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Regional Stratigraphic Mapping and 3D Modelling of the Paleozoic Succession in Northeastern Alberta (Townships 59–104, Ranges 1–19, West of the Fourth Meridian)

T.E. Hauck, K.E. MacCormack and M. Babakhani

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Alberta Energy Regulator
Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, AB T6B 2X3
Canada

Tel: 780.638.4491
Fax: 780.422.1459
Email: AGS-Info@aer.ca
Website: www.ags.aer.ca

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Abstract

The entire Paleozoic succession in northeastern Alberta was mapped at a regional scale to support the production of a high-resolution three-dimensional (3D) model (500 by 500 m grid-cell size). The stratigraphic dataset comprises formation- and member-level picks from 1307 wells covering 874 townships in an area encompassing most of the Lower Athabasca Regional Plan (LARP) area. The LARP area is of critical importance due to the presence of vast bitumen and other hydrocarbon deposits and the industrial footprint associated with the extraction of these resources. Paleozoic stratigraphy in the area includes the lower part of the Middle Cambrian System and the Devonian Elk Point, Beaverhill Lake, Woodbend, Winterburn, and Wabamun groups. The Paleozoic succession is floored by the Precambrian crystalline basement, which in the study area crops out in the far northeast as part of the Athabasca Basin and the Marguerite River complex, beyond the Phanerozoic basin margin. Cambrian deposits subcrop beneath Devonian strata at the sub-Devonian unconformity surface. Strata from the lower part of the Devonian Lower Elk Point subgroup are restricted to two regional sub-basins, whereas the overlying Devonian strata are more laterally extensive and subcrop at the sub-Cretaceous unconformity surface.

Detailed mapping of the Prairie Evaporite Formation enabled us to better delineate the location and extent of the Prairie Evaporite halite scarp, which is a well-known intrastratal dissolution feature that runs south-southeast through the study area. The dissolution of in places more than 200 m thick halite from within the Prairie Evaporite Formation led to structural compensation and collapse of the overlying Devonian succession. The resulting structural depression created substantial accommodation space that was the locale for deposition of much of the lower part of the Lower Cretaceous Mannville Group siliciclastics. Redefining the location and extent of the Prairie Evaporite halite dissolution scarp was accomplished through detailed mapping of internal member and marker bed stratigraphy, combined with net-evaporite mapping of halite and anhydrite using modern log suites.

The top of the Paleozoic succession in the study area is the angular sub-Cretaceous unconformity. This surface forms the interface between Paleozoic and Mesozoic strata, and its proper reconstruction is integral to understanding depositional trends in the latter, as well as basin hydrodynamics in northeastern Alberta. The deep well control used for stratigraphic mapping was also employed to produce a detailed model predicting the location of Devonian subcrop belts at the sub-Cretaceous unconformity surface. Delineation of the unconformity surface was supplemented with an additional 7188 picks, most of which just ‘tag’ the Devonian, as part of the Mesozoic mapping component that completed the Phanerozoic mapping for the 3D model in the LARP area.

1 Introduction

To date, there does not exist a comprehensive regional-scale lithostratigraphic model for the geology of northeastern Alberta—an area of critical importance due to intense hydrocarbon production. Publicly available mapping and modelling studies have been produced only for relatively small portions of the bitumen-bearing Lower Cretaceous Mannville Group. Recently, as part of a broader province-wide 3D modelling program, the Alberta Geological Survey (AGS) conducted a comprehensive mapping and modelling study of the entire sedimentary succession in northeastern Alberta with the aim to construct an integrated and accurate 3D model using geostatistical methods. The model produced by this study will augment efforts to regulate oil and gas activities and provide a stratigraphic framework for hydrogeological assessments aiming to characterize water resources in the Lower Athabasca region. This document describes the methodology and results for the stratigraphic mapping and 3D modelling of the Paleozoic portion of the study. The data, comprising stratigraphic picks described in this document and located within the model domain, are available publicly (Hauck, 2018). Hauck et al. (2017) discusses in greater detail some of the more notable findings of this regional mapping study.

The study area in northeastern Alberta comprises 874 townships—an area of 83 334 km^2, roughly 12 per cent of Alberta (Figure 1). The area is rectangular but encompasses most of the administrative boundary of the Lower Athabasca Regional Plan (LARP) area (Figure 1). The study area includes a large portion of the Athabasca and Cold Lake Oil Sands deposits, as well as the mineable oil sands area of the Athabasca Oil Sands deposit located north of Fort McMurray (Figure 1).

2 Geological Setting and Stratigraphy

The study area covers a sizable portion of the eastward-tapering Phanerozoic sedimentary succession of the Alberta Basin, which is erosionally truncated at the basin margin in the far northeast of the study area (Figure 2). Beyond the Phanerozoic basin margin are metasedimentary deposits of the Precambrian (Paleo- to Mesoproterozoic) Athabasca Basin, and the Marguerite River complex (Figure 2). The Phanerozoic succession can be divided into two major parts related to two major tectonic phases: 1) a Late Proterozoic to Middle Jurassic passive-margin phase, in response to extension and continental breakup; and 2) a Late Jurassic to Eocene foreland phase, in response to convergent tectonics and resulting orogenesis along the western margin of the proto–North American continent (Price, 1994; Pană and van der Pluijm, 2015). In response to the convergent tectonic phase, Paleozoic strata were tilted southwestwards during orogenic loading and subsequently experienced major erosion before deposition of the overlying Mesozoic siliciclastics. This prominent angular unconformity is known as the sub-Cretaceous unconformity (Figure 3). An older major unconformity—the sub-Devonian unconformity—separates Devonian strata from Cambrian siliciclastics in the south and Precambrian crystalline basement in the north (Figure 3).

2.1 Cambrian System

Lithostratigraphic units in the study area are summarized in Figure 3. The Cambrian section comprises basal sandstones and overlying silts and shales that were deposited during a period of transgression and prolonged sedimentation on the North American craton (Aitken, 1993). The Basal Sandstone unit consists of the coarse siliciclastics that were derived from Precambrian basement rocks during transgression and subsequently reworked in marginal-marine to marine settings. The finer grained siliciclastics of the overlying Earlie Formation record fully marine settings outboard of the shoreward sandstones. In the study area, much of the Cambrian succession was removed during erosional events before deposition of the overlying Devonian strata.

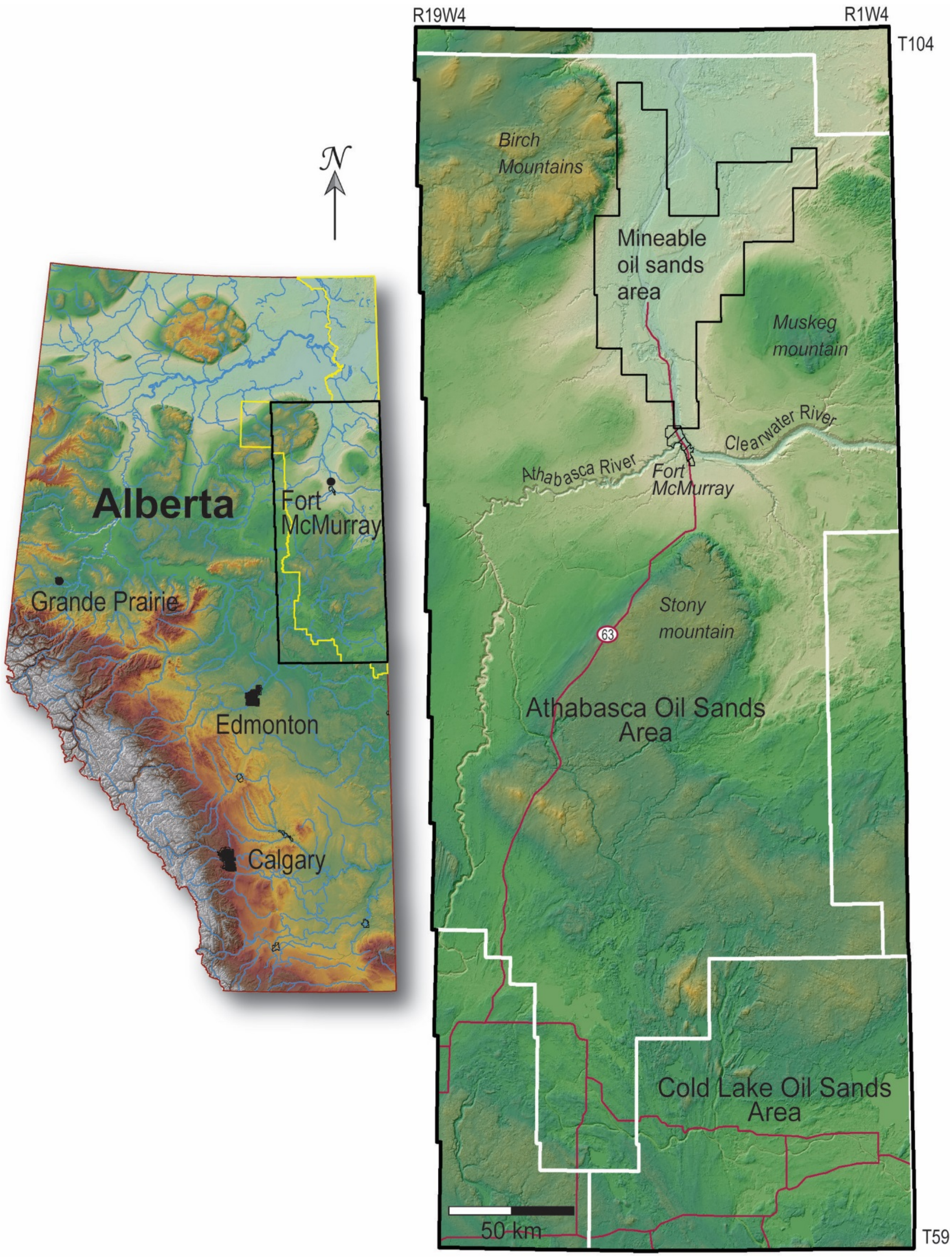

Figure 1. Location of the study area in northeastern Alberta, overlain on a hill-shaded digital elevation model. The model boundary is outlined in black. The administrative boundary of the Lower Athabasca Regional Plan is in yellow. Shown on the map on the right are the administrative boundaries of the Cold Lake and Athabasca Oil Sands areas (white lines) and the mineable oil sands area (thin black line).

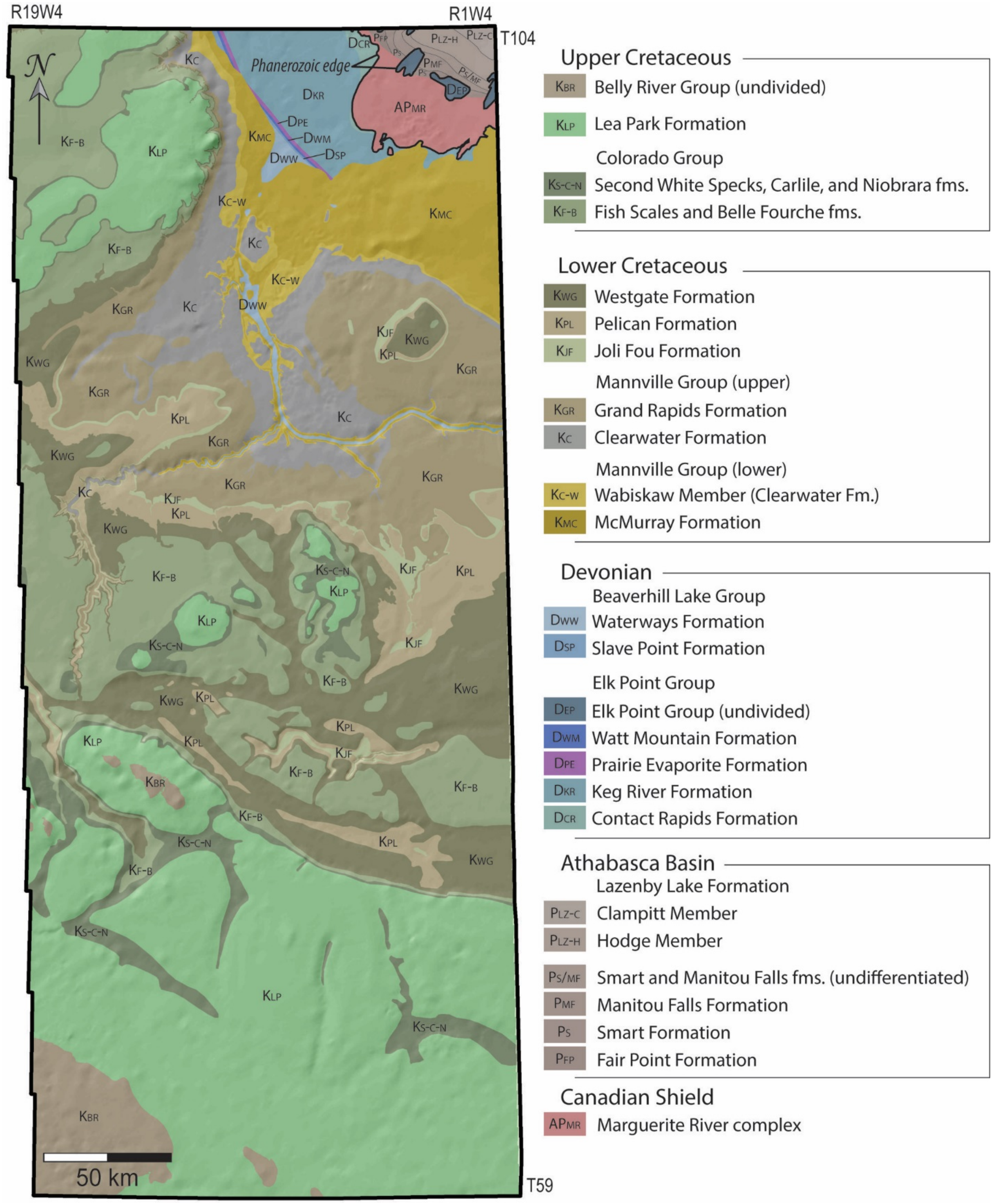

Figure 2. Bedrock geology in the study area (Prior et al., 2013), overlain on shaded bedrock topography (MacCormack et al., 2015). Devonian strata outcrop, or subcrop beneath Cenozoic deposits, near the bedrock-basin margin in the northeastern part of the study area where Cretaceous strata have been removed.

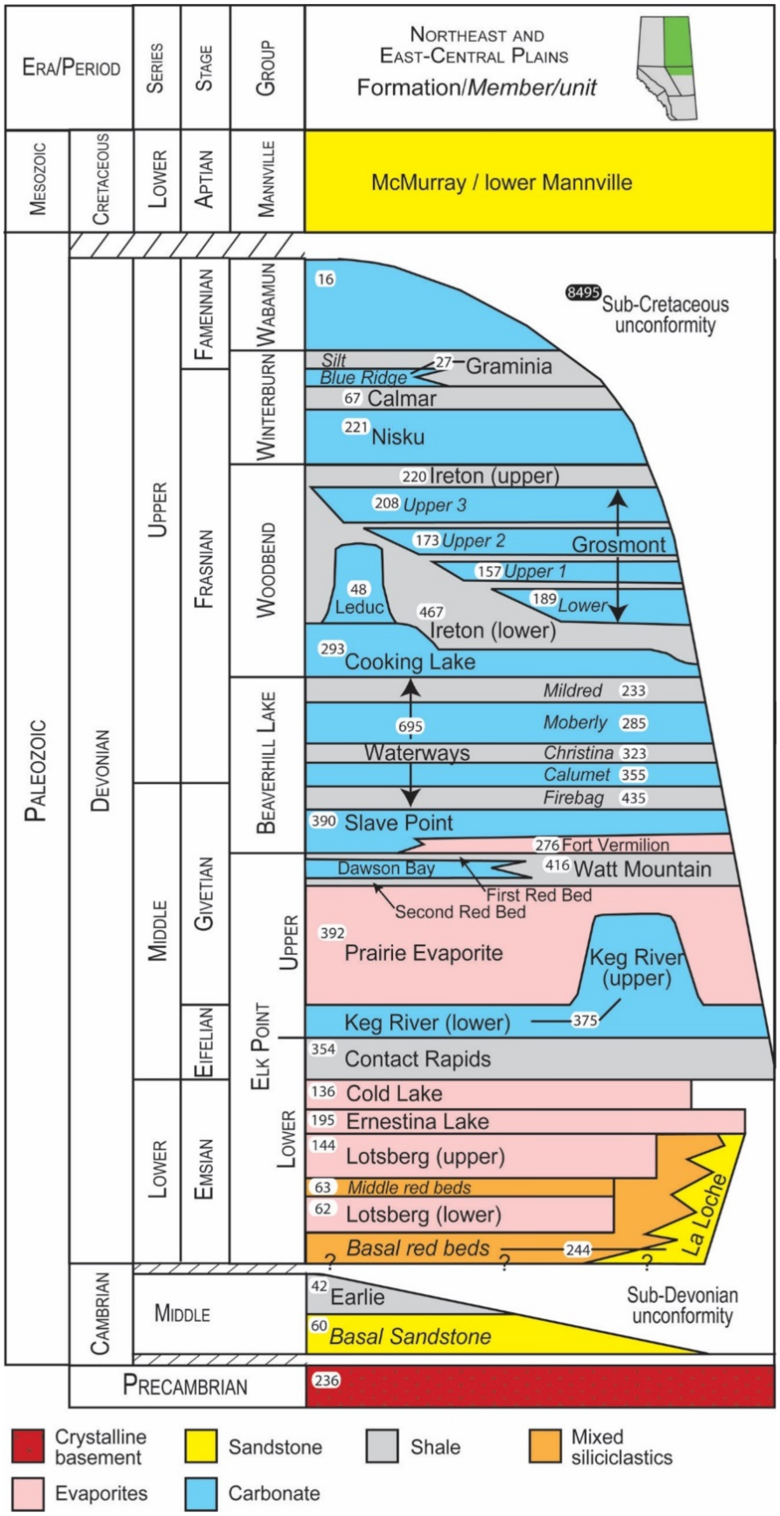

Figure 3. Paleozoic and lowermost Mesozoic lithostratigraphy encompassing the northeastern plains and the northern part of the east-central plains. Numbers on the figure represent well control used to map and model each respective stratigraphic unit. Numbers include well control used outside of the LARP study area boundary to minimize edge effects (e.g., for the Paleozoic succession, 1307 wells were used, 1162 of which fall in the LARP study area boundary; see Figure 4).

2.2 Elk Point Group

The Elk Point Group is subdivided into lower and upper subgroups (Sherwin, 1962), deposited under largely evaporative conditions resulting in the widespread accumulation of halite- and sulphate-dominated strata (Figure 3). At the scale of the Alberta Basin, the division into subgroups reflects the accumulation of the lower subgroup strata into distinct sub-basins or depocentres—the northern and central Alberta sub-basins—developed on the sub-Devonian unconformity surface, with the more widespread Upper Elk Point subgroup strata reflecting a much subdued paleotopography. The boundary between the northern and central Alberta sub-basins falls in the study area between a east-northeast-trending paleotopographic high known as the Athabasca Arch—the eastern extension of the Peace River Arch. Evidence for the sub-Devonian paleotopography is reflected in thickness trends and facies relationships of the overlying strata. Siliciclastic deposits in the form of redbeds and feldspathic sandstones rest on the sub-Devonian unconformity surface, with redbeds being closely associated with overlying evaporite deposits. The Lotsberg Formation halite and lesser anhydrite in the lower part of the Lower Elk Point subgroup are restricted to the central Alberta sub-basin, whereas the anhydrite and halite of the Ernestina Lake and Cold Lake formations, respectively, in the upper part of the Lower Elk Point subgroup are present in both the northern and central Alberta sub-basins. The Lower Elk Point subgroup is nearly completely capped by the widespread anhydrite-bearing dolomitic shales of the Contact Rapids Formation.

The Upper Elk Point subgroup comprises more regionally extensive stratigraphic units, the first of which marks a departure from intense evaporitic drawdown and a return to normal-marine conditions across the basin. During this time, carbonates of the Keg River Formation were deposited; these can be subdivided into a more extensive lower platform or ramp member and a less widespread upper member consisting of buildups variously ascribed to banks, isolated reefal mounds, isolated reefs, and atolls (Campbell, 1992; Moore, 1993; Meijer Drees, 1994; Chow et al., 1995). Precambrian basement paleotopography played a large role in the distribution and type of late-stage Keg River buildups, which ultimately controlled the distribution and type of overlying evaporite deposits (Hauck et al., 2017). Northwest of the study area in Alberta, British Columbia, and the Northwest Territories, Keg River Formation carbonates formed a prominent barrier reef—the Presqu'ile Barrier—which bordered the open ocean to the northwest. Towards the end of Keg River buildup growth within the LARP study area, the vertically accreting Presqu'ile Barrier carbonates coalesced into a continuous barrier that acted to restrict the Elk Point Basin from its open-marine connection. This resulted in intense evaporitic drawdown and the accumulation of the thick evaporites of the Prairie Evaporite Formation.

The uppermost units of the Upper Elk Point subgroup are an enigmatic association of shales, carbonates, and evaporites, which unconformably overlie the Prairie Evaporite Formation. This thin but complex amalgam of facies, deposited in a variety of marine and terrestrial environments, is the result of widespread changes in relative sea level associated with at least one major subaerial unconformity (Meijer Drees, 1994). The Dawson Bay Formation, including the dolomitic and calcareous argillaceous shale of its basal Second Red Bed Member, and the overlying First Red Bed unit, can be correlated from Saskatchewan into the southern part of the study area (Dunn, 1982). The Dawson Bay Formation pinches out to the north and west. In this study the whole interval is mapped as the Watt Mountain Formation.

Orogenic loading during the formation of the Canadian Cordillera resulted in gentle westerly dips of Paleozoic strata in the study area, which, as a consequence, subcrop youngest to oldest successively from west to east at the sub-Cretaceous unconformity. Elk Point strata outcrop at the basin margin in the east, or subcrop beneath a relatively thin veneer of Cenozoic siliciclastics. As such, these strata have been subjected to a protracted period of subaerial exposure and numerous episodes of infiltration by meteoric water. One such event occurred before and during Cretaceous Mannville Group sedimentation, resulting in the removal of halite and anhydrite from the Prairie Evaporite Formation. This evaporite dissolution resulted in the collapse of the overlying Devonian succession (Beaverhill Lake Group and younger), which created a very large volume of accommodation space—an elongate subsidence trough (Warren, 2006)—that was subsequently filled by lower Mannville Group sediments (Wightman and Pemberton, 1997; Hein, 2006; Broughton, 2015). Intrastratal dissolution of halite within the Prairie Evaporite Formation resulted in the development of a conspicuous southeast-trending dissolution scarp throughout northeastern Alberta that continues along the basin margin in central Saskatchewan (Meijer Drees, 1994). Part of this mapping study involves improving the location and extent of the Prairie Evaporite halite dissolution scarp in the study area using recent well control.

2.3 Beaverhill Lake Group

Deposits of the Beaverhill Lake Group mark a significant change in conditions across the Alberta Basin. The predominance of evaporites accumulating during restricted-basin conditions, as in the older Elk Point Group strata, made way for persistent open-marine conditions and the accumulation of thick successions of carbonates and calcareous, fine-grained siliciclastics. Initial conditions after deposition of the Watt Mountain Formation show a gradual increase in marine influence, with sabkha-like (anhydritic) deposits of the Fort Vermilion Formation overlain gradually and conformably by carbonates of the Slave Point Formation (Figure 3). From the Slave Point Formation on, conditions in most of the basin remained favourable for carbonate growth; however, for the first time in the Devonian, large volumes of terrigenous, fine-grained clastics were introduced into the basin, ostensibly from the drowning of the Presqu'ile Barrier and the transport of clastics from the northerly Franklinian or Caledonian orogenic belts (Boghossian et al., 1996; Wendte and Uyeno, 2005). During Beaverhill Lake Group time, stratigraphic architecture is one of basin-margin fringing carbonate platforms and associated isolated reefs, with intervening basinal environments accumulating fine-grained, mostly argillaceous siliciclastics with varying amounts of reef-derived calcareous material. On the east side of the basin, the Eastern Shelf complex (Wendte and Uyeno, 2005) is separated from the western Swan Hills Formation carbonate complex by the Waterways sub-basin. The biostromal carbonates of this system form the carbonate-rich members (Calumet and Moberly) of the Waterways Formation (Figure 3). In the study area, argillaceous members of the Waterways Formation are the Firebag, Christina, and Mildred members.

2.4 Woodbend Group

The deposition of mixed carbonates and fine-grained argillaceous siliciclastics continued from Beaverhill Lake time into the Woodbend Group. Carbonates of the Cooking Lake Platform were deposited over the Eastern Shelf complex, with similar western extents. An increase in the rate of relative sea-level rise accommodated the growth of thick, isolated, atoll-like reef complexes of the Leduc Formation. These reef complexes accumulated in a continuous barrier-like fashion along the western margin of the Cooking Lake Platform, with some isolated complexes inboard of the margin. The northernmost extent of the barrier reef trend (Rimbey-Meadowbrook) occurs in the northwest of the study area and is known as the Calling Lake reefs (Switzer et al., 1994). Overlying the Cooking Lake Platform, and encasing the Leduc reef complexes, are the argillaceous carbonates and calcareous shales of the Ireton Formation. Also encased in the Ireton Formation shales is the Grosmont Formation platform complex, which prograded to the south and southwest. The Grosmont Formation is partly equivalent to the Leduc Formation and also postdates it (Stoakes, 1980). Deposition of the Grosmont Platform carbonates is related to regressive basin filling of Ireton clinoforms and represents the landward expression of such clinoforms (Stoakes, 1992a). The Grosmont Formation can be subdivided into four shoaling-upwards cycles, the bases of which comprise basinal argillaceous carbonates that are regionally correlatable (Cutler, 1983). In ascending stratigraphic order, they are the lower Grosmont and upper Grosmont 1, 2, and 3 units (Figure 3). The Grosmont Formation is overlain by argillaceous carbonates recognized as the 'upper' Ireton, which mark the cessation of carbonate deposition during Woodbend Group time.

2.5 Winterburn and Wabamun Groups

Strata of the Winterburn and Wabamun groups are restricted to a geographically small area in the southwest of the study area. Following deposition of the upper Ireton Formation, renewed relative sea-level rise in the basin resulted in carbonate deposition of the Nisku Formation (Watts, 1987; Stoakes, 1992b). The Nisku Formation is overlain by a thin silty shale known as the Calmar Formation, which is in turn overlain by carbonates of the Blue Ridge Member of the Graminia Formation. Blue Ridge carbonates are overlain by the upper Graminia Silt member (Meijer Drees et al., 1998). Carbonates of the Wabamun Group overlie the Graminia Silt member and are undifferentiated in the study area. Within the Alberta Basin, Wabamun Group strata formed an extensive and thick carbonate-ramp succession (Halbertsma and Meijer Drees, 1987).

3 Methods

There are 76 584 wells drilled in the 874 townships that span the study area (Figure 4). The majority of these wells were drilled for hydrocarbon prospectivity in the Cretaceous Mannville Group. Using wells drilled to November of 2014, only 1307 wells are drilled to depths that allow for the delineation of Paleozoic stratigraphy in the study area (Figure 4). Of these wells, only 235 are drilled through the entire sedimentary succession into the Precambrian basement (204 within the model boundary). The Paleozoic dataset of 1307 wells represents the most comprehensive and regionally extensive database of such well control in northeastern Alberta to date. Within the model boundary, 1162 wells penetrate the Paleozoic succession, from which 8470 individual stratigraphic picks were made.

Many of the 76 584 wells in the study area are drilled into the Devonian succession, but these wells commonly bottom out roughly 10–20 m within the Devonian, just below the sub-Cretaceous unconformity, which hampers delineation of the stratigraphy with any confidence. These wells provide important information on the elevation of the sub-Cretaceous unconformity surface; however, they usually do not provide any additional information regarding the underlying Devonian stratigraphy. In addition to the 1307 wells forming Paleozoic well control, 7188 wells that just tag the sub-Cretaceous unconformity were used to construct the structural elevation of that surface (Figure 4). This additional dataset for the unconformity was produced by AGS geologists B. Hathway and J.T. Peterson, and includes previous datasets (i.e., Wynne et al., 1994; Alberta Energy and Utilities Board, 2003) that were reviewed for consistency and accuracy with respect to recent AGS picks at the unconformity.

Even though there is a relative paucity of wells drilled to any significant depth into the Paleozoic succession, a surprising number of lengthy cores have been taken therein. These cores provide a wealth of important information on the composition of the succession under scrutiny and allowed for lithological calibration of wireline logs.

3.1 Lithostratigraphic Correlation

Lithostratigraphic correlation was accomplished using the computer software Petra. A comprehensive suite of well logs—electric, porosity, and lithology—was used to delineate subsurface stratigraphy. An extensive series of strike- and dip-oriented cross-sections was used for correlation. Where available, cores were reviewed for lithological calibration of logs and for determining criteria for the lithostratigraphic pick framework. Vertical wells were used preferentially, but where data sparsity necessitated the use of deviated wells, additional quality control criteria were followed to make sure the associated deviation surveys were implemented properly.

There are very few wells drilled into the Devonian strata in the northeastern part of the study area, near the edge of the Phanerozoic succession (Figure 4). Subcrop edges from Prior et al. (2013) and Okulitch (2006) were used to aid in modelling the Paleozoic succession. Updates to these subcrop edges were made based on new well control.

A number of additional mineral exploration cores and outcrops provided lithological and structural information used in the construction of the model: two cores of Waterways Formation strata at the Hammerstone Quarry north of Fort McMurray and two outcrops of Waterways Formation strata along the Athabasca River north of Fort McMurray.The stratigraphic pick datasets produced in Petra for 38 surfaces

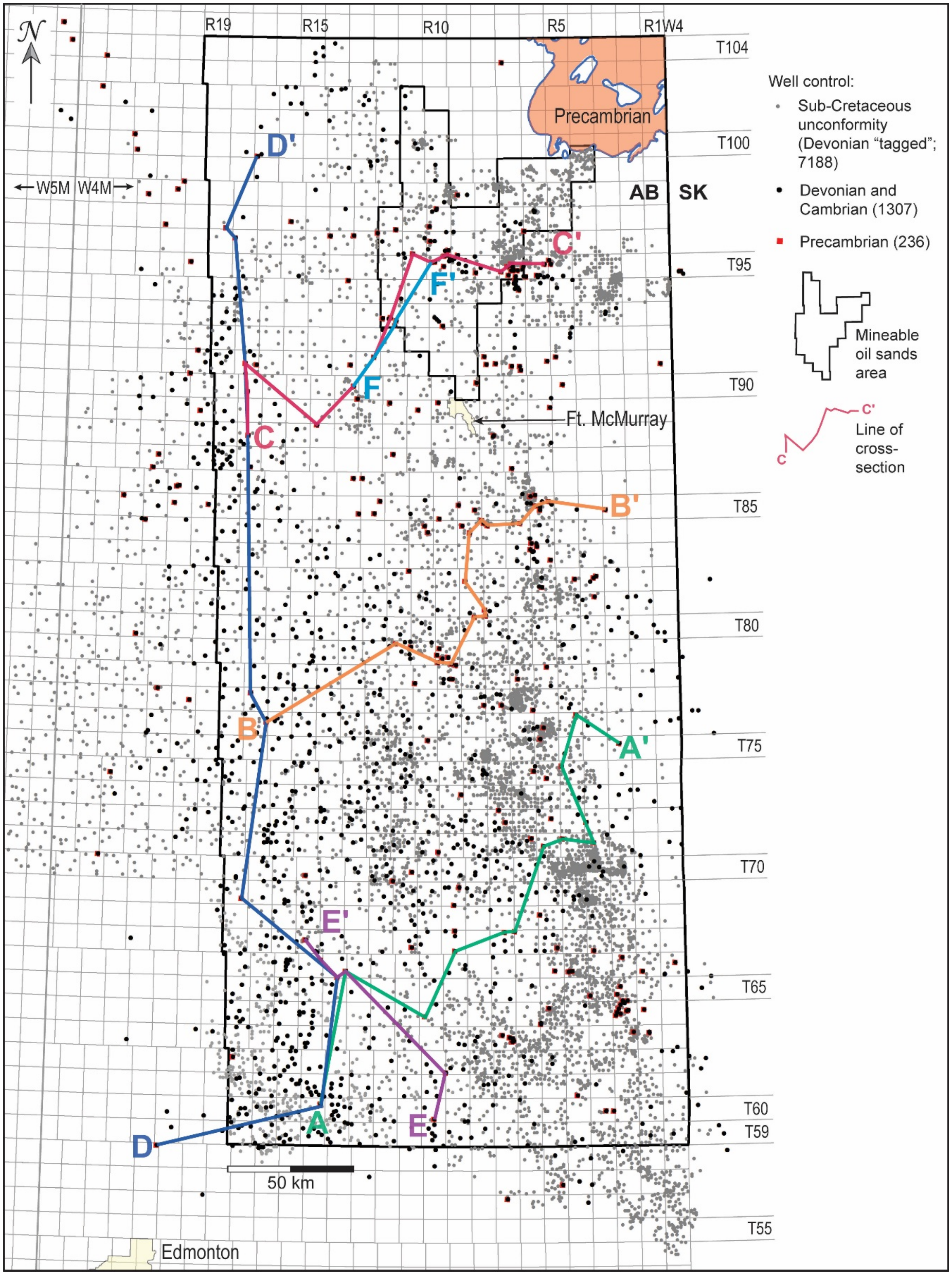

Figure 4. Well control used for mapping the Paleozoic succession (black dots) and the sub-Cretaceous unconformity surface (grey dots) in the study area. The model boundary is in black, within which 1162 wells were used to build the model (Hauck, 2018). Lines of cross-section representing Figures 5, 9, 10, 11, 12, and 14 are shown.

(Paleozoic strata and the sub-Cretaceous unconformity surface; Figure 3) were imported into ArcMap for geostatistical evaluation and outlier detection. Early stages of data culling involved subtracting the reported kelly bushing (KB) elevation from the reported ground elevation (GR); a difference of more than 7.3 m (a common maximum distance of the KB from the ground on a triple drilling rig) is commonly indicative of erroneous data, leading to inaccurate calculated elevation values for the stratigraphic pick in the subsurface. Where the difference was greater than 7.3 m, the reported KB and GR elevations were reviewed on an original raster log from the well; these reported values replaced the erroneous ones in the database; if the KB and GR difference remained greater than the threshold, the well was removed from the dataset. Wells in the sub-Cretaceous unconformity, McMurray, and Wabiskaw pick datasets were further culled by comparing the reported GR to a digital elevation model sampled to the well trace in Petra. Wells were culled where there was a difference greater than 2 ±9 m (i.e., –7 to 11 m) in these two values.

3.2 Refining the Delineation of the Prairie Evaporite Halite Dissolution Scarp

Net evaporite mapping of halite and anhydrite within the Prairie Evaporite Formation was undertaken to support the delineation of the Prairie Evaporite halite dissolution scarp with increased accuracy. In the study area, 370 wells penetrate through the Prairie Evaporite Formation. These wells provided information on the thickness of the formation. A dataset of 177 modern wells (post-1985) was used to produce net thicknesses of halite and anhydrite based on their distinct log responses in modern log suites (Figure 5). In addition, we used 36 wells drilled before 1970 with net evaporite data for halite and anhydrite derived from older electric logs and supplemented with core and drill cuttings (Hamilton, 1971).

A number of regionally correlatable members and marker beds were mapped throughout the study area, which provided information on the nature of the dissolution of the Prairie Evaporite deposits within the dissolution scarp. The member and marker-bed nomenclature is a combination of that used in Saskatchewan (Reinson and Wardlaw, 1972), eastern Alberta (Meijer Drees, 1986, 1994), and one additional new marker bed—the Conklin—named after the town of Conklin, where it was first recognized (Figure 5).

3.3 Modelling the Surfaces in 2.5D

Before importing the stratigraphic picks into Petrel for 3D modelling, 2.5D surfaces of the top of each stratigraphic unit were interpolated using the ordinary kriging algorithm within ESRI’s ArcMap software. The 2.5D surfaces were built in order to visualize the top surface of each unit within 3D space and assess where potential issues (such as cross-overs between surfaces) may arise when building the 3D model (Figure 6).

The geostatistical wizard in ArcMap allowed a local first-order trend to be modelled and removed from the data before interpolation. Cross-validation results were calculated for each surface, and errors based on the difference between the predicted and measured values were reviewed for potential outliers. The tolerance for the outliers depended on the structural complexity of the surface but typically remained within two or three standard deviations from the mean. Picks identified as potential outliers were reviewed in Petra, and the appropriate changes were made if necessary. A number of cross-validation iterations were done for each stratigraphic unit before the final set of data points was imported into Petrel to build the 3D model.

Devonian subcrop edges at the sub-Cretaceous unconformity surface were produced in two ways: 1) for the Cooking Lake Formation and younger units, the subcrop edges were produced by viewing well control ascribed to stratigraphic units at the sub-Cretaceous unconformity surface, and lines were drawn accordingly; and 2) for the members of the Waterways Formation (Firebag, Calumet, Christina, Moberly, and Mildred), modelled elevation surfaces of each respective member were intersected with the modelled elevation surface of the sub-Cretaceous unconformity (Figure 7). The intersection of the two surfaces was

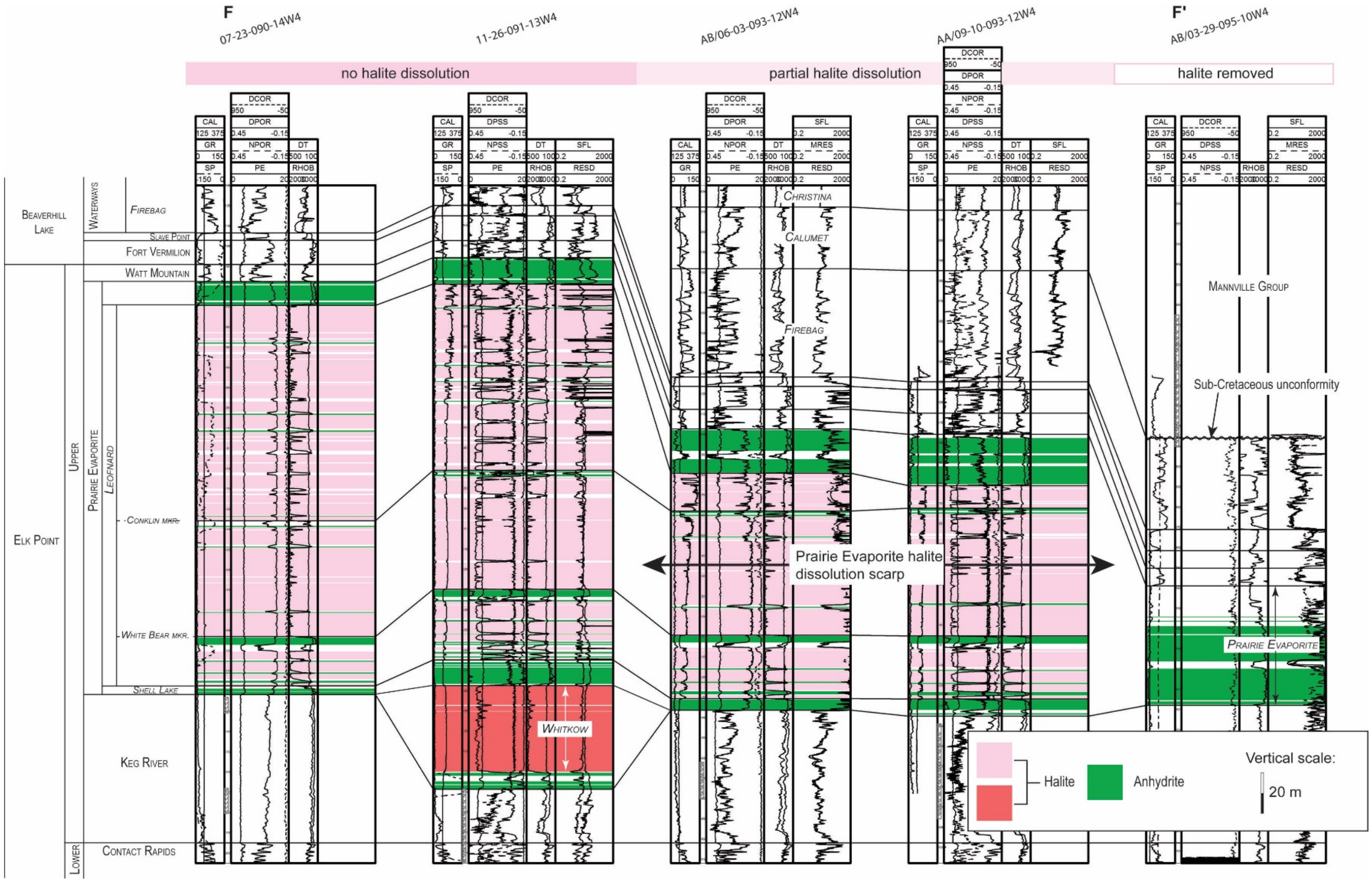

Figure 5. Northeast-southwest stratigraphic cross-section F-F′ (Figure 4; datum = top Contact Rapids Formation), showing the distribution of mapped halite and anhydrite within the Prairie Evaporite Formation. The cross-section runs across the Prairie Evaporite halite dissolution scarp (see Figure 4). Prairie Evaporite member and marker bed stratigraphy used herein are shown. Abbreviations: CAL, caliper (mm); GR, gamma-ray (API); SP, spontaneous potential (mV); DCOR, density correction (g/cm^3); DPOR, density porosity (limestone matrix, v/v); NPOR, neutron porosity (limestone matrix, v/v); DPSS, density porosity (sandstone matrix v/v); NPSS, neutron porosity (sandstone matrix, v/v); PE, photoelectric effect (barns/electron); DT, sonic travel time (µs/m); RHOB, bulk density (g/cm^3); SFL, spherically focused log (shallow resistivity, ohm-m); MRES, medium resistivity (ohm-m); RESD, deep resistivity (ohm-m).

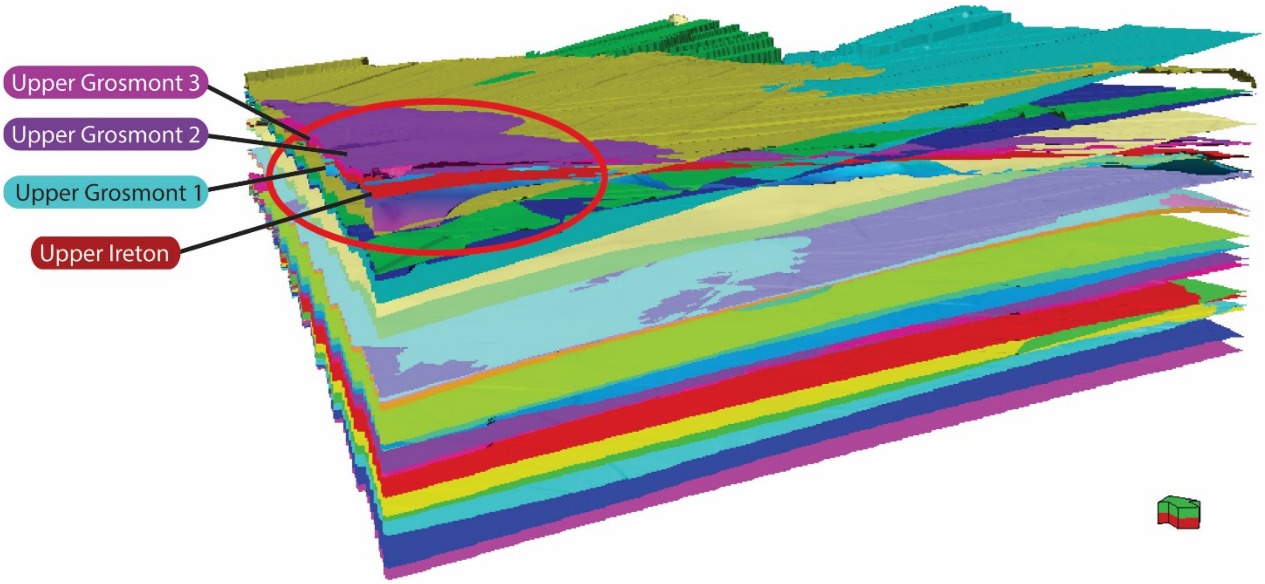

Figure 6. Example of cross-overs in 2.5D structural surfaces built within ArcMap using the ordinary kriging algorithm. The red circle highlights an area where the grids for the upper Ireton (red), upper Grosmont 1 (light blue), upper Grosmont 2 (purple), and upper Grosmont 3 (pink) initially crossed over one another, thus requiring additional manual manipulation to ensure a more accurate geological representation. The model has a vertical resolution of 50x.

transformed into a polyline that could be used to help constrain the geological unit extents during 3D model construction. This procedure works well for areas unaffected by structure caused by the removal of halite in the Prairie Evaporite Formation; however, east of the dissolution scarp, structure is largely controlled by the paleotopography created by the draping of the Waterways Formation over underlying Keg River buildups. As such, using the polygons created by the intersection of member surfaces with the sub-Cretaceous unconformity is tenuous. Instead, the intersection was used as a rough guide and was combined with well control and overlain on the paleotopographic reconstruction of the sub-Cretaceous unconformity surface. Together, these elements were used to better inform the drawing of subcrop edges for the members of the Waterways Formation.

3.4 Building the 3D Model

The geostatistically verified picks, 2.5D surfaces, and geo-edges for each formation were imported into Petrel to be integrated into the 3D model. The picks for each formation were modelled in Petrel using a convergent interpolator and then compared to the grids produced in ArcMap by the geologists to ensure consistency. The surfaces were modelled using a grid-cell size of 500 m, which provides a high level of detail for a study area covering 83 334 km^2. Models covering similar geographic extents typically use grid-cell sizes between 1000 m and 5000 m (Berg et al., 2011), making the model and grids produced for this study substantially more detailed.

The Petrel surfaces were intentionally modelled to cover the entire study area, ensuring that the volume occupied by each stratigraphic unit was completely sealed during construction of the 3D model. However, the majority of the stratigraphic units in this model do not cover the entire study area, which required the integration of geo-edges (subcrop and zero-edge) provided by the geologists to constrain the surfaces in areas where they are not present. The geo-edges were used to modify the 2.5D surfaces so that they could be merged with other intersecting grids in areas where the units were either eroded or not deposited (Figure 7). This allowed the 2.5D surface for each stratigraphic unit to extend across the entire model area to ensure that the 3D model volumes were sealed and the spatial extent for each unit was accurately represented. Once all the surfaces that required merging were properly characterized, the modified surfaces were selected and their relationship to the other surfaces was defined as either base, conformable, or erosional in the modelling workflow in Petrel. The majority of the stratigraphic unit surfaces were set to be conformable to one another, with the exception of the Precambrian surface, which was set as the base of the model, and the sub-Cretaceous unconformity and bedrock topography surfaces, which were set as erosional and thus truncate any surface that intersects them from below. The sub-Devonian due to poor well control, was modelled as two separate surfaces: the Precambrian surface in the north and the top of the Cambrian succession in the south.

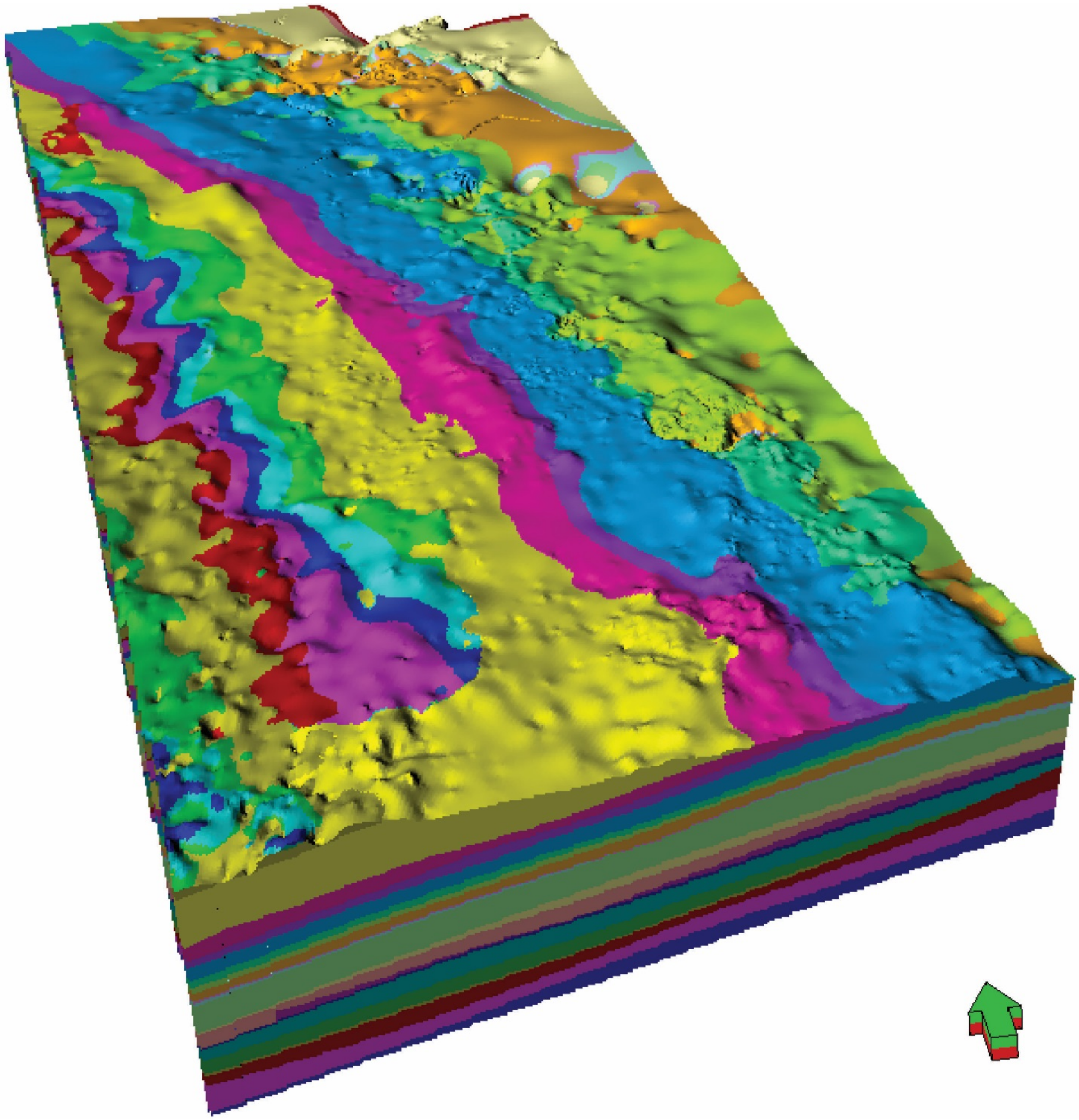

Figure 7. View of the sub-Cretaceous unconformity in the LARP model, looking to the northeast (see Figure 13 for map view and names of the subcropping units). Model width is 183.5 km and has a vertical exaggeration of 50x.

3.4.1 Modelling Complications

There were a few modelling complications that required extra attention during the construction of the 3D model, such as the modelling of the sub-Cretaceous unconformity and that of the Grosmont Formation carbonate complex. All underlying geological units were modelled and projected through the sub-Cretaceous unconformity to determine the projected subcrop extent. Subcrop extents provided by the geologist were imported and compared against the projected extents. Areas where these two extents differed were highlighted and sent back to the geologist for review. The final subcrop extent polyline was used as control data to constrain and merge the stratigraphic unit surface into the sub-Cretaceous unconformity surface beyond the subcrop extent line. This was necessary to ensure that no formation artifacts (occurrences of stratigraphic units beyond their known zero-edge or subcrop extent) were present in the final 3D model.

The Grosmont Formation is present in the southwestern corner of the study area and represents a multilevel carbonate complex that prograded to the south and southwest. Ensuring that the complex nature of the Grosmont carbonates was accurately represented in the model required multiple steps to build the Grosmont complex from the bottom up. The first step involved building the lower Ireton Formation, which both underlies the Grosmont and thickens appreciably to the southwest of the Grosmont complex, where it transitions to shales along a series of clinoforms. The thickness of the Grosmont Platform in the southwest corner of the study area is therefore taken up lithostratigraphically by the shaly lower Ireton Formation. Modelling this geometry results in a thick lower Ireton zone that reaches the base of the Nisku Formation in the southwestern corner of the model (Figure 8).

There were multiple modelling-process steps that were performed in order to ensure that the complex stratigraphic architecture of the Grosmont Formation and the equivalent off-platform shales of the lower Ireton Formation were accurately characterized. The first step involved constraining the lower Grosmont unit, which covers a small portion of the lower Ireton relative to the overlying Grosmont units (i.e., progrades over the lower Ireton to a lesser extent; Figure 8), by merging the lower Grosmont surface with the lower Ireton surface in the areas outside of the lower Grosmont geo-edge. For the upper Grosmont 1 unit, which is more extensive and covers a greater portion of the lower Ireton (Figure 8), the spatial extent of the upper Grosmont 1 unit was constrained by making the surface outside the upper Grosmont 1 polygon equal to the lower Grosmont surface (where the unit is present) and then equal to the lower Ireton surface where the lower Grosmont unit is not present. The same approach was subsequently applied to the upper Grosmont 2 and 3 and upper Ireton units. For all units described, this process constrained the spatial extents by using the geo-edge polygons to merge the Grosmont and upper Ireton surfaces to the underlying surfaces outside their respective polygon extents. This correlation and modelling approach means that some of the lower Ireton unit outside of the Grosmont Formation will include a small portion of the time-equivalent upper Ireton unit.

4 Results

4.1 Mapping

4.1.1 Precambrian Basement

Precambrian basement rocks floor the Phanerozoic sedimentary succession in the study area. Precambrian crystalline rocks have been modified by metamorphism, deformation, and magmatism during Archean to Paleoproterozoic tectonic events (Burwash et al., 1994). In the study area, Precambrian rock underlies most of the Devonian succession, with the exception of the area where Cambrian siliciclastics are present in the southern part of the study area. Precambrian basement rocks have wide-ranging wireline log characteristics but generally display high resistivity values and sharp increases in such readings across the basement unconformity (Figures 9, 10, 11, and 12). A total of 236 wells that penetrate the basement were used in the study, with 204 of these within the model boundary (Figure 4).

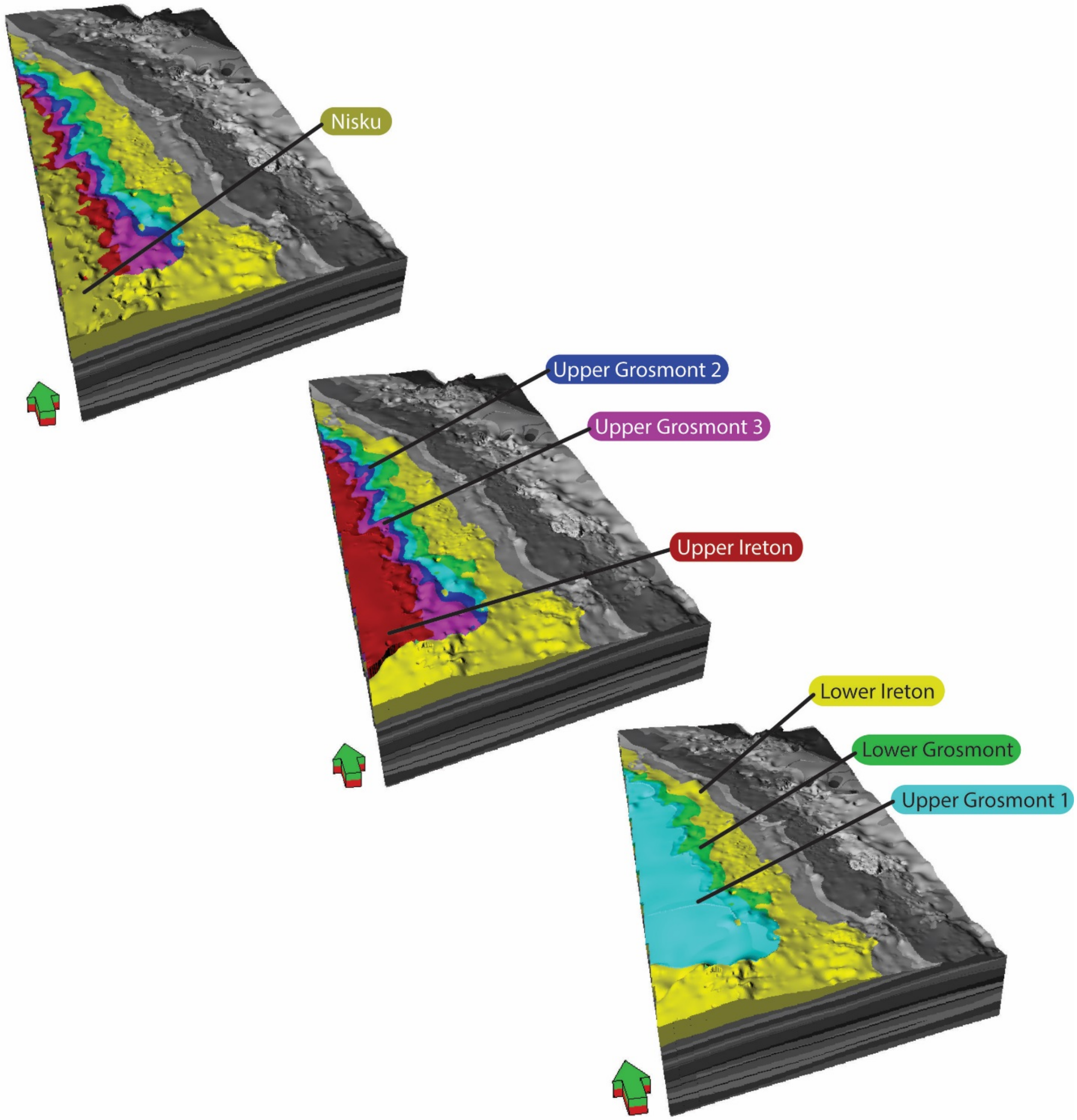

Figure 8. Images of the 3D LARP model showing the individual units of the Grosmont Formation and associated bounding strata. Complexity in the architecture of the Grosmont Formation interval is a result of each unit having different depositional extents (i.e., Grosmont facies transition to lower Ireton shaly facies to the southwest) coupled with erosional truncation at the sub-Cretaceous unconformity. Model width is 183.5 km and has a vertical exaggeration of 50x.

4.1.2 Cambrian System

Cambrian strata are restricted to the southern part of the study area, having been erosionally truncated before Devonian deposition (i.e., they form part of the sub-Devonian unconformity; Figure 13A). The lowermost Cambrian unit is the Basal Sandstone unit, which comprises arkosic sandstones that are increasingly mature and quartzose up-section. The sandstones nonconformably overlie Precambrian crystalline rock. The upper contact with the silty and sandy shales of the Earlie Formation is gradational (Figures 9 and 12), recording continued transgression, gradual deepening in the basin, and deposition of finer siliciclastics in shoreface settings. At the sub-Devonian unconformity, the Earlie Formation and the Basal Sandstone unit are overlain by Lower Devonian clastics in the form of redbeds deposited in the central Alberta sub-basin (Meijer Drees, 1994; Figures 9 and 13).

4.1.3 Lower Elk Point Subgroup

Strata of the Lower Elk Point subgroup (Figure 3) record Early(?) to Middle Devonian deposition on pronounced regional topography in the basin. Two major depocentres are evident in the study area: the central Alberta sub-basin and the southern part of the northern Alberta sub-basin. These depocentres are separated by the Athabasca Arch—the eastern extension of the Peace River Arch located in west-central Alberta.

4.1.3.1 La Loche Formation and Basal Red Beds Unit of the Lotsberg Formation

The base of the Devonian succession in the study area comprises a mixture of redbeds and arkosic to quartzose sandstones of the basal red beds unit of the Lotsberg Formation and the La Loche Formation, respectively. The basal red beds are closely associated with deposition of the overlying Lotsberg Formation evaporites in the central Alberta sub-basin (Figures 9, 10, 12, and 13A). The sandstones of the La Loche Formation become more distinct in the central to northeastern part of the study area, thickening in paleotopographic lows of the Precambrian basement. Due to the difficulty in distinguishing the basal red beds from the La Loche Formation where modern log suites are absent, the two units are combined for modelling purposes. The combined clastics cover most of the study area up to the Phanerozoic edge, with rare instances where the clastics are missing over Precambrian basement highs (Figure 13A).

4.1.3.2 Lotsberg Formation

The Lotsberg Formation comprises two distinct halite packages that are fringed, and bounded above and below, by redbeds. The upper and lower Lotsberg units are separated by the middle red beds unit of the Lotsberg Formation (Figure 3). The middle red beds merge with the basal red beds beyond the depositional limit of the lower Lotsberg, which is areally smaller than the overlying upper Lotsberg (Figures 9, 10, 11, and Figure 13A). The deposits of the Lotsberg Formation are restricted to the central Alberta sub-basin. The northern limit of upper Lotsberg halite roughly defines the northern edge of the central Alberta sub-basin (Figure 13A).

4.1.3.3 Ernestina Lake Formation

The Ernestina Lake Formation overlies the halite of the Lotsberg Formation in the area of the central Alberta sub-basin, and the basal Devonian clastics (basal red beds unit / La Loche Formation) beyond the limit of Lotsberg Formation halite (Figures 9, 10, 11, and 12). Where the Ernestina Lake overlies halite of the Lotsberg Formation, a lower red bed unit forms the base of the formation (Figures 9, 10, and 12); however, where the Ernestina Lake Formation overlies the basal Devonian clastics, wireline logs alone do not allow for the differentiation of the basal Devonian clastics from the lower red bed unit associated with the Ernestina Lake Formation (Figure 11). In this case, the lower red bed interval of the Ernestina Lake Formation is mapped with the basal Devonian clastics (i.e., basal red beds unit / La Loche Formation). The Ernestina Lake Formation is absent in the northeastern part of the study area (Figure 13A).

4.1.3.4 Cold Lake Formation

Overlying the anhydrite of the Ernestina Lake Formation, the Cold Lake Formation consists of halite with an associated lower red bed unit. This formation is restricted in the study area to the northern and central Alberta sub-basins, which are separated by the Athabasca Arch (Figure 13A). The eastern edge is roughly coincident with the eastern edge of the Prairie Evaporite halite dissolution scarp (Figure 13B), suggesting possible similar halite dissolution in the unit rather than a strictly depositional eastern limit (Figure 13A). However, in the central Alberta sub-basin, anhydrite of the Ernestina Lake Formation persists beyond the

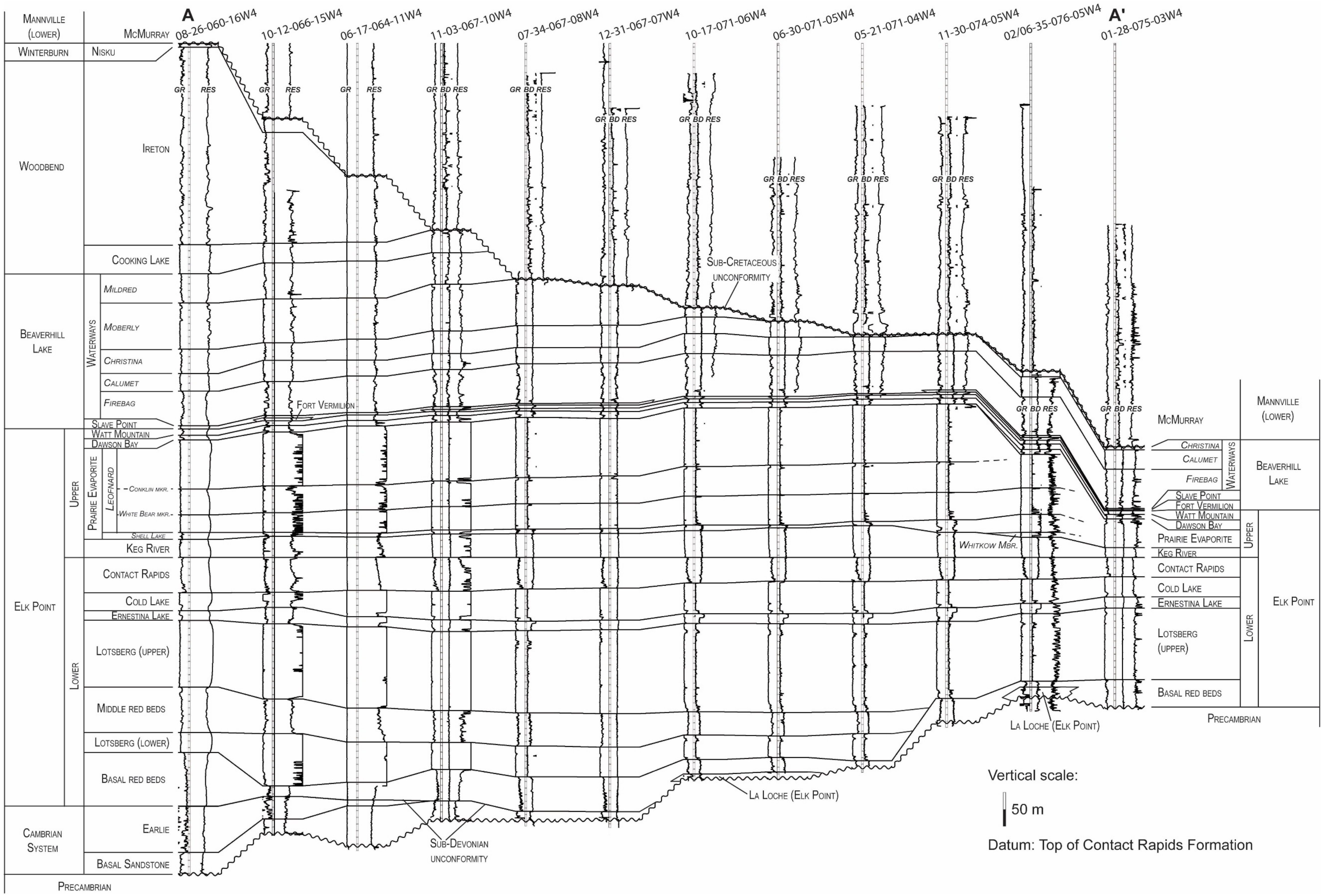

Figure 9. Dip-oriented stratigraphic cross-section A–A′ (Figure 4; datum = top of Contact Rapids Formation). The cross-section runs through the Prairie Evaporite halite dissolution scarp. The mapping of member and marker beds within the Prairie Evaporite Formation reveals that halite in the dissolution scarp area was removed from the top down. In well 02/06-35-076-05W4, the halite of the upper portion of the Leofnard Member has been removed, whereas the halite from the Conklin marker bed downwards remains intact.

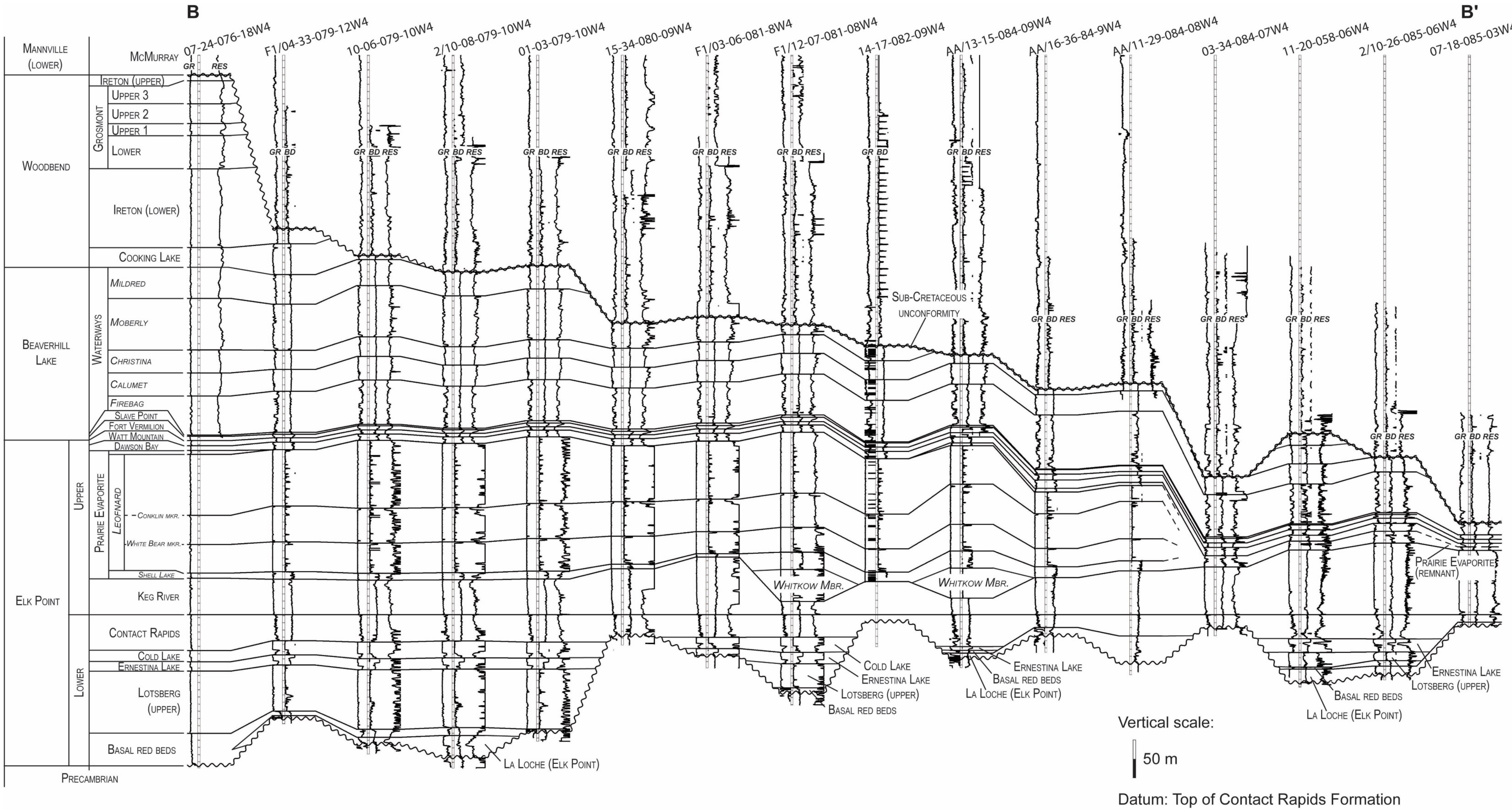

Figure 10. Dip-oriented stratigraphic cross-section B–B′ (Figure 4; datum = top of Contact Rapids Formation). The cross-section runs through the Prairie Evaporite halite dissolution scarp. The mapping of member and marker beds within the Prairie Evaporite Formation reveals that halite in the dissolution scarp area was removed from the top downwards. In wells AA/16-36-084-9W4 and AA11-29-084-08W4, the halite of the upper portion of the Leofnard Member has been removed, whereas the halite from the Conklin marker bed downwards remains intact. East of the dissolution scarp where all halite has been removed, the strata of the Beaverhill Lake Group drape the topography created by Keg River paleotopography (wells 03-34-084-07W4 and east to B′).

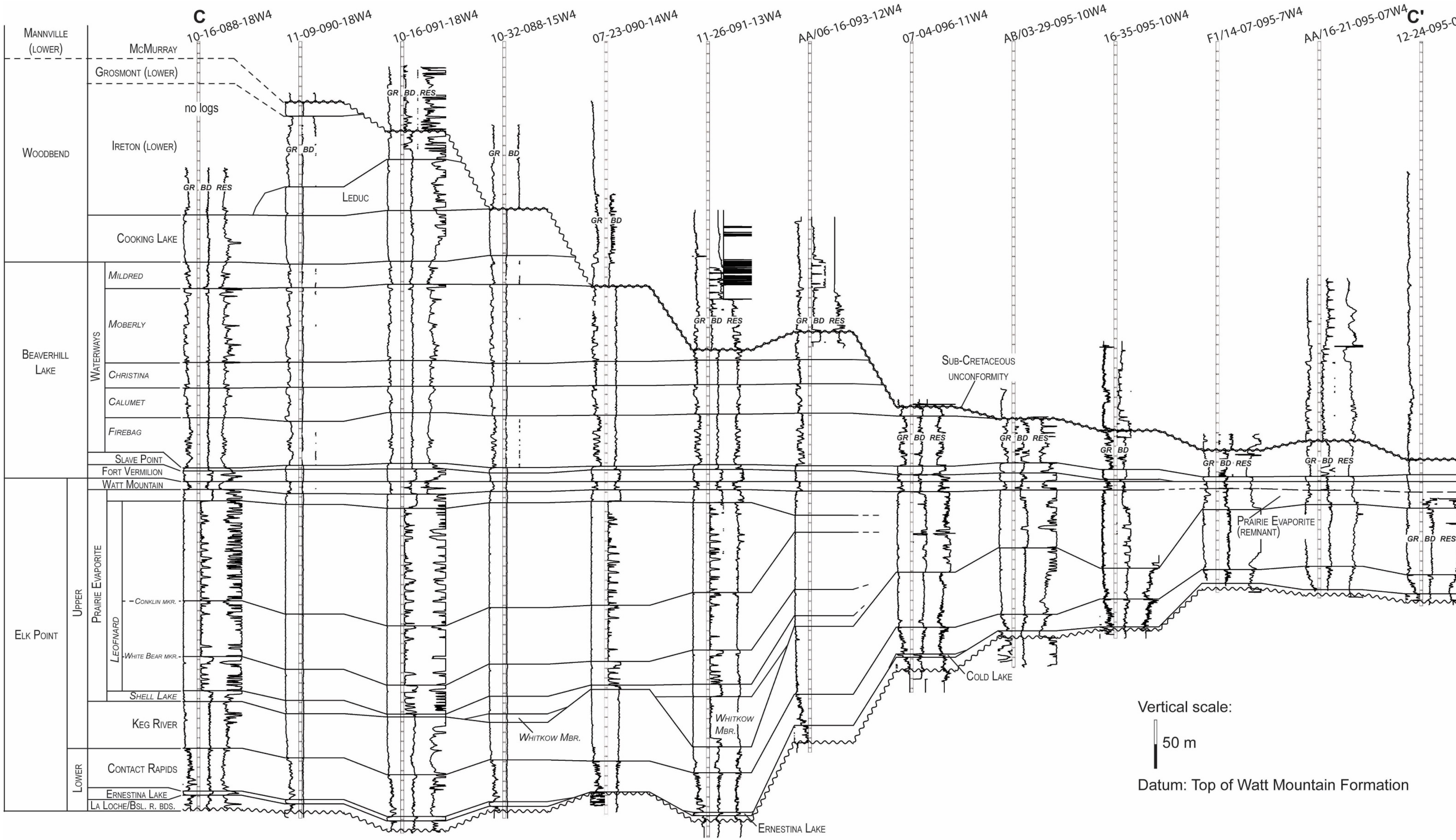

Figure 11. Dip-oriented stratigraphic cross-section C–C′ (Figure 4; datum = top of Watt Mountain Formation). The cross-section shows the Leduc Formation reefs (Calling Lake reefs) subcropping at the sub-Cretaceous unconformity (between wells 10-16-091-18W4 and 10-32-088-15W4). The top-down removal of halite in the Prairie Evaporite Formation is evident.

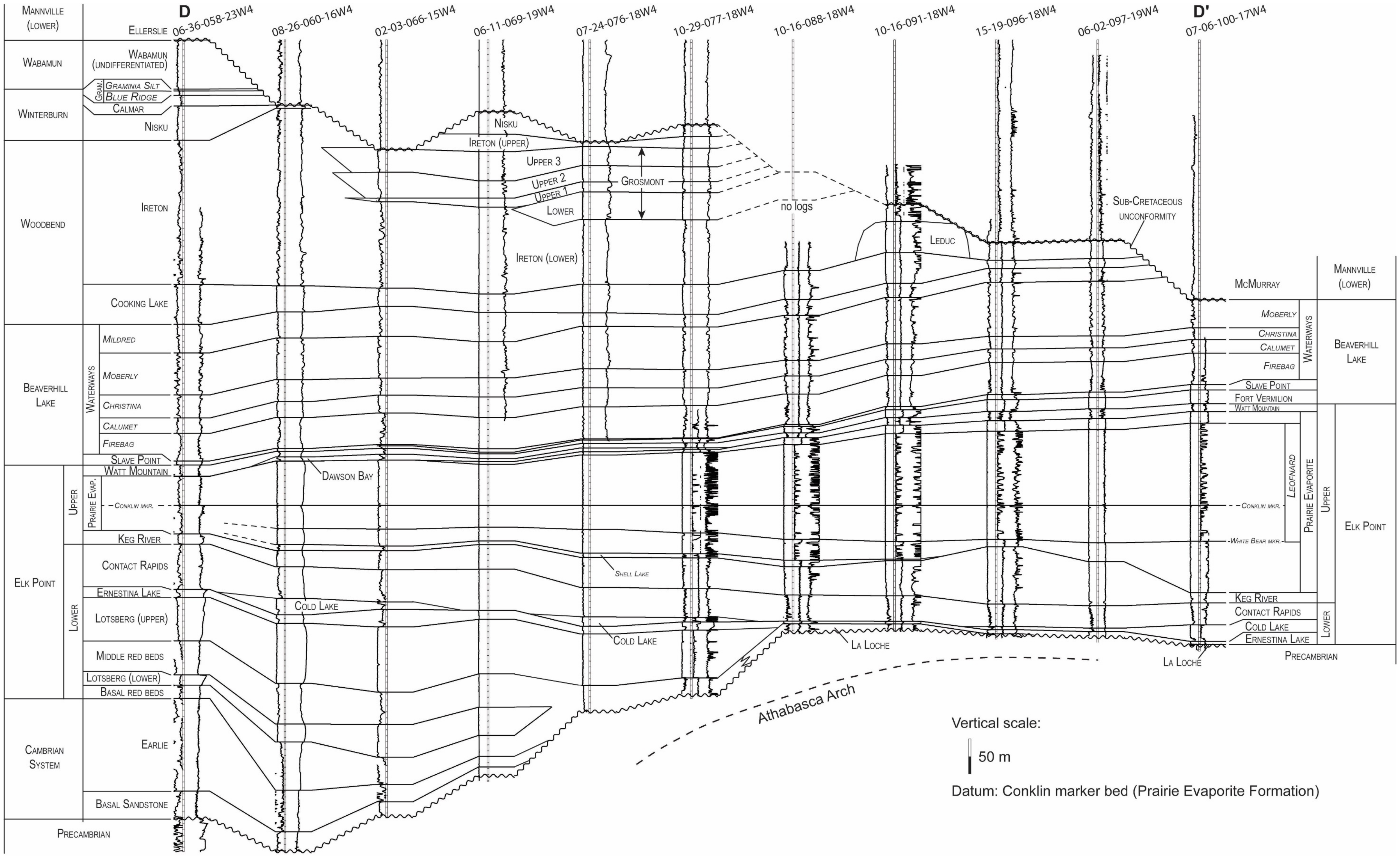

Figure 12. Strike-oriented stratigraphic cross-section D–D′ (Figure 4; datum = Conklin marker bed of the Prairie Evaporite Formation). The cross-section runs across the Wabamun Group, Winterburn Group, and Grosmont Formation subcrop belts. The sub-Devonian unconformity occurs at the top of the Cambrian strata. The central Alberta sub-basin is present where the Lotsberg and Cold Lake formations accumulated in the south (left). Farther north, at well 07-06-100-17W4, the halite of the Cold Lake Formation accumulated in the northern Alberta sub-basin.

Figure 13. Depositional and erosional (subcrop) extents of Paleozoic strata in the study area: A) Cambrian to Keg River extents; nondepositional inliers occur for the basal siliciclastics (basal red beds unit and La Loche Formation); one nondepositional inlier occurs in the south for the Keg River Formation (see Figure 10); B) Prairie Evaporite Formation to Beaverhill Lake Group extents, with the location of the Prairie Evaporite halite dissolution scarp; C) subcrop extents of the members of the Waterways Formation to the Wabamun Group (see inset); most subcrop extents parallel the orogenic front due to basin tilting to the southwest and subsequent erosional backstripping. Subcrop belts of the Moberly, Christina, and Calumet members are more complex due to the draping of these members over Keg River paleotopography—coupled with sub-Cretaceous erosion—past the Prairie Evaporite halite dissolution scarp.

eastern edge of the Cold Lake Formation, which may be due to the lower solubility of anhydrite rather than suggesting that both units are unaffected by dissolution in this area.

4.1.3.5 Contact Rapids Formation

The Contact Rapids Formation is the uppermost stratigraphic unit in the Lower Elk Point subgroup (Figure 3) and records deposition across a much subdued sub-Devonian paleotopography. As such, the unit overlies a wide range of older Devonian units (Figures 9, 10, 11, and 12). The eastern extent of the Contact Rapids Formation is roughly coincident with the Phanerozoic edge in the northeastern part of the study area (Figure 13); due to a scarcity of well control in the northeast, this erosional/depositional limit is taken from the bedrock geology map of Prior et al. (2013). There is one well penetration in which a nondepositional inlier (i.e., Contact Rapids Formation was not deposited at this location) is recognized west of the erosional edge (Figure 13). The Contact Rapids Formation is mostly uniform in thickness across the study area but may thin considerably over Precambrian basement paleotopographic highs along the northern limit of the central Alberta sub-basin in the central part of the study area (Figure 10).

4.1.4 Upper Elk Point Subgroup

The Upper Elk Point subgroup records Eifelian to Givetian deposition (Figure 3). Strata of the Upper Elk Point subgroup herald significant changes in the basin, with extensive carbonate complexes developing during the early part of the subgroup's deposition. Carbonates were deposited across much of the basin during renewed flooding and establishment of marine conditions conducive to the carbonate factory. Marine conditions once again deteriorated due to a continuous barrier reef—the Presqu'ile Barrier—that blocked the open-marine connection to the northwest of the Elk Point Basin. Thick deposits of evaporites were subsequently deposited for much of the remainder of the Upper Elk Point subgroup time.

4.1.4.1 Keg River Formation

The Keg River Formation can be informally subdivided into a widespread lower platform or ramp member and a less widespread fossiliferous upper member that accumulated with noticeable topography on the lower member (Figure 3). In the model, the two informal members are mapped together as one unit due to the difficulty in separating the two of them based on wireline logs alone. The Keg River Formation rests conformably on the calcareous and dolomitic shales of the Contact Rapids Formation. The unit is present across most of the study area up to the Phanerozoic edge in the northeast, where it also forms part of an undifferentiated package of Elk Point Group deposits as erosional outliers resting on Precambrian deposits of the Athabasca Basin (Figure 13A; Prior et al., 2013). The Keg River Formation is absent in one well in the southernmost part of the study area, which will be discussed in Section 4.1.4.4.

The differential buildup of Keg River carbonates results in significant variability in the thickness of the formation across the study area, with a minimum thickness of 12 m and a maximum of 112 m. In the south, the Keg River Formation is mostly uniform in thickness (Figure 9); however, in central to northern locations, the thickness variability is high, with many of the late-stage Keg River buildups associated with Precambrian basement highs (e.g., Figure 10, wells 15-34-080-09W4 and 14-17-082-09W4 and Figure 11, well 07-23-090-14W4; see Hauck et al., 2017).

4.1.4.2 Prairie Evaporite Formation

The Prairie Evaporite Formation consists mainly of halite, with lesser anhydrite, dolomite, and argillaceous shale. The boundary between the Prairie Evaporite and Keg River formations is complex, with a series of transitional facies that records the change from normal-marine conditions to a period of intense evaporitic drawdown (Rogers, 2012). The lowermost unit of the Prairie Evaporite Formation mapped in the study area is the halite of the Whitkow Member, which accumulated in interbuildup areas of the Keg River carbonate complexes (Figures 9, 10, and 11). Flanking the Keg River buildups and overlying them are the dolomudstones and anhydrite of the Shell Lake Member, followed by the halite of the Leofnard Member (Figures 9, 10, 11, and 12). Two regionally correlatable marker beds were mapped within the Leofnard Member to understand the nature of the dissolution of evaporites in the Prairie

Evaporite halite dissolution scarp: the White Bear marker bed (Meijer Drees, 1994) and the Conklin marker bed (Hauck et al., 2017), which both record a pause in evaporitic drawdown in the basin with accompanying deposition of carbonate and sulphate sediments (Figures 9, 10, 11, and 12).

Thickness variability in the Prairie Evaporite Formation west of the dissolution scarp is due to the accumulation of the lower Whitkow Member halite in interbuildup areas of the Keg River Formation. The evaporites in the Prairie Evaporite Formation were subjected to substantial dissolution by undersaturated waters during exposure of the formation at the basin margin (Figures 9, 10, and 11). Removal of halite ensued at the basin margin everywhere the unit came into contact with undersaturated groundwater, resulting in a southeast-trending dissolution scarp through the study area (Meijer Drees, 1994); the location and extent of this feature are substantially updated in this study based on the evaluation of modern well control combined with historical datasets (Figure 13B; Hamilton, 1971). The dissolution scarp occupies the area extending from the edge at which the Prairie Evaporite is intact (western edge), through a zone over which halite is partially removed, to an eastern edge at which point all halite is removed (Figure 13B). East of the dissolution scarp, anhydrite and gypsum remain in the Prairie Evaporite up to a point, beyond which only insoluble residues persist. Where only insoluble residues persist, a 'remnant Prairie' pick is made, which approximates the remaining Prairie Evaporite Formation up to the erosional edge (Figures 10 and 11).

4.1.4.3 Watt Mountain and Dawson Bay Formations

The uppermost units in the Upper Elk Point subgroup are a relatively thin and complex series of deposits that unconformably overlies the Prairie Evaporite Formation. In the study area, the Dawson Bay Formation carbonates, the dolomitic and calcareous argillaceous shales of its basal Second Red Bed Member, and the overlying First Red Bed unit can be correlated from Saskatchewan into the southern part of the study area (Figure 3; Dunn, 1982). To the north and west in the study area, the Dawson Bay interval is replaced by anhydritic beds at the top of the Prairie Evaporite Formation overlying the Leofnard Member, over which rest calcareous and dolomitic shales mapped as the Watt Mountain Formation. Strata associated with the Dawson Bay Formation are mapped together with the Watt Mountain Formation for modelling purposes. The Watt Mountain Formation is mappable across the study area up to its erosional edge in the northeast (Figure 13), and forms an excellent stratigraphic datum separating the Elk Point Group from the overlying Beaverhill Lake Group (Figures 9, 10, 11, and 12).

4.1.4.4 Anomalous Elk Point Group Stratigraphy

Most Elk Point Group strata can be mapped as laterally continuous across the study area and with relative uniformity in thickness up to their respective erosional and depositional edges at the eastern basin margin. Exceptions to this include 1) Lower Elk Point subgroup strata that onlap, but do not completely cover, Precambrian basement paleohighs (Figure 13A); 2) the reef-forming Keg River Formation, with its high depositional relief; 3) the lowermost Prairie Evaporite Formation members, which were deposited only within basinal settings between Keg River Formation buildups; and 4) several localized stratigraphic anomalies recognized in a number of wells in the southern part of the study area (Figure 14). These localized anomalies warrant mentioning here, as they have significant effects at the Elk Point Group level within the model. Meijer Drees (1986; after Hamilton, 1971) discussed an anomalous situation in well 06-25-066-16W4, where the normally anhydritic Ernestina Lake interval comprises a thick halite bed (Figure 14). Equally anomalous arkosic sandstones occur at the Ernestina Lake interval approximately 10 km northwest of the 06-25 well in well 06-21-067-16W4 (Figure 14; see Meijer Drees, 1986, Figure 41).

Southeast of the aforementioned wells, another anomalous stratigraphic section is recognized in well 08-01-062-11W4 (Figure 14). The anomalous section occurs from the upper Lotsberg level to the Prairie Evaporite level. Overthickened upper Lotsberg and Cold Lake halite occur, ostensibly, at the expense of the Contact Rapids, Prairie Evaporite, and Keg River formations, the latter of which is missing (Figure 14). Based on the interpretation of stratigraphy herein, it is difficult to explain the series of events that led to the present stratigraphic configuration, especially considering the lack of similarly anomalous sections in any nearby wells. The absence of carbonates of the Keg River Formation is significant and suggests possible nondeposition or erosion. The stratigraphic configuration may be associated with basement faulting that was reactivated over an extended period of Elk Point time.

4.1.5 Beaverhill Lake Group

Strata of the Beaverhill Lake Group cover a large portion of the study area, with an extensive subcrop of Waterways Formation strata at the sub-Cretaceous unconformity—the largest of any Devonian unit (Figure 13C). The Waterways Formation subcrop floors a very large portion of bitumen-bearing lower Mannville Group deposits and constitutes an important series of alternating aquifers (carbonate) and aquitards (calcareous shale and argillaceous carbonate) that underlie the Cretaceous clastics. The lowermost two formations in the Beaverhill Lake Group—the Fort Vermilion and Slave Point formations—are very thin in the southern part of the study area but are nevertheless mapped, as they record the important change from predominantly arid evaporative conditions of the Elk Point Group to the long-standing growth of carbonate complexes with intercalated shaly strata across the basin.

4.1.5.1 Fort Vermilion Formation

The anhydrites and lesser dolostone and shale of the Fort Vermilion Formation are the lowermost deposits of the Beaverhill Lake Group. They rest conformably on the Watt Mountain Formation. In the northern half of the study area, the Fort Vermilion is a relatively thick anhydrite package that is easily recognized on wireline logs (Figures 11 and 12). To the south, the formation thins to zero thickness (Figure 13), the location of which is based on the absence of any recognizable anhydrite on density logs (Figure 12). The eastern edge represents the dissolution of anhydrite in a similar fashion to that of the evaporites of the underlying Prairie Evaporite Formation. Noticeable dissolution of Fort Vermilion anhydrite is evident directly north of Fort McMurray, where the edge takes a marked westward excursion (Figure 13).

4.1.5.2 Slave Point Formation

The Slave Point Formation comprises a relatively thin interval of carbonates that conformably and gradually overlie the anhydrites of the Fort Vermilion Formation (Figures 9 and 13). The Slave Point Formation is a very thin interval that can be difficult to discern on wireline logs, especially in the southern part of the study area (Figure 9); however, every core that was reviewed displayed a distinct—albeit thin—carbonate interval directly overlying the Fort Vermilion or Watt Mountain formations. The carbonate interval is distinct from the overlying Waterways Formation by comprising dark-coloured lime mudstones to wackestones with few allochems of low diversity. A phosphatized hardground commonly occurs at the top of the formation. In the area around townships 66 to 74, ranges 1 to 7, west of the Fourth Meridian, the Slave Point Formation is interpreted as absent or too thinly developed to discern (Figure 9, wells 10-17-071-06W4, 06-30-071-04W4, and 05-21-071-04W4; Figure 13). Like the underlying Fort Vermilion Formation, the Slave Point Formation thickens appreciably northwards (Figures 11 and 12).

4.1.5.3 Waterways Formation

The intercalated shallow-water carbonates and argillaceous carbonates to calcareous shales of the Waterways Formation make up the bulk of the Beaverhill Lake Group in the study area (Figure 3). The Waterways Formation has been subdivided into five members, which were originally defined from the subsurface near Fort McMurray by Crickmay (1957). In ascending stratigraphic order, they are the Firebag, Calumet, Christina, Moberly, and Mildred members (Figure 3). Lithostratigraphic correlation of the Waterways members is based on the revisions of Keith (1990), where he included a clean limestone bed—originally placed in the Mildred Member by Crickmay—with the Moberly Member. Shallow-marine limestones of the Calumet and Moberly members make up part of an extensive carbonate bank with some minor isolated carbonate reefs, known as the Eastern Shelf complex, intercalated with the argillaceous carbonates and calcareous shales of the Firebag, Christina, and Mildred members (Wendte and Uyeno, 2005).

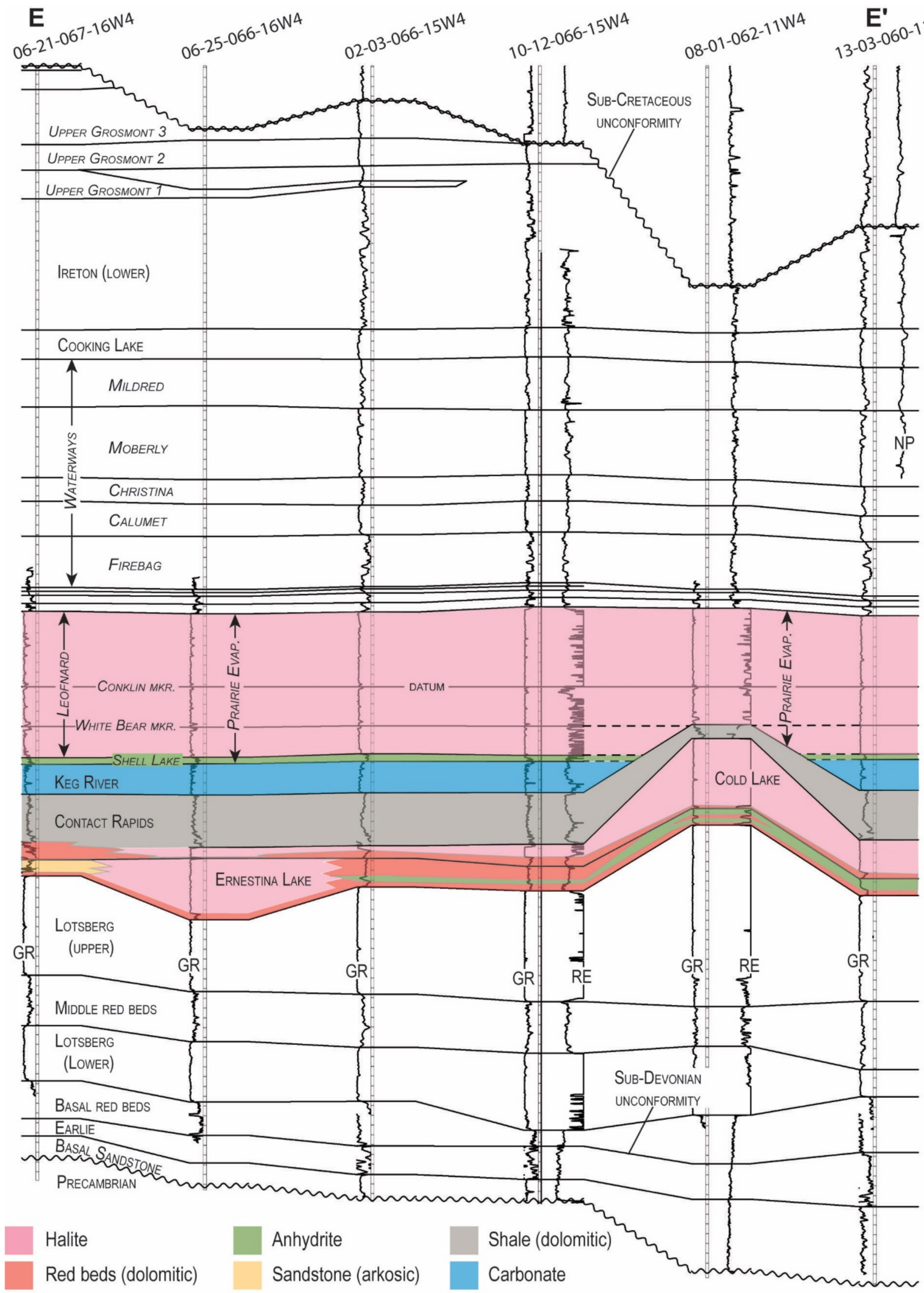

Figure 14. Stratigraphic cross-section E–E′, showing anomalous Elk Point Group strata in the southern part of the study area (Figure 4; datum = Conklin marker bed of the Prairie Evaporite Formation). In well 08-01-062-11W4, strata of the Keg River Formation and Shell Lake and lower Leofnard members are interpreted as missing. Abbreviations: GR, gamma-ray (API); RE, deep resistivity (ohm-m); NP, neutron porosity (v/v).

Where unaffected by erosion at the sub-Cretaceous unconformity, strata of the Waterways Formation and individual members therein are very uniform in thickness across much of the study area (Figures 9, 10, 11, and 12). Much of the reefal strata of the Eastern Shelf complex is biostromal in nature, showing little topographic expression. Exceptions include parts of the shallow-water carbonates of the Moberly Member, which appear to form possible bioherms in uppermost Moberly strata in townships 71 and 72, Range 11, and Township 74, Ranges 10 and 11, west of the Fourth Meridian. In these areas, the Moberly Member thickens appreciably at the expense of the overlying Mildred Member. The exact extent and nature of the Moberly Member buildups is obscured by a lack of well control, but they may be similar in nature to those described in the Eastern Shelf complex by Wendte and Uyeno (2005) south of the study area. A number of Moberly Member buildups in these areas were cored in the upper part of the Moberly Member (e.g., 12-10-074-11W4 and 03-30-074-10W4), presumably due to anomalies at the Moberly level observed in seismic profiles in this area; however, tests run in the Moberly buildups produced no hydrocarbons.

Along with the lower Beaverhill Lake and uppermost Elk Point Group strata, the Waterways Formation experienced a substantial change in structural attitude where it overlies the Prairie Evaporite dissolution scarp (Figure 13B, C). The removal of well over 200 m of halite from the Prairie Evaporite Formation resulted in structural collapse of the overlying succession; however, the units remain in their relative stratigraphic positions, allowing them to be correlated over and eastwards of the dissolution scarp (e.g., Figures 9 and 10). Over the scarp, the structural dip of Beaverhill Lake Group strata changes from the regional westward dip to an eastward dip. The structural attitude of the strata returns to a shallow westward dip farther eastwards.

4.1.6 Woodbend Group

Strata of the Woodbend Group are found in the western portion of the study area (Figure 13C), west of the Prairie Evaporite halite dissolution scarp. Extensive carbonate platforms and atoll-like reefs developed within the Alberta Basin during Woodbend Group time. These carbonate complexes are encased in, and overlain by, basinal argillaceous carbonates and calcareous shales, much like those of the underlying Beaverhill Lake Group. Where carbonate complexes of the Woodbend Group subcrop at the sub-Cretaceous unconformity surface, they form important hosts of bitumen within karsted strata.

4.1.6.1 Cooking Lake Formation

The Cooking Lake Formation comprises shallow-water carbonates that gradationally and conformably overlie the Waterways Formation. Locally, the contact between the clean carbonates of the Cooking Lake Formation and the calcareous shales of the Mildred Member of the Waterways Formation appears abrupt. Where the transition is abrupt, Wendte and Uyeno (2005) called the transition a regressive surface of marine erosion, generated by storm waves during stable or falling sea level. In these areas, the thickness of the Mildred Member is reduced. The thickness of the Cooking Lake Formation is variable in the study area (Figure 12). Thickness variation is attributed to differential carbonate growth/deposition on the carbonate platform during later stages, when areally smaller carbonate shoals developed (Wendte, 1992, 1994). These shoals are often the nucleation sites for the overlying reefs of the Leduc Formation (Wendte, 1992). In the study area, the Cooking Lake Formation thickens in the northwest near the edge of the Cooking Lake Platform, which coincides with the location of the overlying Leduc Formation reefs. West of this edge, the carbonates of the Cooking Lake Formation decrease in thickness substantially (Figure 12, wells 15-19-091-18W4 and 06-02-097-19W4). The edge of the Cooking Lake Platform coincides with the most progradational limit of the Eastern Shelf complex of the Waterways Formation, as defined by Wendte and Uyeno (2005). The Cooking Lake Formation is thickest in the southern part of the study area and beyond the study area boundary to the south, which is the location of the Redwater and Smoky Lake shoals in the upper Cooking Lake, both of which saw the growth of isolated Leduc reefs (Wendte, 1994).

4.1.6.2 Leduc Formation

Biohermal reefs of the Leduc Formation are found in the northwestern part of the study area (Figure 13C). These reefs represent the northernmost part of the Calling Lake reefs that formed along the edge of the Cooking Lake Platform (Figure 3). The reefs are considerably thinner than their southern counterparts, which is a result of earlier reef termination due to the advance of prograding Grosmont-Ireton strata from the northeast (Stoakes, 1992a). The bioherms of the Leduc Formation conformably overlie the Cooking Lake Platform. Part of the northernmost Leduc Formation reef subcrops at the sub-Cretaceous unconformity surface (Figure 13C), where karsted vuggy dolostones host bitumen (Dembicki and Podivinsky, 2012). In the west-central part of the study area, another Leduc reef is found east of the platform edge (Figure 13C). This off-trend bioherm was also recognized by Dembicki and Machel (1996) but is poorly constrained due to a lack of well control.

4.1.6.3 'Lower' Ireton Formation

In areas away from Leduc Formation reefs, the Cooking Lake Formation is overlain by the argillaceous carbonates and calcareous shales of the Ireton Formation. The Ireton Formation is subdivided into informal lower and upper intervals, where the 'lower' Ireton defines the strata underlying the Grosmont Platform and the 'upper' Ireton overlying it (Figures 3, 10, 11, and 12). Beyond the edge of the Grosmont Platform, the entire Ireton interval is mapped as the lower Ireton (undivided Ireton) for modelling purposes, resulting in an extensive subcrop in the southwest (Figure 13C). The Duvernay Formation and its equivalents, which can be mapped to the south and west of the study area, were not recognized in the study area strictly from logs. In the core of the Bear Biltmore No. 1 well (07-11-087-17W4), Belyea (1952) noted that the Ireton shales directly overlie the Cooking Lake Formation. Without extensive core control, it appears that strata resting on the Cooking Lake Formation represent an argillaceous, bituminous-poor interval. The strata here are interpreted to have developed in shallower water in slope settings of the Grosmont-Ireton clinoform assemblages rather than the basinal anoxic toes of the clinoforms (Stoakes, 1980). The thickness of the lower Ireton interval is variable because it is affected by the depositional extents of the overlying units of the Grosmont Formation and by the presence of Leduc bioherms—the lower Ireton can thin to less than 2 m over the Leduc Formation (e.g., over the off-trend Leduc bioherm in Township 80, Range 16, west of the Fourth Meridian; Figure 13C).

4.1.6.4 Grosmont Formation

The Grosmont Formation carbonate complex comprises a series of variably dolomitized, stacked, shallowing-upward successions that are restricted to the western part of the study area (Figure 13C). Each of the Grosmont subdivisions is underlain by regionally mappable shale breaks separating broadly progradational to aggradational cycles that originated from the northeast. The shallow-water carbonate component of the Grosmont complex transitions basinwards into the argillaceous carbonates and calcareous shales of the Ireton Formation in subtle clinoform geometries. The basinward extent of each subdivision varies, but generally each successive subdivision progrades beyond the previous (Figure 12). The upper two subdivisions (upper Grosmont 2 and 3) display more of an aggradational architecture and their depositional extents are beyond the western edge of the study area (Figure 13C). The lower two subdivisions contain depositional extents that dip below the subcrop in the southwestern part of the study area (Figure 13C). The described stratal architecture of the Grosmont Formation, coupled with it being encased in Ireton shales, poses a large challenge for modelling. For information on how the Grosmont Formation was modelled, refer to Section 3.4.1.

The subcrop of the Grosmont Formation at the sub-Cretaceous unconformity is complex, in part due to the internal subdivision of the complex and the fact that the Grosmont experienced deep weathering and prolonged meteoric karst processes before Cretaceous deposition. At and near the subcrop, the Grosmont Formation hosts substantial volumes of bitumen in karsted and brecciated strata, as well significant volumes of gas.

4.1.6.5 'Upper' Ireton Formation

The 'upper' Ireton Formation is a relatively thin unit that marks a distinctive lithological break between the shallow-water carbonates of the Grosmont and Nisku formations (Figures 3 and 12). The upper Ireton was mapped only where it rests on carbonates of the Grosmont Formation. The transition from the Grosmont Formation to the upper Ireton records an overall shallowing-upward succession from shallow-marine to peritidal to sabkha settings (MacNeil, 2014). Recently, carbonates in the upper Ireton have been shown to host bitumen in stratiform breccias, in similar fashion to the underlying Grosmont Formation (McNeil, 2015), which may have resulted from evaporite karst in the upper Ireton (Lonnee, 2015).

4.1.7 Winterburn Group

Strata of the Winterburn Group mostly subcrop along the far western part of the study area, with the bulk of the strata located in the southwest corner (Figure 13C). After deposition of the upper Ireton—and associated strata as part of the lower Ireton in positions off of the Grosmont carbonate complex—renewed rise in relative sea level once again resulted in extensive carbonate deposition in the basin. A number of regionally mappable shale and siltstone intervals form part of the Winterburn strata, the youngest of which is associated with the Frasnian-Famennian boundary in the subsurface of Alberta.

4.1.7.1 Nisku Formation

Dolomitized carbonates of the Nisku Formation were deposited in a broad ramp-like complex that likely covered much of the study area at the time of deposition (Watts, 1987). The Nisku Formation conformably overlies the Ireton Formation (Figures 3 and 12). Upwards, the Nisku Formation becomes increasingly interbedded with argillaceous deposits and some marls (MacNeil et al., 2013). The Nisku subcrop in the study area is complex, with a number of erosional inliers and outliers mapped inboard and outboard of the subcrop belt, respectively (Figure 13C).

4.1.7.2 Calmar Formation

The silty shales of the Calmar Formation conformably overlie the Nisku Formation (Figures 3 and 12). The contact between the two formations appears gradational in the study area and is often difficult to discern due to the lithological similarity between the upper part of the Nisku Formation and the lower part of the Calmar Formation. The Calmar Formation is restricted to the southwestern part of the study area, forming a broad subcrop even though it is a relatively thin unit (Figure 13C). Where unaffected by erosion at the sub-Cretaceous unconformity, the Calmar Formation ranges in thickness from less than 5 m to 17 m.

4.1.7.3 Graminia Formation

The Graminia Formation includes two members: the lower carbonates of Blue Ridge Member and the upper Graminia Silt member (Figures 3 and 12). Both units are thinly developed in the far southwestern part of the study area (Figure 13C) and are modelled together in this study. The carbonates of the Blue Ridge Member gradationally overlie the Calmar Formation. The contact between the Blue Ridge and Graminia Silt members is erosional (Meijer Drees et al., 1998). Without modern log suites, this uppermost Winterburn Group interval is difficult to correlate. Where modern log suites exist, the carbonates of the Blue Ridge Member can be differentiated from both the underlying Calmar Formation silty shales and the overlying silty shales of the Graminia Silt member.

4.1.8 Wabamun Group

Wabamun Group strata are undifferentiated in the study area largely because the strata are present only as erosionally thinned subcrop at the sub-Cretaceous unconformity in very small areas in the southwestern part of the study area (Figure 13C). The undifferentiated Wabamun deposits form a dolomitized carbonate unit that conformably overlies the Graminia Formation (Figures 3 and 12).

4.2 Sub-Cretaceous Unconformity

Paleogeographic reconstructions of the sub-Cretaceous unconformity surface were modelled in ArcMap to aid in the delineation of Devonian subcrop belts (Figure 15). The structural elevation surface was geostatistically interpolated in ArcMap using 8495 picks. The sub-Cretaceous unconformity surface is a critical component of the 3D geological model because it represents a major erosional surface in the area and was used to truncate the underlying stratigraphic units. For additional information on how the sub-Cretaceous unconformity was used to build the 3D geological model, see Section 3.4.1.

The paleotopography of the sub-Cretaceous unconformity surface was generated by subtracting a trend surface, which in this case was a third-order global polynomial, from the structural elevation surface. The residual values produced by this grid math process provide a representation of the paleotopography of the sub-Cretaceous unconformity surface.

There are a number of factors responsible for the present-day configuration of the subcrop model:

1) Due to the subtle westward to southwestward dip of Devonian strata—a result of orogenic loading during the formation of the Canadian Cordillera—stratigraphic units subcrop youngest to oldest west to east in bands that roughly parallel the orogenic front.
2) The subcrop of Waterways Formation strata is complex due to the Prairie Evaporite halite dissolution scarp, where Waterways strata roll over the scarp and display dip reversals to the east. The general westward dip gradually returns farther east towards the basin margin.
3) East of the Prairie Evaporite halite dissolution scarp, Waterways strata drape over Keg River buildups due to the complete removal of halite overlying the Keg River Formation. This causes a departure from the more regular southeastward banding of subcrop stratigraphy seen in strata to the west. This is especially evident in the area east and northeast of Fort McMurray, where the subcrop area of the Waterways members extends farther east over an area where the Keg River Formation overlies the Athabasca Arch (the eastward extension of the Peace River Arch; Figure 15). The Bitumount Basin is located north of this Keg River feature (a possible Keg River bank; see Hauck et al., 2017).
4) A noticeable paleotopographic low in the sub-Cretaceous unconformity surface, evident in the eastern part of the study area (Figure 15), is the direct result of the removal of halite in the Prairie Evaporite Formation, the subsequent collapse of the overlying Devonian section, and the creation of significant accommodation space for the deposition of the lower Mannville Group strata. Strata of the lower Mannville Group are thickest over and east of the Prairie Evaporite halite dissolution scarp within this zone of accommodation. Direction of sediment transport along this accommodation trend was to the north-northwest.
5) Fluvial erosion before and during deposition of the overlying lower Mannville Group strata produced a series of erosional lows and headlands along the subcrop of the Woodbend Group succession (Figure 15). These erosional lows trend northeastwards (which was also the direction of sediment transport along these paleovalleys), and they experienced the preferential accumulation of lower Mannville Group strata. Conversely, lower Mannville Group strata thin over the resistant highs—most pronounced along the Grosmont subcrop belt (Figure 15).
6) Very high well density for the sub-Cretaceous unconformity surface around townships 69 to 76, ranges 3 to 6, west of the Fourth Meridian reveals a meandering channel west of the Prairie Evaporite halite dissolution scarp (Figure 15). This channel saw increased fluvial erosion down through the Moberly and Christina members into the Firebag Member of the Waterways Formation.

4.3 Results of the 3D Modelling

The 3D model produced for the Lower Athabasca region covers an area of 83 334 km^2 and is composed of 51 geological units (Figure 16A); however, this report focuses on the 33 Paleozoic surfaces (Figure 16B). The 3D model provides an effective mechanism for visualizing the complex geometry of

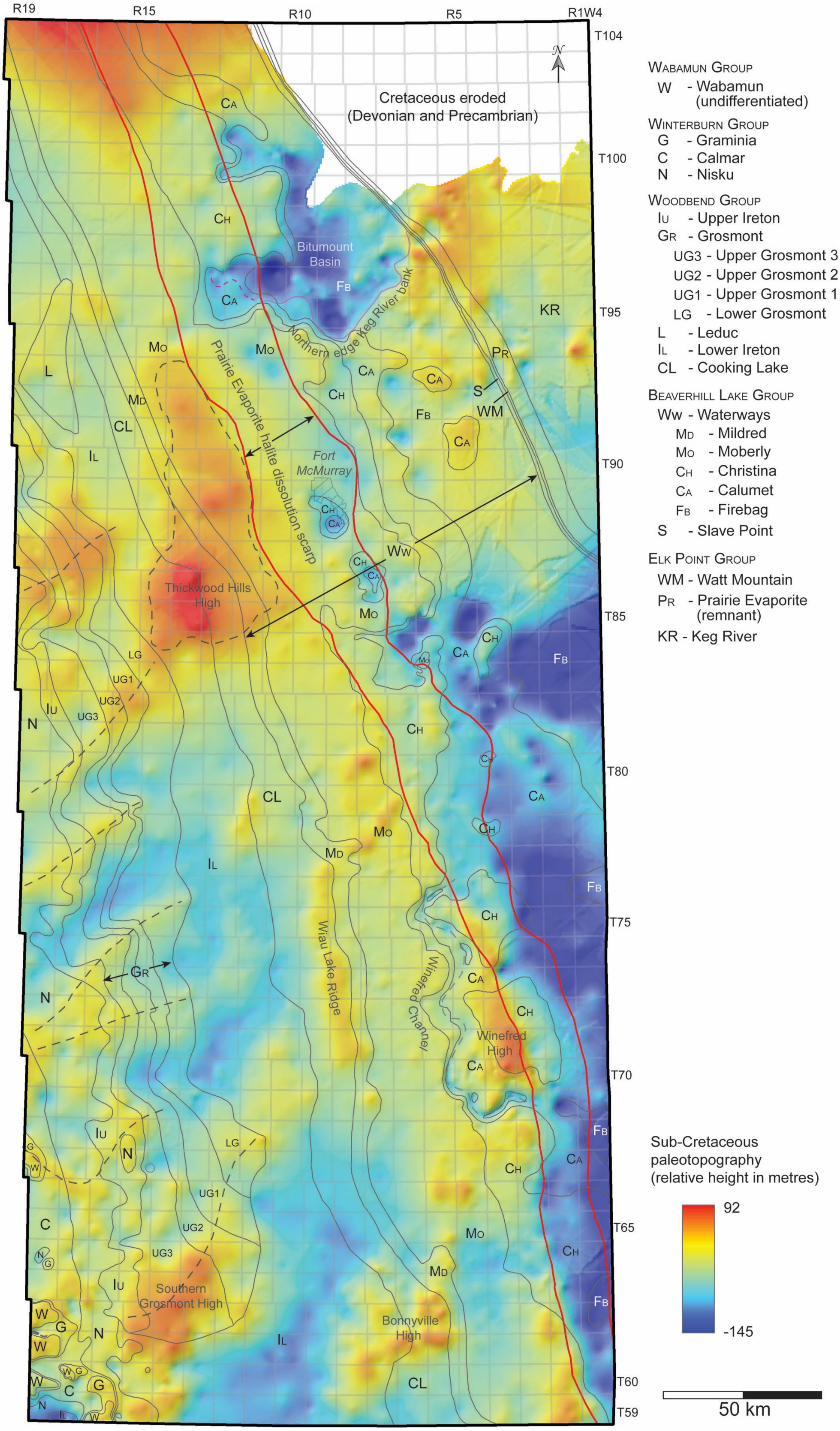

Figure 15. Paleotopography (relative height in metres) on the sub-Cretaceous unconformity with Devonian subcrop extents. A number of notable paleotopographic features are named based on their geographic location.

the geological units within study area. The model results characterize the complex geometry of the geological units subcropping at the sub-Cretaceous unconformity (Figure 6). The model also provides important visualizations of the 3D geospatial variability of the Moberly, Christina, Calumet, and Firebag members of the Waterways Formation, as well as the Slave Point, Fort Vermilion, and Watt Mountain formations, that have been affected by salt dissolution within the Prairie Evaporite Formation along theeastern portion of the study area (Figure 17). This feature is identified by a pronounced and abrupt decrease in the elevation of the Cristina, Calumet, and Firebag members of the Waterways Formation, as well as the Slave Point, Fort Vermilion, and Watt Mountain formations, from west to east (Figure 17).

Although the model results provide seemingly realistic predictions of the geological complexity that corresponds with the current scientifically-agreed-upon understanding of these units, it is important to realize that the model is a prediction of the most likely geometry and distribution of the geological units given the data currently available. Every effort was made to ensure that the 3D geological model represents the input data as accurately as possible; areas of uncertainty varied spatially for each of the geological units.

The standard deviation, which is a measure of the variation in the predicted value relative to the mean predicted value, was calculated for each geological unit. Low standard deviation values indicate that there is good consistency in the predicted grid value, whereas a high standard deviation value indicates that there is higher variability at that location of the modelled surface. Higher variability is typically the result of one or more of the following factors: geological complexity, low quantities of available data, and sparsely distributed data.

To better understand the factors contributing to model uncertainty, maps were produced that are able to characterize the standard deviation using multiple subset realizations of the elevation values at multiple locations across the model area. These uncertainty maps were produced for six geological units (in stratigraphically ascending order): Precambrian basement, Keg River Formation, Prairie Evaporite Formation, Slave Point Formation, Moberly Member of the Waterways Formation, and lower Grosmont unit of the Grosmont Formation (Figure 18). The local uncertainty maps reveal how dramatically the uncertainty varies, both spatially (across the study area) and from one geological unit to another. For example, uncertainty for the Moberly Member varies from 0 to 25 m with an average of 3.9 m across the entire study area (Figure 18E), but the Slave Point, Prairie Evaporite, and Keg River formations have uncertainty values ranging from 0 to 60 m, with averages of 6.5 m, 5.4 m, and 7.1 m, respectively (Figure 18B–D). Although the uncertainty values seem much higher for the Slave Point, Prairie Evaporite, and Keg River formations, the uncertainty maps show that the grids for these three formations have quite low uncertainty (5 m or less) across most of the study area, and the higher uncertainty values are constrained to the northeastern portion of the model in the vicinity of the halite dissolution scarp. High uncertainty values in this region of the study area are to be expected, considering the extreme spatial variability in the observed data values and the complex topography of these two structural surfaces in areas where halite dissolution has occurred. See Babakhani (2016) for a discussion of the methodology used for the uncertainty mapping.

Uncertainty values for the Precambrian basement were among the highest, with values ranging from 0 to 60 m and averaging 7.8 m. Considering the number of wells available for the Precambrian basement (204), these uncertainty values are reasonable (Figure 18A). The lower Grosmont unit was modelled using only 138 data points and had uncertainty values ranging from 0 to 22 m and averaging 3.3 m (Figure 18F). Although the number of data points used to model this surface is less than the number used to model the Precambrian basement, this unit only covers a small portion of the study area, and the available data points were well distributed across the geospatial extent.

5 Summary

The Paleozoic stratigraphic succession has been mapped and modelled in 3D for a large part of the Lower Athabasca Regional Plan (LARP) area in northeastern Alberta. All existing deep well control has been

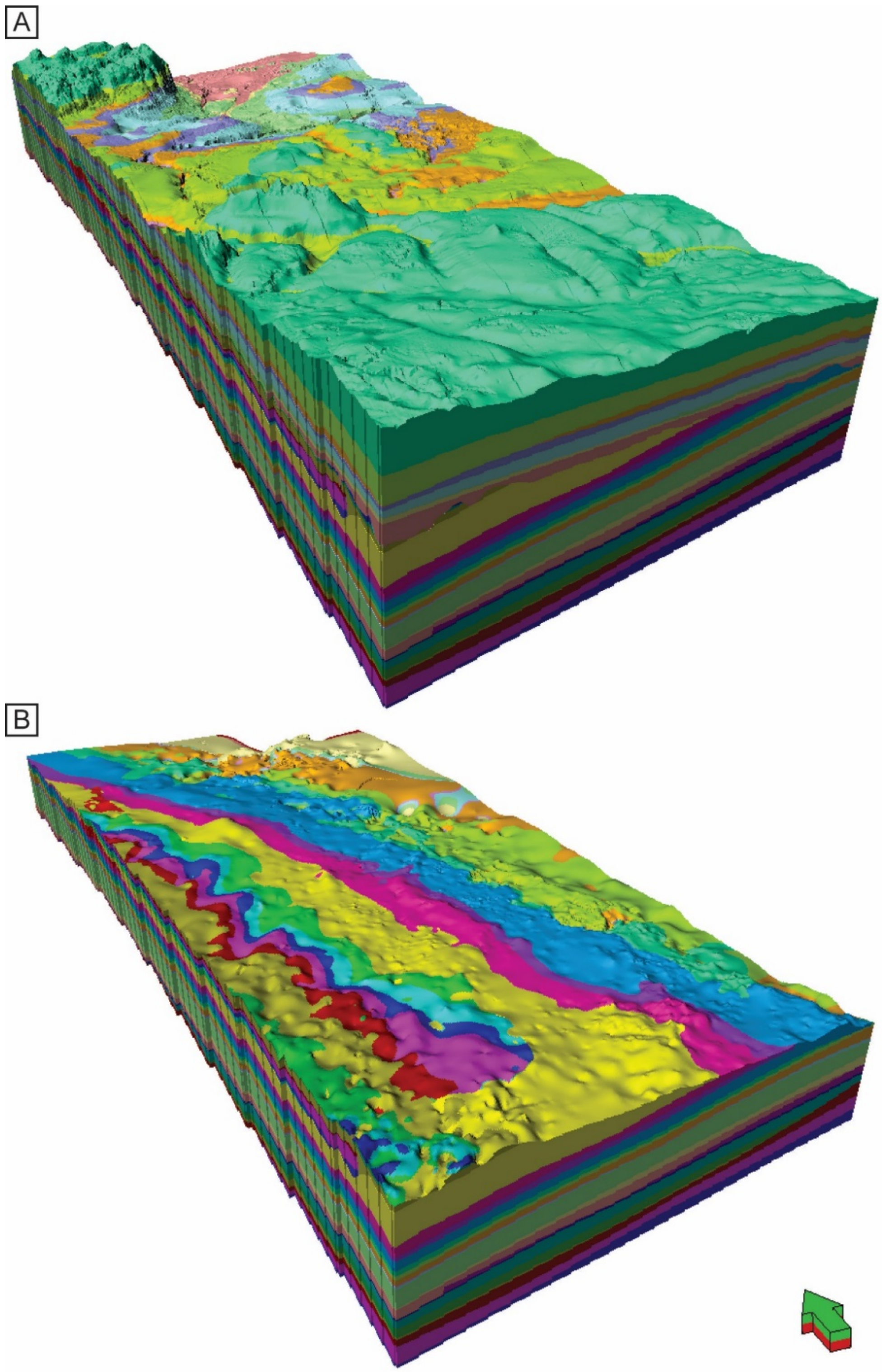

Figure 16. Views of the LARP model, looking to the northeast: a) all stratigraphic units from the Precambrian basement to the top of bedrock, and b) stratigraphic units from the Precambrian basement to the sub-Cretaceous unconformity (see Figure 13 for a map view and the names of the subcropping units). Model width is 183.5 km and has a vertical exaggeration of 50x.

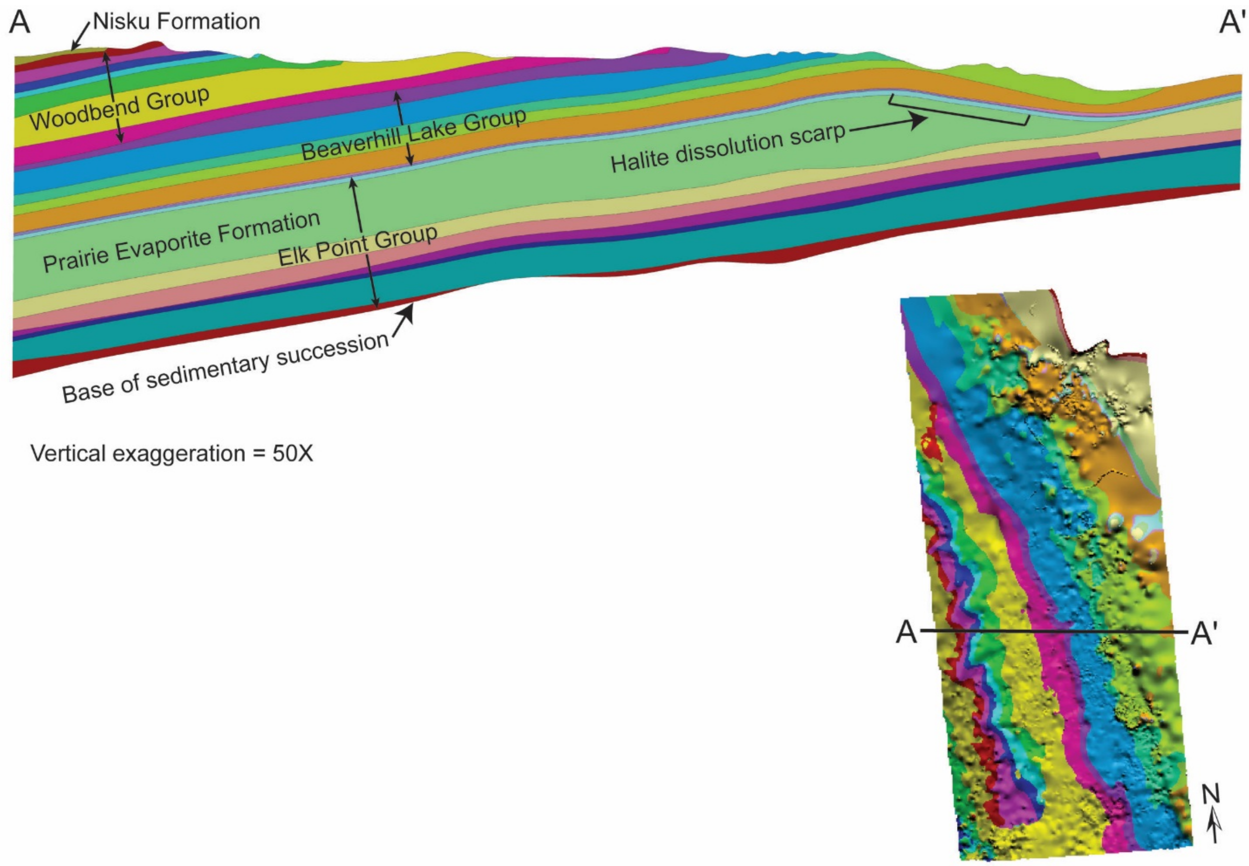

Figure 17. Cross-section of Paleozoic strata in the LARP area. Dip reversal can be observed in strata overlying and east of the Prairie Evaporite halite dissolution scarp. Model width is 183.5 km and has a vertical exaggeration of 50x.

incorporated in the mapping, resulting in an up-to-date picture of the distribution of Paleozoic strata beneath the sub-Cretaceous unconformity. Paleozoic strata include those of the lower part of the Middle Cambrian System, the Elk Point Group, the Beaverhill Lake Group, the Woodbend Group, the Winterburn Group, and the Wabamun Group (Figure 3).

Cambrian strata are restricted to the southern part of the study area and, together with the Precambrian basement to the north, form the base of the Devonian succession at the sub-Devonian unconformity. A number of large sub-basins formed on the sub-Devonian unconformity surface, along with irregular topographic relief on the Precambrian basement portion of this major unconformity. Both of these scales of topographic relief had a large role in the stratigraphic architecture and distribution of facies belts within the overlying Elk Point Group strata. Initially, evaporites of the Lower Elk Point subgroup were restricted to the broad sub-basins (central and northern Alberta sub-basins), which gradually filled these depocentres. The subsequent deposition of carbonates of the Keg River Formation was highly influenced by the irregular topographic relief on the Precambrian basement, the highs of which were shallowly covered by the shale of the uppermost Lower Elk Point subgroup. These basement highs are especially evident in the region known as the Athabasca Arch, which runs eastwards across the middle of the study area. Carbonate deposition was prolonged and gained a greater paleobathymetric relief where the Precambrian basement formed highs. This late-stage differentiation of Keg River carbonates into reefs and banks acted to produce interbuildup basins. Following Keg River deposition, the basin once again became restricted and experienced protracted periods of evaporitic drawdown and the deposition of halite

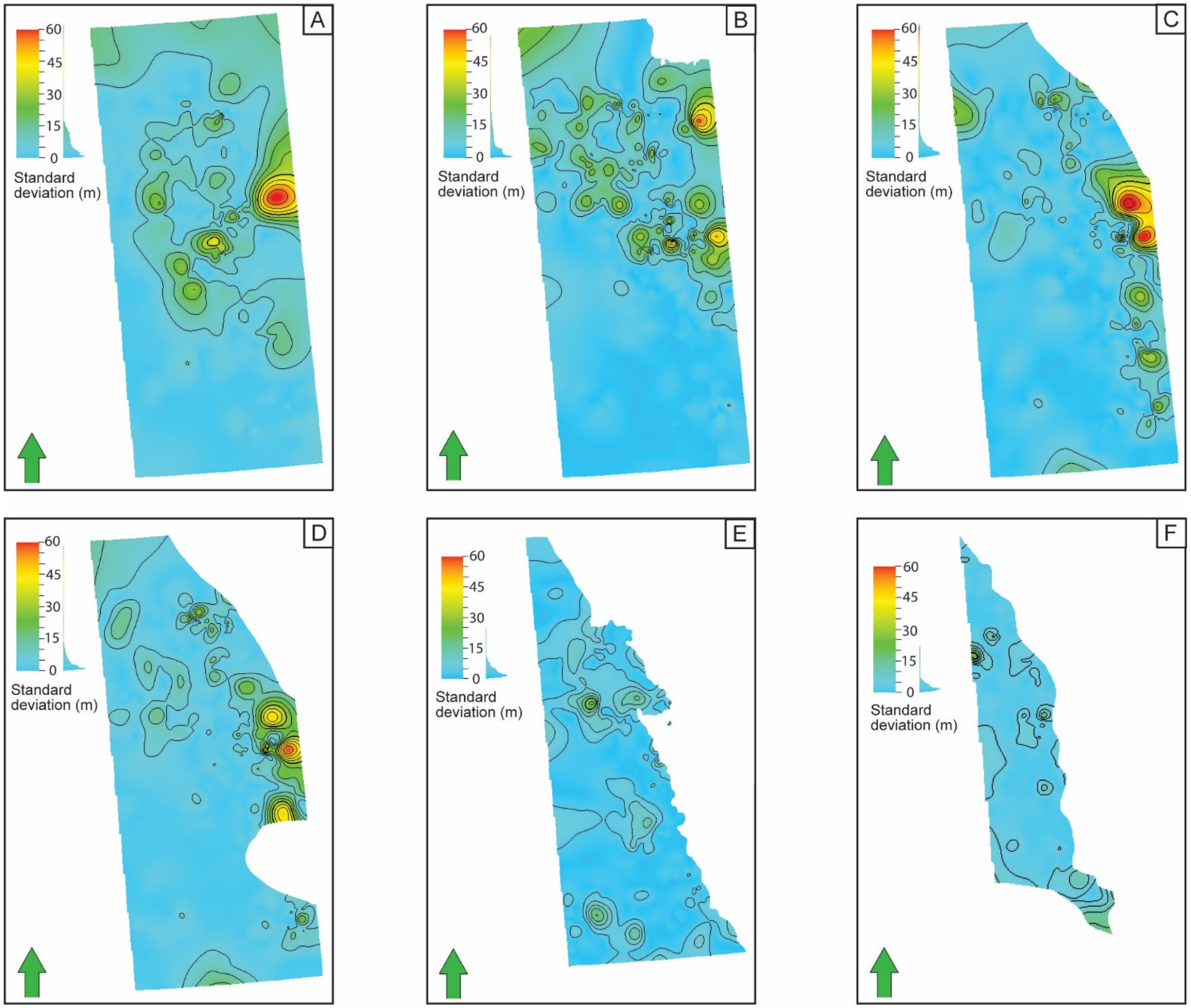

Figure 18. Uncertainty maps showing the standard deviation values from multiple subset realizations across the study area for selected geological units: a) Precambrian basement, b) Keg River Formation, c) Prairie Evaporite Formation, d) Slave Point Formation, e) Moberly Member of the Waterways Formation, and f) lower Grosmont unit of the Grosmont Formation. Model width is 183.5 km.

and anhydrite of the Prairie Evaporite Formation. The interbuildup basins between Keg River carbonates saw the accumulation of halite of the lower part of the Prairie Evaporite Formation (Whitkow Member), especially over and south of the Athabasca Arch.

The Beaverhill Lake to Wabamun groups mark a time during which carbonate complexes flourished within the Alberta Basin. Extensive biostromal platforms and lesser atoll-like reefs developed within the study area, flanked and encased in mixtures of off-reef argillaceous carbonates and calcareous shales. All of the lithostratigraphic formations, members, and units within these strata have an associated subcrop at the sub-Cretaceous unconformity surface due to a shallow westerly tilt in the basin towards the Canadian Cordillera—the subcrop edges mostly parallel the orogenic front (Figure 13).

Before the deposition of Mannville Group sediments on the sub-Cretaceous unconformity, halite and lesser anhydrite in the Prairie Evaporite Formation experienced dissolution associated with the exposure of the formation along the eastern basin margin through Mesozoic orogenic loading. Greater than 200 m of halite was removed through dissolution by undersaturated water. Dissolution of halite proceeded downdip, westwards from the basin margin, which resulted in a dissolution 'scarp' that, much like the overlying Beaverhill Lake to Wabamun Group subcrops, parallels the orogenic front of the Canadian Cordillera (Figure 13). Regional correlation of member and marker bed stratigraphy within the Prairie Evaporite Formation reveals that, according to the present geometry of the scarp, halite dissolution occurred top-down along the dissolution scarp. Halite of the upper part of the Leofnard Member was removed first and proceeded into lower levels of the evaporite succession. The removal of halite within the Prairie Evaporite had a significant effect on the local and regional structure of the overlying Devonian succession, which collapsed over the Keg River Formation in the absence of the Prairie Evaporite Formation.

A regionally extensive model of the sub-Cretaceous unconformity, modelled with a comprehensive set of data points to delineate subcropping Devonian stratigraphy, demonstrates a number of topographic features on the unconformity surface (Figure 15). East of the dissolution scarp, Keg River Formation buildups influenced structure at the sub-Cretaceous unconformity, with the southern boundary of the Bitumount Basin correlating with the northern margin of a contiguous Keg River bank (Figure 15). West of the dissolution scarp, southeast-trending subcrop belts of Beaverhill Lake Group to Wabamun Group carbonates and intervening shales influenced structure on the unconformity surface. The most pronounced of these features formed on Grosmont and younger formations as a series of ridges and paleovalleys perpendicular to the subcrop belts. These paleovalleys formed a series of tributaries that fed the main paleovalley, the latter of which was a direct result of the removal of halite in the Prairie Evaporite Formation and the subsequent collapse of the overlying Devonian succession.

The data points compiled and produced for this study were used to build a 3D model of the LARP area, which was used to visualize the complex stratigraphic architecture of the sedimentary succession. The 3D model was created by geostatistically interpolating the available data points to produce grids representing the uppermost surface for each geological unit. Uncertainty maps were generated for each of the predicted geological surface grids to assess the spatial variability of uncertainty as a way to assess the quality and confidence of modelled surfaces. These surface grids were subsequently combined into a 3D model using a methodology that accounts for the geological relationship of each modelled unit to its overlying and underlying neighbours. The resulting 3D model is particularly effective at characterizing the complexity of the geological units subcropping at the sub-Cretaceous unconformity (Figure 16), as well as the spatial variability of the formations and members impacted by the salt-dissolution scarp (Figure 17). The 3D model corresponds well with our understanding of the subsurface geology in the Lower Athabasca region; however, if additional reliable data become available within the study area, the 3D model can be easily updated.

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