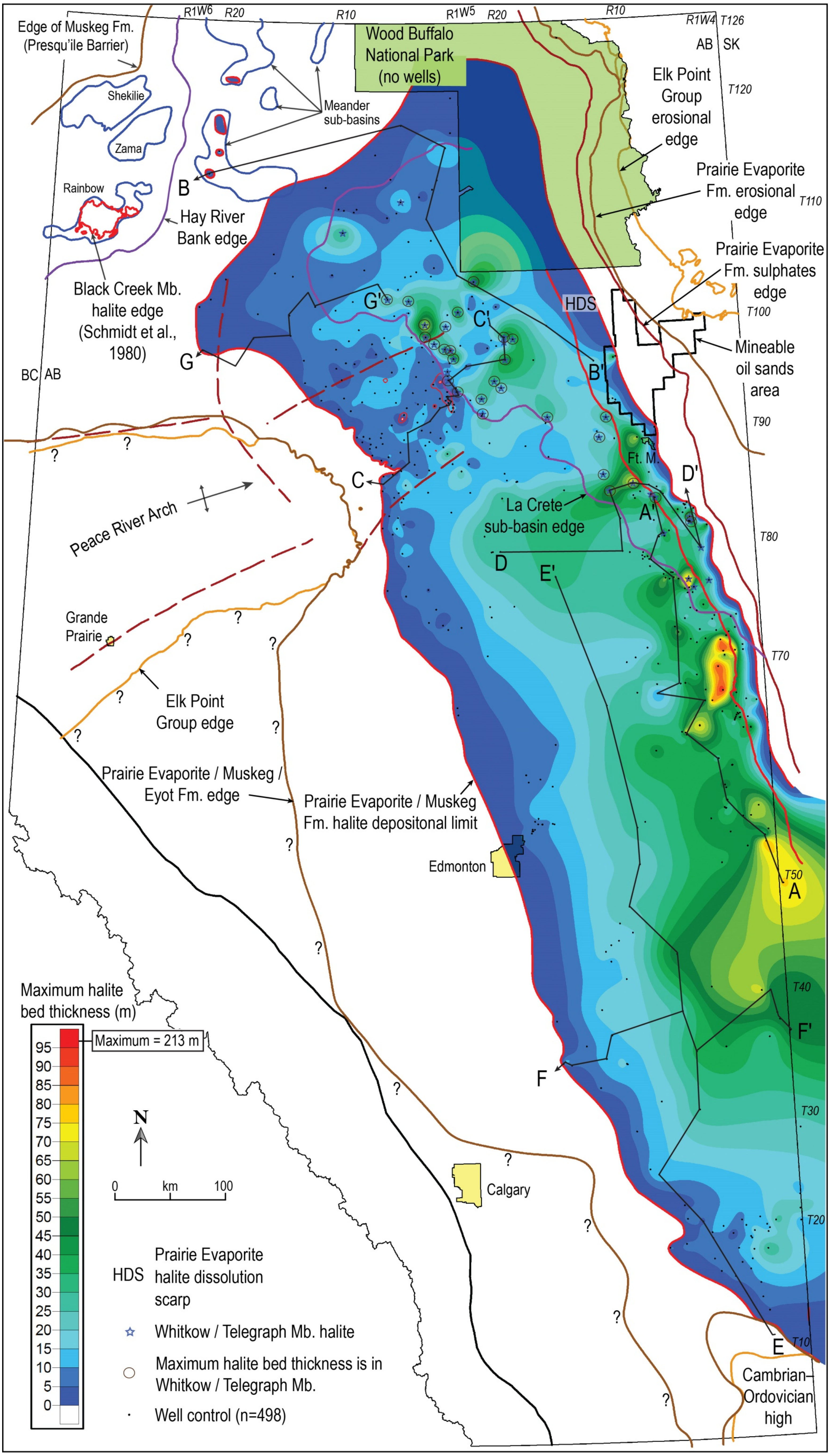


Figure 23. Maximum halite bed thickness in the Prairie Evaporite and Muskeg formations, Alberta. Relevant lines of cross-section are shown. The Shekilie, Zama, and Rainbow sub-basins located on the Hay River Bank are from Davies and Smith (2006). Red long-dash lines outline the Peace River Arch (from O'Connell, 1994). Abbreviation: Ft. M., Fort McMurray.

Outside of the La Crete sub-basin, cumulative halite thickness is more consistent owing to the lack of upper Keg River Formation buildups—the Keg River is more shelflike in these areas. Towards the north, the halite deposits decrease gradually in thickness as they interfinger with increasing numbers of anhydrite beds of the Muskeg Formation (Figures 2, 9). Towards the west, the halite deposits also thin gradually, but in addition to anhydrite, they interfinger with increasing amounts of terrigenous clastic rocks associated with the PRA and WAR (Figures 10, 15). The southernmost portion of the halite deposits is lacking in anhydrite entirely, and only carbonate and shale make up the nonhalite interbeds (Figure 8).

A number of local halite outliers are found west of the edge of consistent halite beds within the Prairie Evaporite and Muskeg formations interval within northwestern Alberta (Figure 22). All of these halite beds occur near the base of the Muskeg Formation (e.g., Figure 9, well 05-18-113-22W5), and coincide with subtle lows within the Keg River shelf on the Hay River Bank behind the Presqu'ile Barrier (Figure 14). This relationship suggests that early evaporite deposition in this area saw the accumulation of halite in these lows, which have been collectively called the Meander sub-basin (e.g., Moore, 1993; Wiebe et al., 2013). However, Figure 14 suggests that there are a number of disconnected lows, possibly defining a number of subtle sub-basins, rather than a continuous one as outlined in Moore (1993).

A number of anomalies are recognized in the cumulative halite isopach map (Figure 22). In east-central Alberta, a local thickness anomaly is associated with overthickening of the underlying Lower Elk Point subgroup succession (Hauck et al., 2018b). Along the eastern flank of the PRA, there are a number of local zones where halite has experienced dissolution. In at least three wells, halite has been completely removed (Figure 22). Dissolution of the halite proceeded top-down, as revealed by continuity of individual halite beds from outside and into the zone of dissolution (Figure 10).

Measured halite parameters (Table 2) reflect the large number of nonhalite interbeds in the Prairie Evaporite Formation in certain areas of the province. Halite can make up to 97.4% of the Prairie Evaporite Formation, but the average is just 55.2%, which is a reflection of the aforementioned interbedding. The maximum number of halite beds (58) is also a reflection of significant nonhalite interbedding in certain areas (e.g., transition with Muskeg Formation). The maximum individual halite bed thickness in the Prairie Evaporite is 93.0 m, which occurs outside of the La Crete sub-basin in east-central Alberta in Twp. 67, Rge. 4, W 4th Mer. (Figure 23). This is coincident with the greatest cumulative halite thickness and thickest individual halite beds within both the lower and upper Lotsberg halite (Figures 17–19). Within the La Crete sub-basin, almost all of the thickest individual halite beds are within the Whitkow and Telegraph members interval (Figure 23), which generally lacks nonhalite interbedding (Figure 2).

Cumulative anhydrite thickness within the Muskeg and Prairie Evaporite formations is presented in Figure 24. The eastern edge of the anhydrite falls east of the halite dissolution scarp, where the infiltration of undersaturated fluids along the basin margin resulted in the dissolution of halite as well as anhydrite. The thickest anhydrite deposits occur behind the Hay River Bank in northwestern Alberta. Anhydrite decreases somewhat abruptly on the backside of the Presqu'ile Barrier, which is a consequence of an increasing Keg River Formation thickness towards the apex of the barrier (Figure 9). Cumulative anhydrite thickness decreases more gradually to the southeast where anhydrite interfingers with halite. South of the Peace River–Athabasca Arch, anhydrite makes up a minor component in the Prairie Evaporite Formation, with cumulative thicknesses generally less than 30 m (Figure 24). Bull's-eye patterns of anhydrite thickness greater than 40 m are restricted to the eastern part of this area and are closely associated with Aurora Member anhydrite in the interbuildup basinal areas of the La Crete sub-basin (Figure 24, Twp. 74–91, Rge. 1–10, W 4th Mer.).

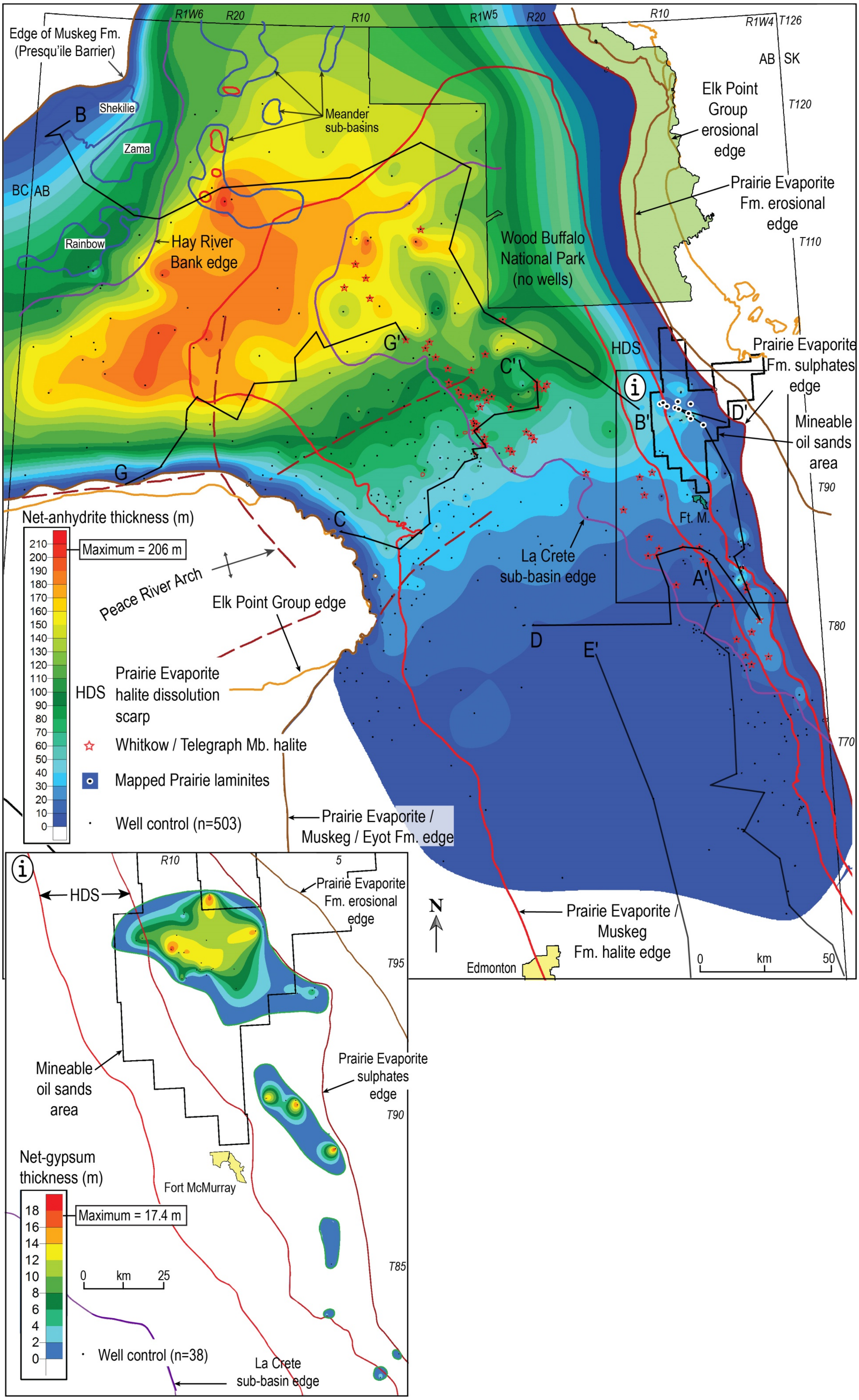


Figure 24. Cumulative anhydrite and gypsum (inset) thickness in the Prairie Evaporite and Muskeg formations, northern Alberta. The Shekilie, Zama, and Rainbow sub-basins located on the Hay River Bank are from Davies and Smith (2006). Red long-dash lines outline the Peace River Arch (from O'Connell, 1994). Abbreviation: Ft. M., Fort McMurray.

Gypsum deposits—the product of rehydration of anhydrite—are present only within the zone of remaining sulphates within northeastern Alberta near the basin margin, almost exclusively east of the Prairie Evaporite halite dissolution scarp (Figure 24). Cumulative gypsum thickness can reach 17.4 m. Thick gypsum is found predominantly at the top of the remaining sulphates where halite has been removed (Figure 13). Thin deposits of gypsum also are found bordering carbonate interbeds within the remaining anhydrite (Figure 13, wells AA/12-07-095-08W4, 09-19-096-10W4). Thick gypsum deposits typically occur within the Aurora Member of the interbuildup basinal areas of the Keg River Formation in the La Crete sub-basin (Figure 13). In northeastern Alberta, anhydrite beds within the Leofnard Member are typically too thin to form thick gypsum deposits.

6 Discussion

6.1 Paleogeography of the Keg River, Prairie Evaporite, and Muskeg Formations

The reconstruction of the paleogeography of the Keg River Formation at provincial-scale has suffered from a lack of data regarding the location and extent of the La Crete sub-basin. Even though the presence of this large sub-basin has been known for some time (Bebout and Maiklem, 1973), reconstructions of this depositional realm have been vague at best (Figure 25), which is largely due to a lack of well control. By delineating the distinct evaporite suites of the Prairie Evaporite Formation—specifically those below the Leofnard Member—the location of the La Crete sub-basin can be refined (Figures 14, 16). When combined with the Keg River isopach map (Figure 14), the presence of the halite of the Whitkow and Telegraph members, which formed strictly within interbuildup basinal areas, provides an improved means to delineate the margins of the sub-basin. This delineation is important for understanding not only what type of Keg River features to expect (e.g., isolated buildups within the La Crete sub-basin or shelf-like outside the sub-basin), but also understanding trends in the distribution of evaporites within the lower Prairie Evaporite and Muskeg formations (Figure 26). The latter has bearing on the interpretation of evaporite karstification along the basin margin. For example, thick gypsum deposits record active sulphate rehydration in northeastern Alberta, and these deposits are only associated with the presence of thick anhydrite strata of the Aurora Member, which is restricted to interbuildup basinal areas within the La Crete sub-basin.

Hauck et al. (2017) interpreted the presence of thick anhydrite at the Whitkow Member level to represent variation in the mode of evaporite deposition in response to a contiguous Keg River barrier along the northern margin of the Athabasca Arch. According to Hauck et al. (2017), this putative barrier acted to further restrict interbuildup basinal areas on the Athabasca Arch, which resulted in the accumulation of Whitkow halite preferentially south of this barrier. Placed in the context of the province, it is revealed that, even though there does seem to be a series of upper Keg River Formation buildups of large extent on the Athabasca Arch, the distribution and type of evaporites in the interbuildup basinal areas are much more complex (see Rogers, 2017). Evaporative processes responsible for the deposition of anhydrite and/or halite within these sub-basins likely operated in a similar fashion along the full length of the La Crete sub-basin (see yellow stars on Figure 14); however, in general, halite at this stratigraphic level is more common to the southeast, whereas anhydrite is more common in the north (Figure 26). This reflects a more regional pattern of distance to the open ocean, towards the Presqu'ile Barrier. The processes responsible for either the deposition of Aurora Member anhydrite or Whitkow Member halite within the Saskatchewan Basin have been discussed by Fu et al. (2006). Through a southeasterly directed flow of fresh seawater from the northwest—driven in part by elevation head established through evaporative drawdown—evaporative brines would have been flushed through the upper Keg River buildups within the La Crete sub-basin. These brines would have driven dolomitization (Kendall, 1989), which liberated Ca^{2+} and made it available to react with SO_4^{2-} to form gypsum. Given the southeasterly directed flow of these brines, the preferential accumulation of thick gypsum/anhydrite deposits on the southeastern margins of the upper Keg River buildups would be expected, which is the case in Saskatchewan (Fu et al., 2006). This process is interpreted to have occurred in a similar fashion within the Alberta portion of the La Crete sub-basin, and it would be expected to see similar relationships here, such as Aurora anhydrite being found preferentially on the southeastern margins of upper Keg River buildups.

The delineation of the La Crete sub-basin has been largely improved in this study, however, the location of Keg River buildups and their morphology is only partially revealed in Figure 14. The true size, extent, and location of Keg River buildups are still unknown across much of the La Crete sub-basin due to limited well control. Dense well control in the Athabasca Oil Sands region of northeastern Alberta, where many wells were drilled for disposal schemes within the Keg River Formation, has enhanced the understanding of these buildups. However, publicly available 3D seismic reveals that the morphology of these buildups is remarkably complex (Rogers, 2017, Figure 28). Rogers (2017) shows both linear banks and small-scale isolated pinnacle-like mounds at the scale of one township. Based on dense well control in the Athabasca Oil Sands region and facies relationships observed in core, the type of buildups specifically along the Athabasca Arch may vary, with both small isolated buildups and larger scale, isolated rimmed-bank complexes (Rogers, 2017). These larger scale complexes may be associated with paleotopography on the Athabasca Arch (Hauck et al., 2017). In Saskatchewan's potash district, seismic surveys combined with data from wells and underground mines reveal Keg River buildups that are irregularly shaped, roughly 1 to 8 km wide, and 70 to 100 m thick, with interbuildup distances of 1 to 10 km (Gendzwill, 1978). Buildup thicknesses are similar to those observed from well control in the La Crete sub-basin, however, interbuildup distances are poorly known from Alberta. As mentioned, buildups on the Athabasca Arch may be significantly larger in size relative to those in Saskatchewan and north of the Athabasca Arch within the La Crete sub-basin (Figure 26).

Much like in the La Crete sub-basin, the distribution of upper Keg River buildups within the sub-basins on the Hay River Bank is virtually impossible to delineate by well control alone. The buildups within the Rainbow sub-basin have been defined by Schmidt et al. (1980) as comprising over 100 individual 'pinnacles' of mostly oval to elliptical shape (Figure 27), the latter of which include more complex facies associated with peripheral rim and interior lagoon development. As such, this study's isopach map of the Keg River Formation in the sub-basins poorly represents the true picture at a more detailed scale (Figure 27). A better proxy for buildups within the Rainbow sub-basin is provided by the location of Keg River Formation administrative pool orders (Figure 27). Notably, the pool orders within the Rainbow sub-basin are more discontinuous than those within the Zama and Shekilie sub-basins, likely reflecting production from isolated pinnacles of the Keg River within the Rainbow sub-basin, whereas production within the Zama and Shekilie sub-basins includes that from the laterally extensive Zama Member (Figure 2).

An important point to make with respect to the deposition of evaporites within the various sub-basins involves correlation of evaporite strata of the Prairie Evaporite and Muskeg formations. Warren (2006, p. 335) discusses the tendency for stratigraphic correlation to invoke simultaneous gypsum (anhydrite) deposition in shallow water with halite in deeper water. This would require an inclined halocline, which cannot exist due to the shear involved with two brines of different densities (gypsum versus halite saturated). Therefore, within the La Crete sub-basin, halite of the Whitkow and Telegraph members must have formed within lows in the sub-basins during a time when no contemporaneous sulphates were forming (i.e., the Aurora Member), which has implications for correlation. Consequently, net-evaporite mineral intervals, as depicted on regional cross-sections herein, likely represent distinct periods of time during which either anhydrite or halite was being deposited within the sub-basins (e.g., Figure 26).

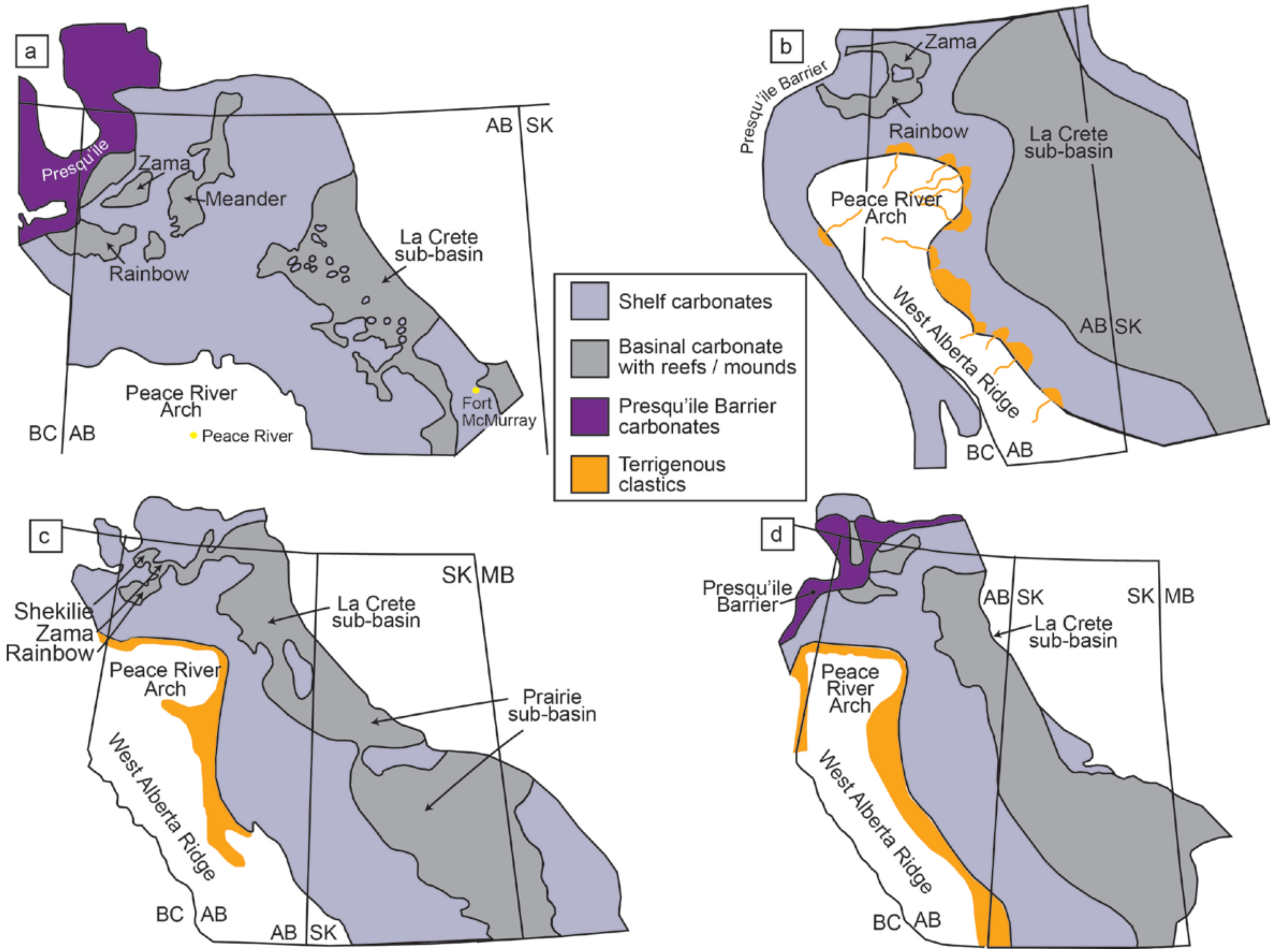
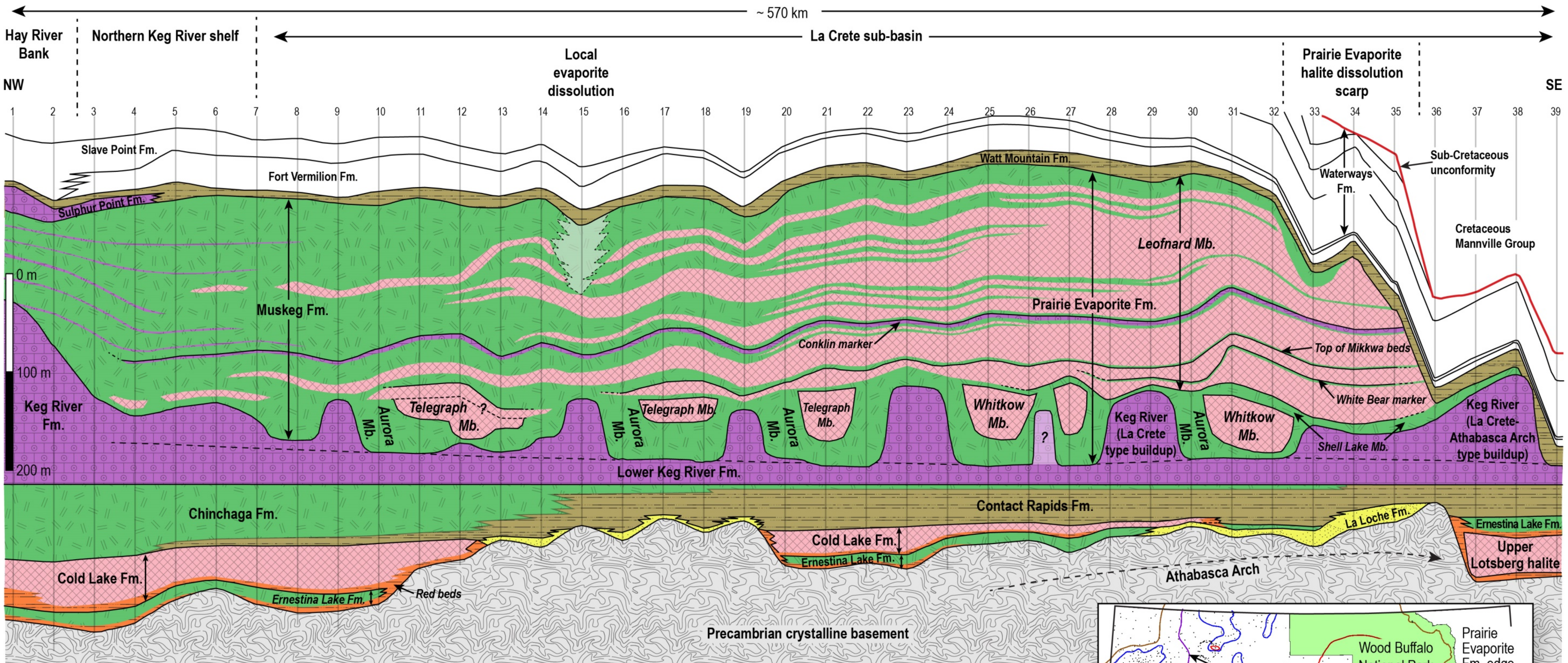


Figure 25. Paleogeography of the Upper Elk Point subgroup within the Elk Point Basin of northern Alberta and the Western Canada Sedimentary Basin from selected papers: a) northern Alberta, modified from Bebout and Maiklem (1973); b) modified from Campbell (1992); c) modified from Wiebe et al. (2013); d) modified from Fu et al. (2004).



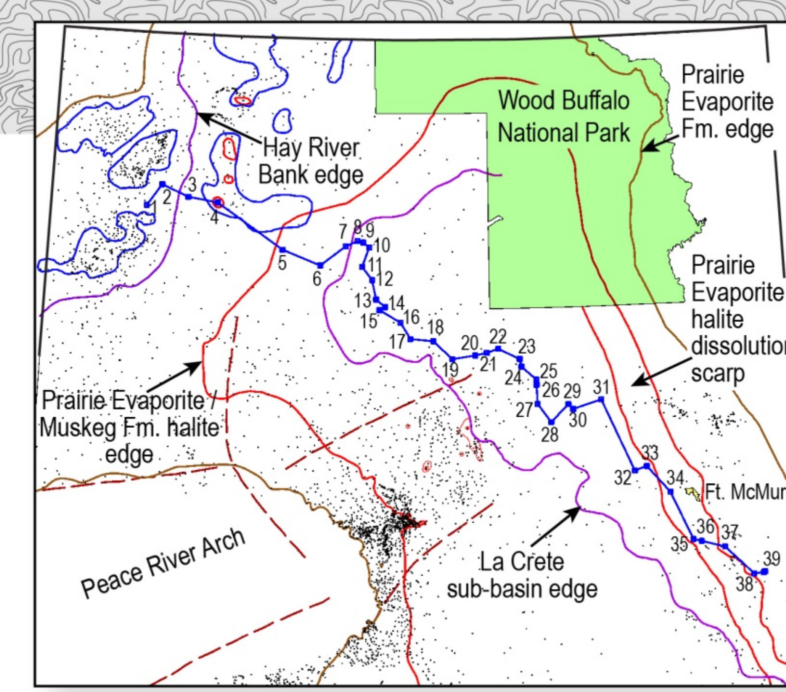


Figure 26. Stratigraphic cross-section in northern Alberta running from the Hay River Bank in the northwest, through the La Crete sub-basin to the Prairie Evaporite halite dissolution scarp in the southeast. The depiction of halite and anhydrite intervals above the Shell Lake, Whitkow and Telegraph members is schematic but based on net-evaporite data. Red long-dash lines in the inset figure outline the Peace River Arch (from O'Connell, 1994). Abbreviations: Ft., Fort; NW, northwest; SE, southeast.

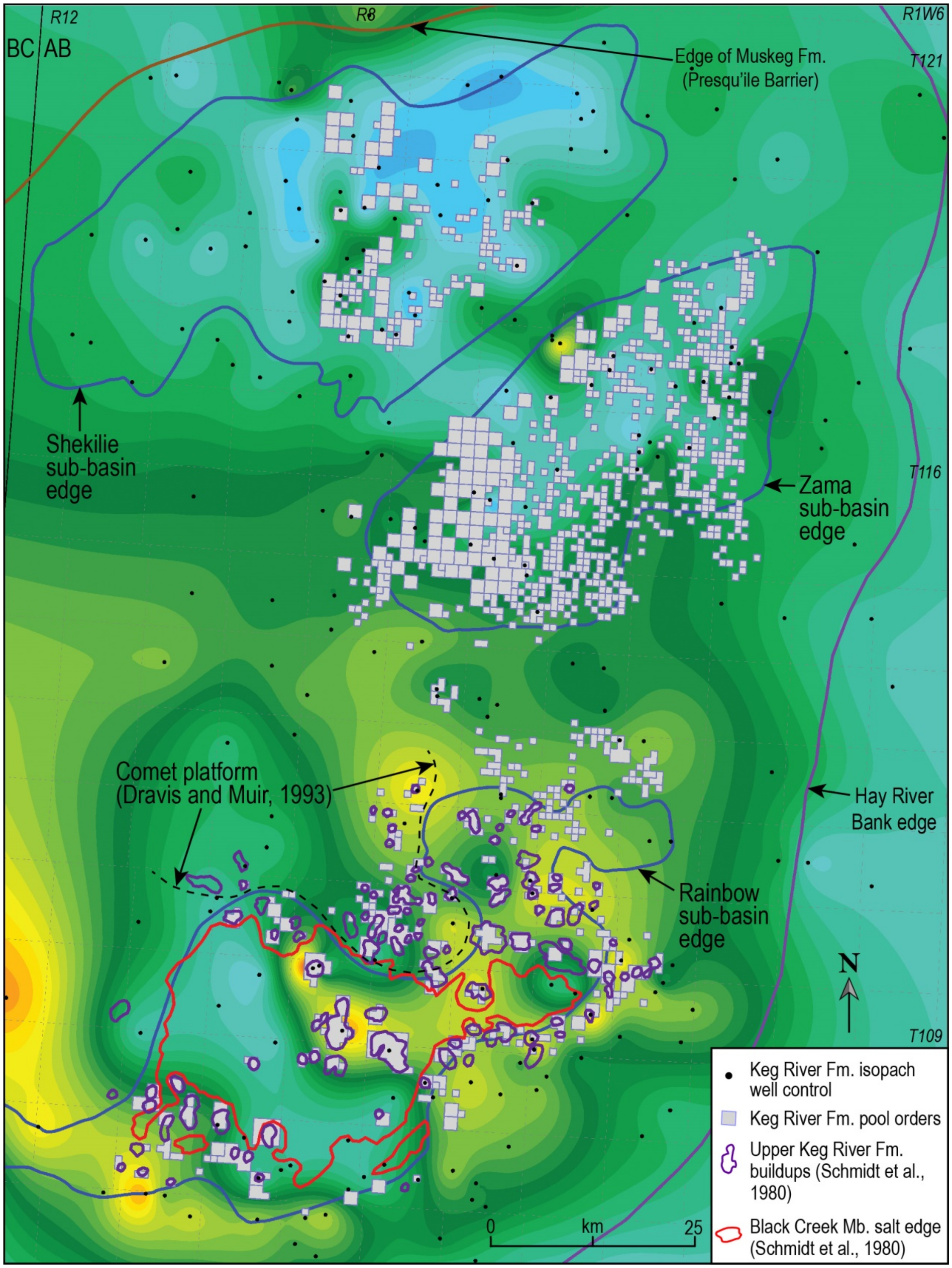


Figure 27. Detailed map of the Rainbow, Zama, and Shekilie sub-basins on the Hay River Bank in northwestern Alberta. The background contour map is extracted from the isopach map of the Keg River Formation (Figure 14). Keg River Formation well control in this study is compared to administrative Keg River Formation pool order boundaries, and the locations of the upper Keg River Formation buildups of Schmidt et al. (1980) in the Rainbow sub-basin. Pool boundaries approximate the location of upper Keg River Formation buildups. The locations of the sub-basins (blue lines) are from Davies and Smith (2006).

6.2 Evaporite Karstification in the Elk Point Group

There are a number of locations within Alberta where evaporite karstification has or is currently occurring. The most well-known of these features is the Prairie Evaporite halite dissolution scarp (Meijer Drees, 1994; Hauck et al., 2017; Figures 10, 16, 19, 22). This regional karst feature is located in northeastern Alberta and coincides with the tapering edge of the Phanerozoic sedimentary succession of the WCSB. The delineation of this feature is important for the consideration of cavern placement within halite of the Prairie Evaporite Formation, as the evaporite karstification has implications for hazards with respect to cavern stability and longevity.

Karstification of evaporites occurs through the influx of undersaturated waters along the basin margin (e.g., Stoakes et al., 2014; Walker et al., 2017), and it is well known that subsidence associated with the removal of evaporites had a pronounced structural effect on overlying Devonian strata (Hauck et al., 2017; Schneider and Cotterill, 2017), and on the sedimentary architecture of the overlying Cretaceous deposits (Broughton, 2014; Barton et al., 2017; Walker et al., 2017). Beyond identifying the presence of the scarp and its relationship to economic deposits of the lower Mannville Group (i.e., bitumen deposits), little work has been done to assess the nature of evaporite karstification. However, the special publication titled *The Devonian beneath the Oil Sands* (Canadian Society of Petroleum Geologists, 2017) does contain details of several relevant studies (e.g., Barton et al., 2017; Hauck et al., 2017; Walker et al., 2017). Within this volume, Hauck et al. (2017) outlines the use of regional marker beds to establish the nature of evaporite karstification. These regional marker beds (Figure 2) record significant pauses in evaporitic drawdown within the Alberta portion of the Elk Point Basin, and in concert with member correlation, have been used to define the *top-down* dissolution of the Prairie Evaporite Formation along the halite dissolution scarp (Hauck et al., 2017). This is in contrast to the style of evaporite karstification over Keg River (Winnipegosis) Formation buildups in Saskatchewan, which has occurred bottom-up through the circulation of undersaturated fluids within the Keg River (e.g., Gendzwill, 1978). East of the scarp, dolomite in these marker beds show patterns of dedolomitization associated with sulphate karstification—through the influx of undersaturated groundwater along the basin margin (Hauck et al., 2018a). Furthermore, sulphate karstification east of the scarp reveals a continuation of the top-down pattern of dissolution, marked by thick gypsum deposits at the top of the Prairie Evaporite succession (Figure 13, wells 07-11-091-07W4, AA/12-07-095-08W4, 09-19-096-10W4). These gypsum deposits formed through the rehydration of anhydrite. The presence of thick gypsum deposits is only associated with Aurora Member anhydrite (Figure 2) within the La Crete sub-basin. Gypsification of anhydrite is also noted internal to the remaining anhydrite, and it is these locations that are associated with dedolomitization of marker bed dolomite (Figure 13, wells 06-16-085-06W4, AA/12-07-095-08W4, 09-19-096-10W4).

Basin-margin evaporite karstification also occurs within halite of the Cold Lake Formation proximal to the Prairie Evaporite halite dissolution scarp. This occurrence is noted by the conformity in location of the edge of halite in the Cold Lake and the dissolution scarp within the Prairie Evaporite Formation (compare Figures 7, 12). Given the significantly smaller thickness of halite within the Cold Lake, this evaporite karstification has a much more subtle expression and its effect on overlying strata is less well defined, and likely far less pronounced when compared with the removal of greater than 200 m of halite in the Prairie Evaporite.

In addition to the regional Prairie Evaporite halite dissolution scarp, recognizable local-scale dissolution within the Prairie Evaporite and Muskeg formations succession occurs along the eastern flank of the PRA. Evaporite karstification in this area has been noted by previous authors (Anderson et al., 1988; Chow et al., 1995), and has been expanded here to define the nature of karstification. Top-down dissolution of halite is distinguished from a number of areas within the Leofnard Member of the Prairie Evaporite and Muskeg above the Keg River shelf (Figure 22). The complete removal of halite has been noted in four wells in this location. The most pronounced of these karstification features occurs along the shelf edge bordering the La Crete sub-basin (Figure 22). In this location, detailed net-evaporite mapping reveals a clear pattern of top-down dissolution (Figure 10). However, there is no overall decrease in the thickness of the Prairie Evaporite Formation here, and only a minor increase in the proportion of measured anhydrite beds (Figure 10). A possible explanation for this is that the accommodation space created through the dissolution of halite was filled with Watt Mountain Formation sediments prior to Beaverhill Lake Group deposition, such that the top of the Prairie Evaporite Formation should be picked lower in the well (Figure 10). The coincidence of this karstification and the edge of the Keg River shelf along the PRA is suggestive of possible fault systems, responsible for both buildup location and later evaporite karstification (see Corlett et al., 2018). Faulting is well-known in the Precambrian basement within this location (Anderson et al., 1988) and farther westwards towards the apex of the PRA (O'Connell, 1994). Another localized zone of top-down evaporite karstification is noted from one well in the northwestern part of the La Crete sub-basin (Figure 26).

The timing of evaporite karstification noted above is much older than the start—and bulk—of dissolution in the Prairie Evaporite Formation along the halite dissolution scarp, which is interpreted to have begun during the formation of the Canadian Cordillera in the mid-Jurassic to Early Cretaceous (Stoakes et al., 2014). Stratigraphic patterns within the overlying Devonian units show no evidence of syndepositional thickening, and structure cross-sections across these features show no indications of possible faulting within the overlying Devonian units. These observations suggest that the dissolution of halite occurred prior to deposition of the overlying Beaverhill Lake Group. Dissolution may have occurred in association with the pre-Watt Mountain Formation unconformity (Meijer Drees, 1986b, 1988).

A younger evaporite karstification event along the eastern flank of the PRA was recognized by Anderson et al. (1988). Halite within the Prairie Evaporite Formation has been completely dissolved in at least one well (Figure 22; Anderson et al., 1988, Figure 15). Unlike other dissolution features on the PRA, dissolution occurred during deposition of the Beaverhill Lake Group, specifically during deposition of the Waterways Formation. At least 55 m of overthickening occurs in the interval corresponding to the Moberly Member of the Waterways Formation. This occurrence, along with the karstification prior to Beaverhill Lake Group deposition discussed previously, speaks to the possible persistence of fault reactivation along the PRA throughout the Devonian.

6.3 Halite Potential, Halite Heterogeneities, and Cavern Placement

The Elk Point Basin is host to one of the Earth's most extensive ancient evaporite deposits (Warren, 2006). The areal extent of the Elk Point Basin within western Canada is estimated at 1.2 million km^2, with at least 500 000 km^2 of halite-bearing strata (Zharkov, 1988). Estimates of evaporite mineral volumes are important because of the industrial uses of evaporites, such as the processing of sodium chloride brine for the manufacturing of chlor-alkali products, and the creation of caverns for use as storage and disposal vessels. Moreover, potash salts of the Prairie Evaporite Formation within Saskatchewan contain 23.3% of the world's potash reserves and supply 29.2% of the world's fertilizer (Natural Resources Canada, 2019), and there are indications of potash potential in southeastern Alberta (Lopez et al., 2020). Halite volume within the entire Elk Point Basin has previously been estimated at 61 400 km^3 (Zharkov, 1988). Based on detailed net-evaporite mapping, the estimated 33 200 km^3 of halite within the province of Alberta is roughly half of that in the Elk Point Basin (Table 3). Of this, about 61% comprises halite of the Prairie Evaporite and Muskeg formations, which accounts for 15.3% of the entire Elk Point Group volume in the province. Anhydrite within the Prairie Evaporite and Muskeg formations makes up a similar volume to halite, accounting for another 15.4% of the total Elk Point Group volume in the province (Table 3). Although volumes are smaller, halite in the Lotsberg Formation, particularly that of the upper Lotsberg halite, is attractive due to its purity and overall lack of sulphates (Table 3).

Table 3. Elk Point Group evaporite mineral volume in Alberta based on isopach grids (percentage of total Elk Point Group volume in brackets).

Formation	Measured Volumes (km^3)		
	Halite	Anhydrite	Gypsum
Prairie Evaporite and Muskeg	20.20×10^3 (15.3)	20.30×10^3 (15.4)	4.9 (negligible)
Cold Lake	3.80×10^3 (2.9)	-	-
Upper Lotsberg	7.90×10^3 (6.0)	-	-
Lower Lotsberg	1.30×10^3 (1.0)	-	-

Measured volume of the total Elk Point Group is 132×10^3 km^3.

Solution mining of salt within the Elk Point Group in Alberta has been ongoing since 1947, starting with the 03-26-056-05W4 well drilled east of Edmonton near the hamlet of Lindbergh (Figure 28). Many of these early solution-mined caverns have subsequently been used for oil-field waste (effluent) disposal, or for the storage of natural gas. There are currently more than 150 active caverns within the evaporite deposits of the Elk Point Group (Figure 28). A new potential use of caverns is for subsurface compressed air energy storage (CAES). This is a mechanical form of energy storage where air is pumped and compressed into a storage vessel, such as an underground halite cavern, and later released to drive a turbine generator to produce electricity. When combined with intermittent wind and solar power generation, CAES is considered a promising technology for 'greening' the power grid (Duhan, 2018). In order for a CAES scheme to be economically feasible in generating electricity, compressed gases need be stored and compressed to pressures that far exceed normal gas storage facilities (Duhan, 2018). Such pressures require special consideration of the rock and geomechanical properties of potential nonhalite interbeds within the target halite formation. When mining a cavern for storage or disposal purposes rather than its chemical constituents, diapiric halite is the preferred target due to thickness and homogeneity (Warren, 2006). Bedded salts, such as the evaporites of the Elk Point Group, tend to contain numerous heterogeneities in the form of nonhalite interbeds. Part of the aim of this study is to provide data on the degree of nonhalite interbedding within the evaporite successions of the Elk Point Group of Alberta to better inform the potential placement of future halite caverns.

Halite potential is greatest in the area where the Lotsberg and Prairie Evaporite formations overlap within the CAS (Figure 6). In this location, the Prairie Evaporite comprises predominantly halite, with relatively minor nonhalite interbedding. Combined net-halite of the Lotsberg, Cold Lake, and Prairie Evaporite formations in this location can reach greater than 400 m in thickness (Figure 29). In the eastern half of the CAS, cumulative halite thickness is generally greater than 280 m. As expected, the vast majority of halite caverns in Alberta are found within the upper Lotsberg and Prairie Evaporite in the CAS; only a few caverns within the Prairie Evaporite are located farther to the south (Figure 28). About 126 caverns, both active and abandoned, can be found within the upper Lotsberg halite just northeast of Edmonton (Figure 28). These caverns are placed in the upper Lotsberg halite where cumulative halite is 40 to 90 m thick (Figure 18), at depths between 1700 and 1900 m. Where data is available for these caverns (12 wells), average vertical cavern height is 47 m, with a minimum and maximum of 26 and 84 m, respectively. Of the 23 caverns in the Prairie Evaporite, only four wells had data for cavern height, and these range from 19 to 101 m. Figure 30 displays examples of cavern placement and associated cavern volumes.

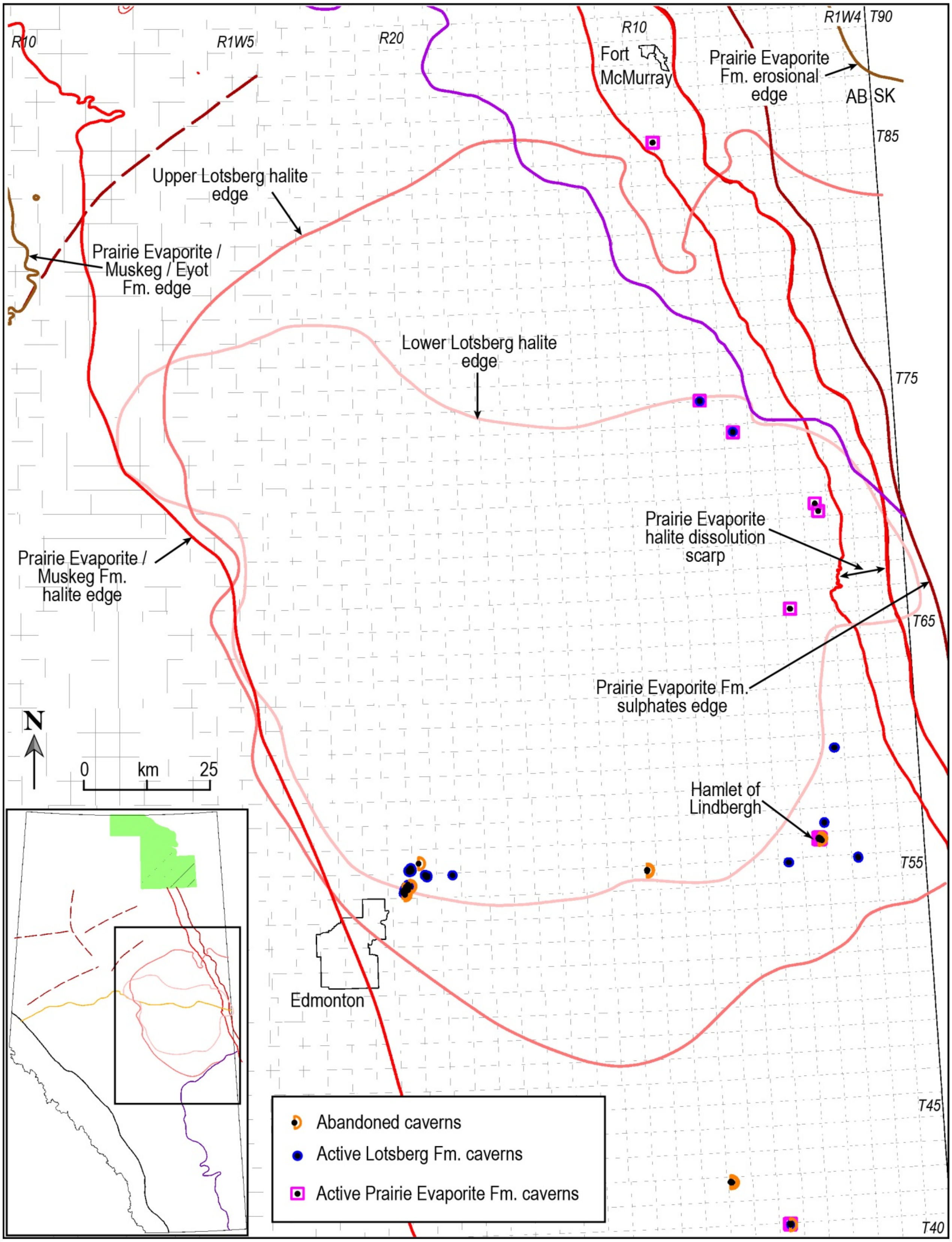


Figure 28. Active and abandoned halite caverns by formation within east-central Alberta. Red long-dash lines outline the Peace River Arch (from O'Connell, 1994).

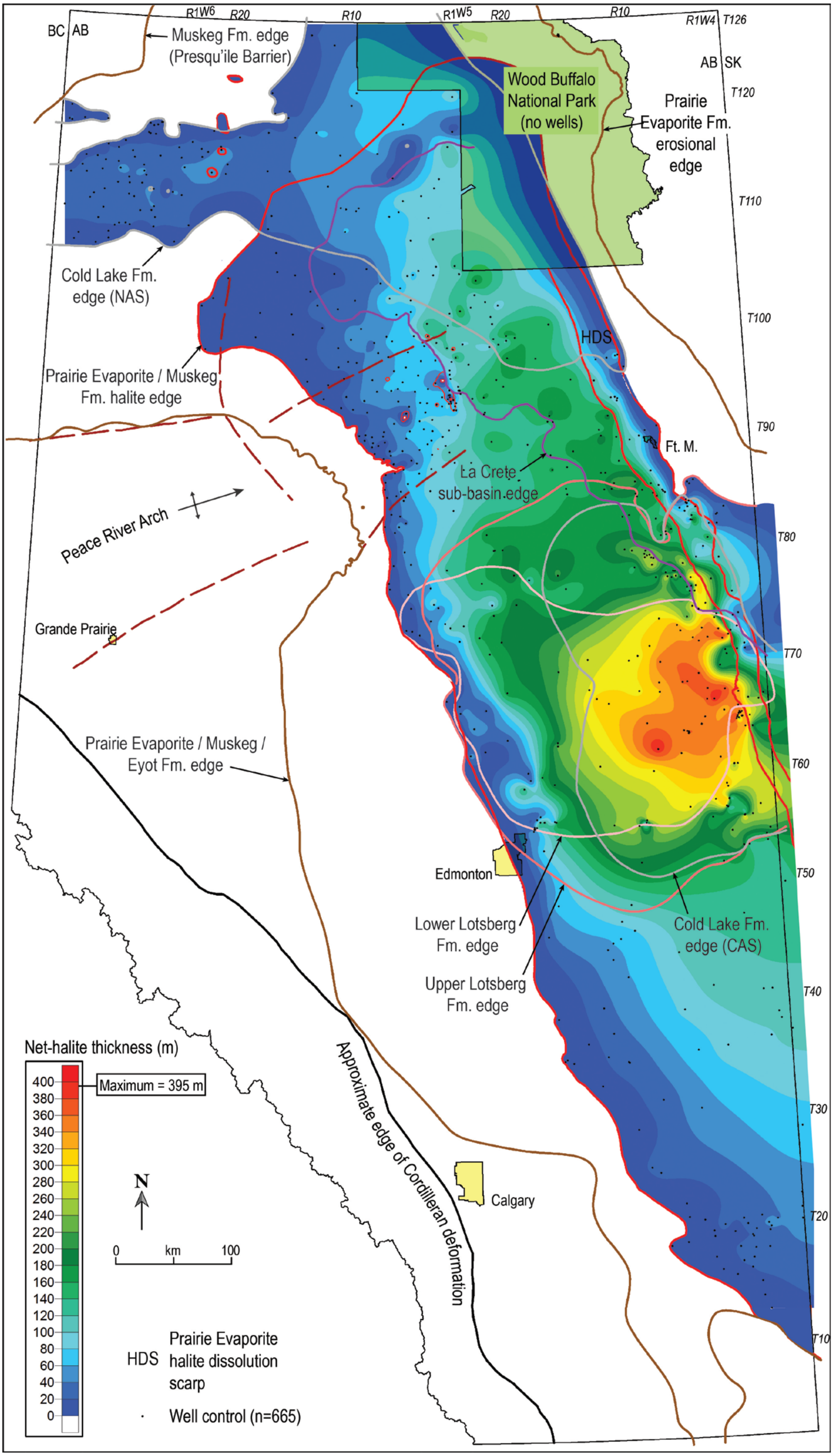


Figure 29. Cumulative halite thickness from the Lotsberg, Cold Lake, and Prairie Evaporite and Muskeg formations, Alberta. Red long-dash lines outline the Peace River Arch (from O'Connell, 1994). Abbreviations: CAS, central Alberta sub-basin; Ft. M., Fort McMurray; NAS, northern Alberta sub-basin.

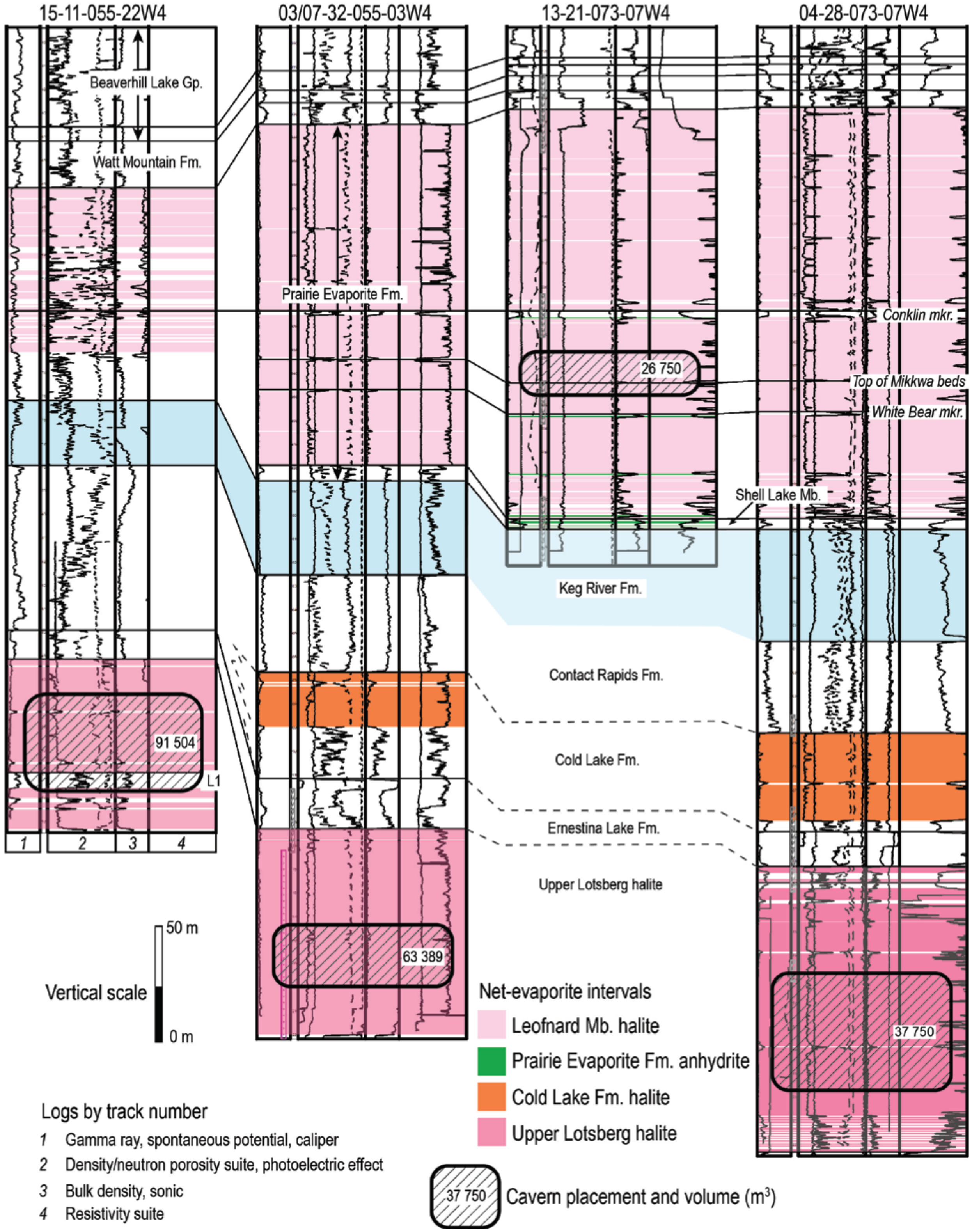


Figure 30. Examples of cavern placement and associated volumes within the Prairie Evaporite Formation and upper Lotsberg halite. Wells from east-central Alberta.

The upper Lotsberg halite has the thickest individual halite beds, the highest average maximum halite bed thickness, and given its overall thickness, the lowest average number of nonhalite beds (Table 2). These characteristics make the upper Lotsberg halite most favourable for cavern placement. The Prairie Evaporite Formation displays the greatest variation in average halite bed thickness and nonhalite interbedding, which is largely a function of interbedding with anhydrite and other insolubles towards the margins of the halite-bearing fairway (Figure 31). In general, the basin-centred evaporites of the Lotsberg and Prairie Evaporite formations have an expected pattern of nonhalite interbedding: thick and relatively uninterrupted salt beds in the evaporite basin centre, with the degree of interbedding increasing towards the margin of the basin, and by association a decrease in the average thickness of salt beds (Figure 31). Exceptions to this trend occur along the Prairie Evaporite halite dissolution scarp (Figure 31).

The high degree of nonhalite interbedding within the Prairie Evaporite Formation outside of the CAS, towards the PRA and into northern Alberta, makes this area less suitable for the placement of caverns. However, to the south of the CAS, the Prairie Evaporite is a potential target for caverns. Cumulative halite thickness is commonly greater than 40 m in this area (Figure 22). Additionally, nonhalite interbedding is much less common compared with the aforementioned locations (Figures 8, 15) and maximum halite bed thicknesses are favourable (Figure 23). Five caverns currently exploit these favourable halite deposits around Twp. 40, Rge. 7, W 4th Mer. (Figure 28).

Halite deposits of the Cold Lake Formation have potential for caverns due to a general lack of nonhalite interbedding (Figure 6), although much of the formation is less than 40 m thick. Areas of relatively thick halite occur in east-central Alberta near Twp. 65, Rge. 1–4, W 4th Mer., and in far north-central Alberta—the latter is likely too far from infrastructure to be of interest for cavern placement (Figure 20).

Areas of known evaporite karstification should be avoided when considering the placement of a cavern. The obvious potential karst hazard is the Prairie Evaporite halite dissolution scarp in northeastern Alberta (Figure 22). The degree of active karstification along the scarp is not well understood; however, groundwater geochemistry (Gue et al., 2015) and bedrock aquifer geochemistry (Cowie et al., 2015) suggest that active karstification is occurring to some degree. Data from this study for the Lotsberg Formation suggests that karstification of evaporites is not present in the Alberta portion of the formation, but is restricted to western Saskatchewan.

In addition to regional karstification along the basin margin, local-scale karstification of halite occurs within the Prairie Evaporite Formation along the eastern flank of the PRA (see Section 6.2); due to a high degree of nonhalite interbedding (Figure 10), this area is not favourable for the placement of future caverns.

7 Summary

Detailed regional lithostratigraphic correlation of the formations and units comprising the Elk Point Group provide an updated picture on their extents and paleogeography in Alberta. Correlation of these strata includes over 24 500 stratigraphic picks from 4644 wells across the province. These stratigraphic picks inform a series of unit extents, which define depositional, erosional, and karst edges (evaporites) of formations within the Elk Point Group. These data contribute to the production of a high-resolution, three-dimensional model of the Phanerozoic sedimentary strata of Alberta.

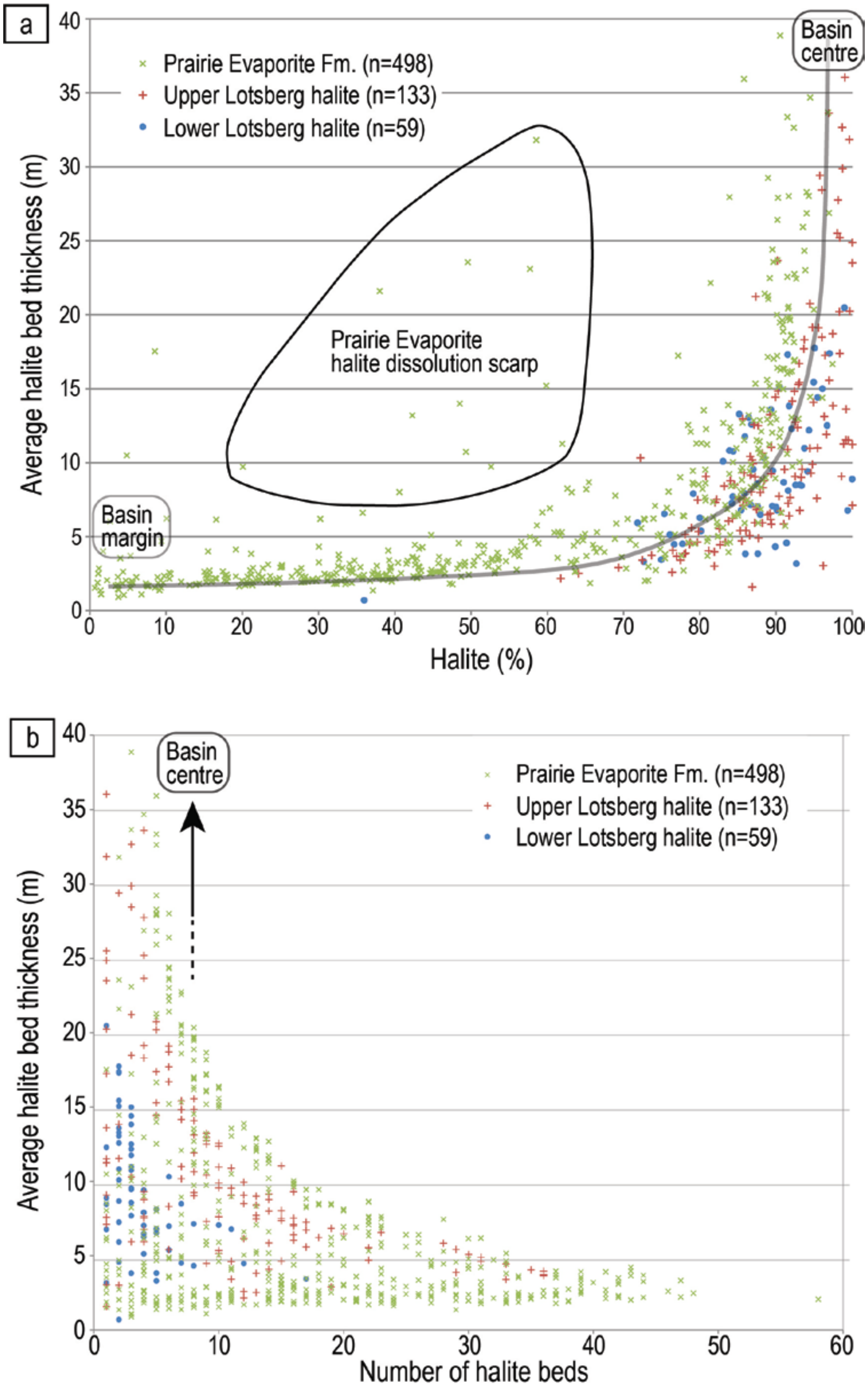


Figure 31. Measured halite parameters by well from the Lotsberg and Prairie Evaporite formations, Alberta: a) average halite bed thickness versus percentage of halite, showing a higher percentage of total halite is correlated with a larger average individual halite bed thickness; b) average halite bed thickness versus number of measured halite beds. Number of data points in brackets after formation.

A net-evaporite methodology using raster logs was employed to define net-evaporite intervals from over 740 wells, comprising over 23 600 individual intervals from the Lotsberg, Cold Lake, and Prairie Evaporite and Muskeg formations. Three principal evaporite minerals, halite, anhydrite, and gypsum, were mapped using this technique. These data provide a detailed assessment of the distribution of evaporite minerals across the province, and deliver a comprehensive picture of heterogeneity within halite-bearing fairways, which has implications for the placement of caverns. The distribution of gypsum provides a picture of active sulphate karstification east of the Prairie Evaporite halite dissolution scarp in northeastern Alberta. Net-evaporite mapping provides new details on the nature of halite karstification along the eastern flank of the Peace River Arch. Based on adjacent stratigraphic and structural patterns, these are interpreted as pre-Cordilleran and record karstification events that occurred before or during deposition of the Beaverhill Lake Group.

The suite of stratigraphic picks, combined with net-evaporite mapping, significantly improve the delineation of paleogeographic elements common to the Keg River, Prairie Evaporite and Muskeg formations succession. This work includes new paleogeographic maps describing the location of the La Crete sub-basin in east-central and northern Alberta, which provides a distinction between Keg River Formation shelf deposits outside the sub-basin and isolated upper Keg River buildups within the sub-basin. This improved paleogeography aids in understanding the relationship between Keg River strata and interbuildup evaporites deposits, such as the restriction of the halite of the Whitkow and Telegraph members to the La Crete sub-basin, and its relationship to Aurora Member anhydrite. Province-wide correlation provides an up-to-date picture of the distribution of Prairie Evaporite Formation members and marker beds, and aids in delineating the nature of evaporite karstification within this succession. Further evidence is provided for a top-down motif of karstification along the Prairie Evaporite halite dissolution scarp, which has occurred within sulphates east of this feature, and within local-scale karst features along the eastern flank of the Peace River Arch. Finally, updated maps of the distribution of halite within the Lotsberg, Cold Lake, and Prairie Evaporite and Muskeg formations are provided for the province. This work includes a special consideration of heterogeneities of the evaporites and the implications for future cavern placement.

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