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ALIGNMENT OF SALINE SPRINGS WITH EVAPORITE KARST STRUCTURES IN NORTHEAST ALBERTA, WESTERN CANADA: ANALOGUE FOR CRETACEOUS HYPOGENE BRINE SEEPS TO THE SURFACE

RAZPOREDITEV SLANIH IZVIROV Z EVAPORITNIMI KRAŠKIMI STRUKTURAMI NA SEVEROVZHODU ALBERTE V ZAHODNI KANADI: ANALOGIJA ZA PRONICANJE KREDNE HIPOGENE SLANICE NA POVRŠJE

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Abstract UDC 553.77(71)

Paul L. Broughton: Alignment of saline springs with evaporite karst structures in northeast Alberta, western Canada: analogue for cretaceous hypogene brine seeps to the surface

Meteoric and glacial meltwater charged groundwater, mixed with dissolved salts from Devonian sources at depth, discharged as saline springs along topographic lows of the Athabasca River Valley, which downcuts into the Cretaceous Athabasca oil sands deposit in northeast Alberta, western Canada. These Quaternary saline seeps have TDS measurements, isotope signatures and other chemical characteristics indicative of the groundwater flows coming in contact with Prairie Evaporite (M. Devonian) salt beds, 200 m below the surface. Migrations up-section of groundwater with dissolved chloride and sulphate salts occurred along salt dissolution collapse breccia zones that cross-cut Upper Devonian limestone strata. Seeps discharged along the karstic Devonian limestone paleotopography, the unconformity surface flooring the Lower Cretaceous McMurray Formation. Saline to brine springs along the Athabasca River Valley have TDS measurements that can exceed 100,000 mg/L. Quaternary salt removal was insignificant compared to the voluminous removal of the 80-130 m thick salt section for 1000s km^2 during the Early Cretaceous configuration of the Devonian paleotopography, which partially controlled depositional patterns of the overlying McMurray Formation, principal host rock of the Athabasca oil sands. Little is known of the storage or disposition of voluminous brines that would

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Paul L. Broughton: Razporeditev slanih izvirov z evaporitnimi kraškimi strukturami na severovzhodu Alberte v zahodni Kanadi: Analogija za pronicanje kredne hipogene slanice na površje

Na območju severne Alberte v zahodni Kanadi se podzemna voda, ki jo napajata meteorna in ledeniška voda, globoko pod površjem meša s slanimi raztopinami, katerih vir slanosti predstavljajo soli devonske starosti. Podzemna voda izvira v topografsko najnižjih delih doline reke Athabasca, ki je vrezana v kredne sedimente oljnega peska. Izmerjene vrednosti skupnih raztopljenih snovi, izotopov in drugih kemijskih lastnosti kvartarnih slanih mezišč so značilne za podzemne tokove, ki prihajajo v stik s plastmi soli srednje devonske starosti (t.i. Prairie evaporiti) 200 m pod površjem. Podzemna voda z raztopljenimi kloridnimi in sulfatnimi solmi proti površju teče vzdolž con in-situ tvorjenih podornih breč, ki prečijo plasti zgornjedevonskih apnencev in so nastale zaradi raztapljanja soli. Na površje mezi vzdolž nezveznosti, ki označuje paleorelief v podlagi spodnjekredne formacije McMurray. Meritve skupnih raztopljenih snovi slanih do hiperslanih vod v izvirih vzdolž doline reke Athabasca lahko presežejo 100.000 mg/l. Količina v kvartarju raztopljenih soli je zanemarljiva v primerjavi z več 1000 km2 obsežnim in 80-130 metrov debelim zaporedjem soli, ki so bile raztopljene med spodnjekrednim oblikovanjem reliefa na devonijskih plasteh. To je deloma vplivalo tudi na vzorce odlaganja formacije McMurray, ki predstavlja osnovno prikamnino oljnim skrilavcem Athabasca. Malo je znanega o

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have resulted from this regional-scale removal of the salt beds below the Athabasca deposit during the Cordilleran configuration of the foreland Alberta Basin. Holocene dissolution trends and discharges at the surface as saline springs are proposed as a modern analogue for voluminous Early Cretaceous brine seeps to the surface along salt dissolution collapse breccia zones, concurrent with deposition of the McMurray Formation. This model links several characteristics of the McMurray Formation as responses to Aptian brine seeps to the surface. These include: (1) the emplacement of a drainage-line silcrete along the margins of the Assiniboia PaleoValley, now partially exhumed by the Athabasca River Valley, (2) distribution of brackish-water burrowing organisms, and (3) diagenesis of calcite-cemented sand intervals.
Key words: Saline seeps, Athabasca River Valley, McMurray Formation, Prairie Evaporite.

skladiščenju ali iztekanju obsežnih slanic, nastalih v predgorskem bazenu Alberte med dvigovanjem Kordiljer zaradi regionalno obsežnega raztapljanja solnih ležišč pod nahajališčem Athabasca. Trende holocenskega raztapljanja in površinskega iztekanja slanic lahko primerjamo z obsežnimi zgodnjekrednimi slanicami, ki so na površino iztekala vzdolž območij breč, nastalih zaradi raztapljanja soli sočasno z odlaganjem formacije McMurray. Ta model povezuje več značilnosti formacije McMurray kot odziv na aptijsko iztekanje slanic na površje. Med te odzive spadajo: (1) nastanek silkret povezanih z linijsko drenažo vzdolž robov paleodoline Assiniboia, ki zdaj delno izdanja v dolini reke Athabasca, (2) razširjenost talnih organizmov, prilagojenih na brakično vodo, in (3) diageneza intervalov peska cementiranega s kalcitom.
Ključne besede: slana mezišča, dolina reke Athabasca, formacija McMurray, prerijski evaporit.

INTRODUCTION

Halite-dominated salt beds as much as 200 m thick accumulated as the Middle Devonian Prairie Evaporite in the Western Canada Sedimentary Basin (WCSB), which extends across western Canada and into adjacent areas of eastern Montana and western North Dakota (Holter 1969; Meijer Drees 1986, 1994). Regionally significant salt dissolution trends developed during the Middle Jurassic-Early Cretaceous Cordilleran tectonism that partitioned the WCSB into the Alberta Foreland Basin to the northwest and the Williston Basin to the southeast (Fig. 1). Earlier dissolution events during Late Paleozoic Antler tectonism were limited to areas of southern Saskatchewan, associated with ancestral structures of the Williston Basin.

The oil sands of the McMurray Formation (Aptian) overlie a 300 km long segment of a 1000 km long salt dissolution trend extending along the eastern up-dip margin of the Middle Devonian evaporite basin (Figs. 1, 2), and coincides with the eastern margin of the Western Canada Sedimentary Basin (WCSB). The Athabasca River Valley incised into the Lower Cretaceous Athabasca oil sands deposit in northeast Alberta. The Quaternary trend of the river valley followed the underlying Late Jurassic-Early Cretaceous Assiniboia PaleoValley, which also paralleled to the underlying regional salt dissolution front in the Prairie Evaporite (Holter 1969; Meijer Drees 1994; Hein 2015; Broughton 2017a, b, 2018a, b).

Discharges of numerous saline springs along the Athabasca River Valley followed the withdrawal of the Laurentide ice sheet. Research studies on the solute salt chemistries of the spring waters indicate that the groundwater came in contact with Prairie Evaporite salt beds in the shallow subsurface, only 200 m below (Hitchon 1969; Gue 2012; Gue *et al.* 2015, 2017; Birks *et al.* 2018). Although it is widely recognized that Quaternary dissolution of the buried Prairie Evaporite strata contributed to the chemistry of these saline springs, this was only the latest in a series of salt removal events since the Late Jurassic in the Cordilleran foreland. Earlier salt dissolution stages occurred during the Late Jurassic-Early Cretaceous Cordilleran tectonism that configured this area of the foreland Alberta Basin (Broughton 2013, 2016a, b, 2017a, b, 2018a, b, c). Subsidence-collapse structures resulted from the removal of up to 130 m of salt section prior to and during the deposition of the Lower Cretaceous McMurray Formation (Fig. 2), the principal reservoir rock of the Athabasca oil sands in northeast Alberta (Broughton 2013, 2015, 2018a, b). The resulting dissolution-collapse structures vary from sinkholes and breccia pipes to 10s km long troughs that consist of differentially subsided fault blocks of Upper Devonian strata infilled with deposits of the McMurray Formation. Along with downcutting effects of surface erosion, this salt dissolution tectonism configured the overlying Upper Devonian strata and paleotopography, and resulted in 10s km long syndepositional trends in the McMurray Formation (Broughton 2013, 2015, 2016a, b).

Little is known about the disposition of what would have been voluminous brine production resulting from 10s of metres of salt removal across 1000s of km^2 during Aptian deposition of the overlying McMurray Formation. The lengthy time scale (millions of years) for production of these brines during McMurray deposition contrast with only the few thousand years associated with this Holocene dissolution event, resulting in saline springs that discharged at surface along the Athabasca

River Valley (Fig. 3) following the withdrawal of the Laurentide ice sheet.

This paper reviews distribution and chemistry of the Holocene saline seeps currently discharging along the Athabasca River Valley north of the town of Fort McMurray, Alberta. A reappraisal of the relationship between groundwater chemistry and the distribution of salt dissolution trends in the Devonian substrate suggests that the pattern of Quaternary saline seeps can be interpreted as a modern analogue for more voluminous salt dissolution trends that would have occurred during the Early Cretaceous deposition of the McMurray Formation and resulted in brine seeps to the surface (Broughton 2018c). This model is linked to the known development of regional salt collapse structures during configuration of the karstic limestone paleotopography and subsequent burial by McMurray Formation deposits. This article examines the scant available, albeit indirect, evidence on the very existence and probable distribution of voluminous brine seeps that would have resulted. Seemingly unrelated lines of evidence are linked to provide a model on the relationship between Cretaceous and Quaternary salt removal events. These characteristics of the McMurray Formation include: (1) the distribution trends of brackish-water organisms; (2) origin and distribution of calcite-cemented sand intervals; (3) the emplacement of a drainage-line silcrete along the margins of the ancestral Athabasca River Valley. Brine migrations up-section from the Devonian evaporitic strata to the overlying McMurray deposits can account for partial to mostly complete disposition of the voluminous brines that would have potentially resulted from Early Cretaceous salt removal trends across 1000s km^2. As such, this paper presents a more robust conceptual model that Holocene distribution of saline seeps along the Athabasca River Valley can be used as a modern analogue for the distribution of Cretaceous (Aptian) brine seeps to the surface (Broughton 2018a, b, c). Both dissolution stages were linked to the relatively stationary position of the underlying salt dissolution front.

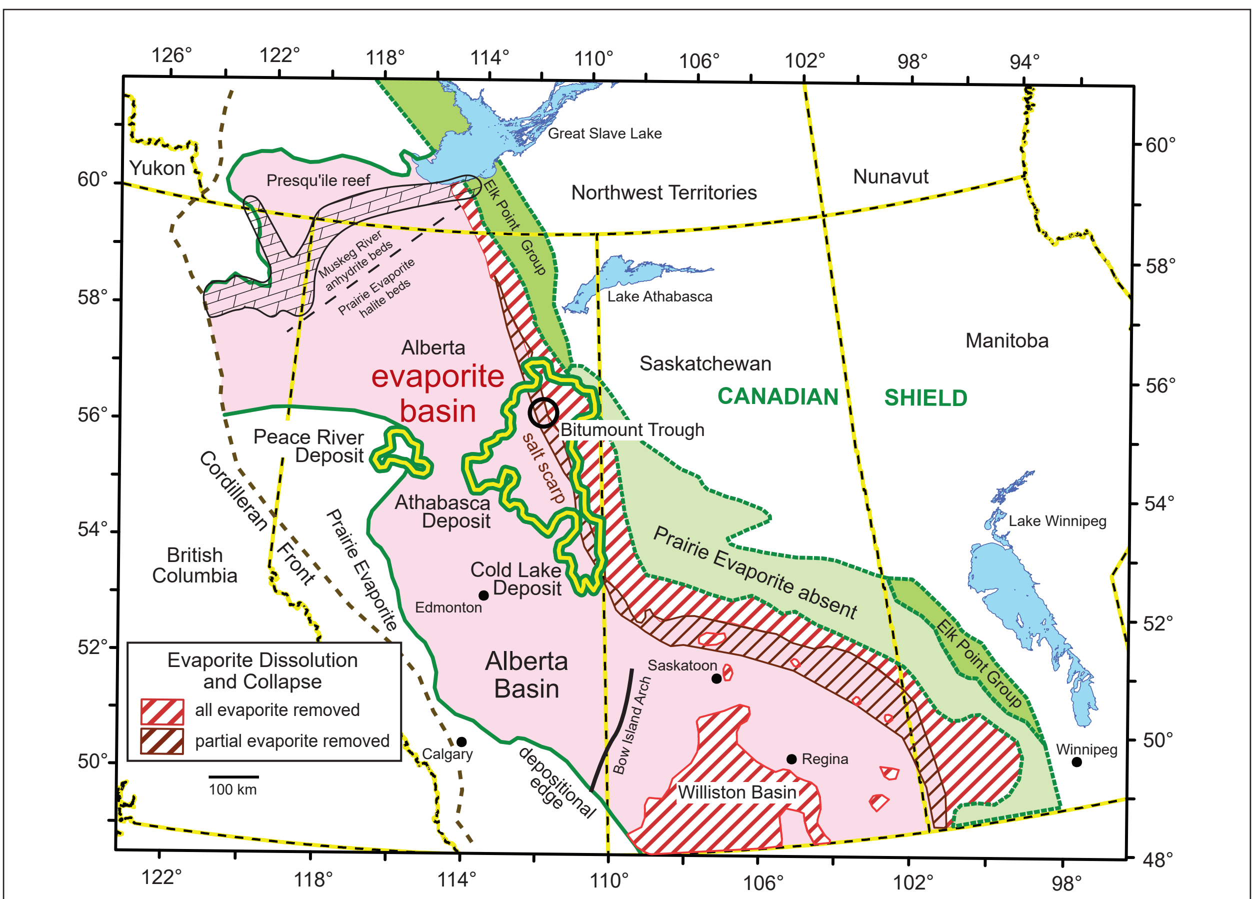

Fig. 1: Regional salt removal trends developed in the Middle Devonian Prairie Evaporite, Western Canada Sedimentary Basin: (1) 1000 km long and 150 km wide dissolution trend along the eastern up-dip margin of the WCSB, and (2) across the southern Saskatchewan area of the northern Williston Basin. The 10-20 km wide salt scarp is a trend of partial dissolution that separates areas of complete salt removal to the east from undisturbed beds to the west. Modified from Broughton (2015).

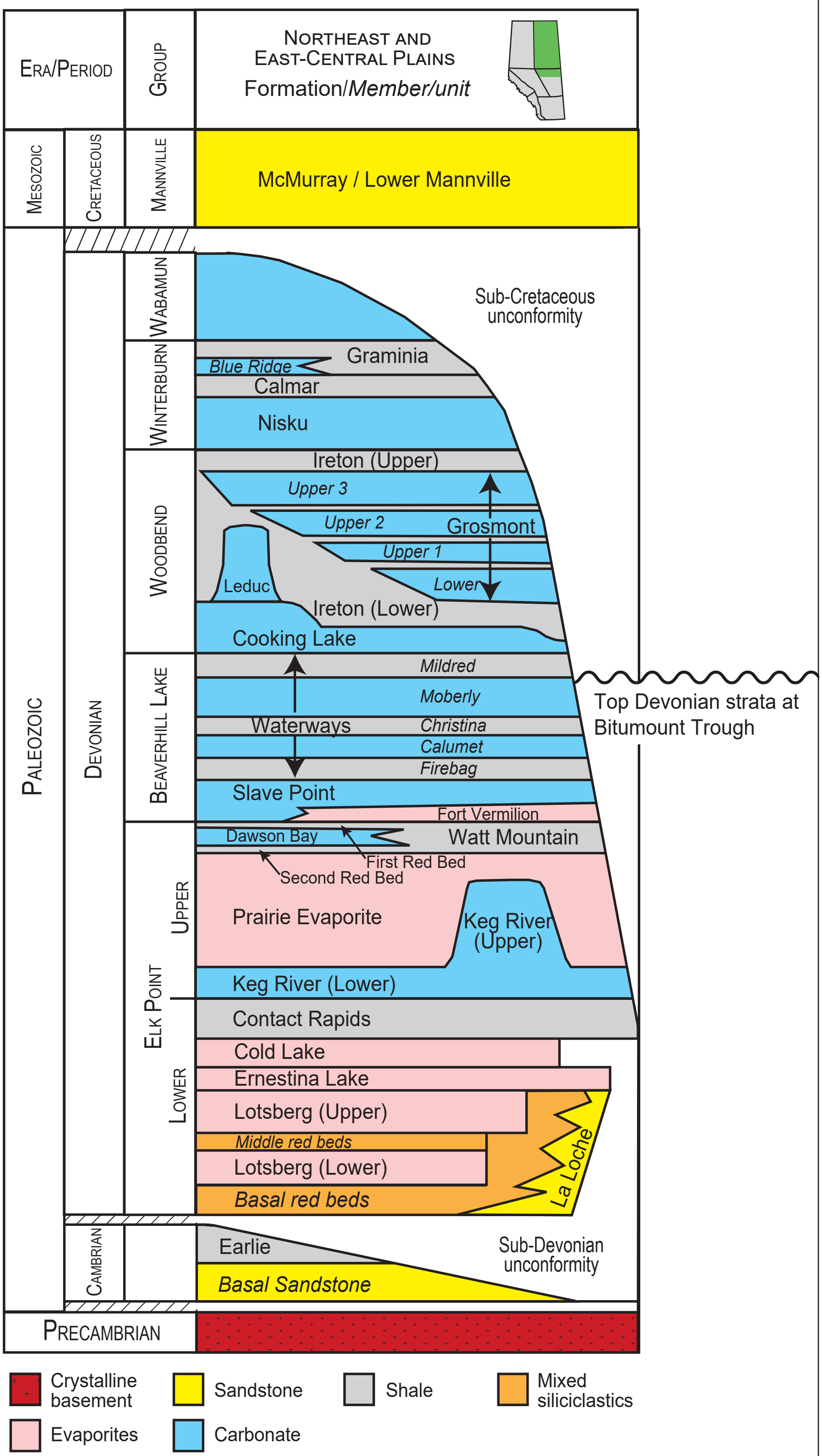

Fig. 2: Stratigraphy of northeast Alberta. The McMurray Formation is unconformable on the Waterways Formation, Beaverhill Lake Group, at the Bitumount Trough area of the Athabasca River Valley. Modified from Hauck et al. (2017) and Broughton (2018c).

STUDY AREA AND TERMINOLOGY

The study area in the northern Athabasca oil sands deposit is where strata of the McMurray Formation has been exposed along the Athabasca River Valley, northward of the town of Fort McMurray (Fig. 3). The river valley thalweg often downcuts to the erosion-resistant Devonian limestone formations. Saline seeps discharge as springs along the river banks, mostly emanating along the Devonian-Cretaceous unconformity near the floor of the river valley. Saline seeps also permeate bottom muds of the river, and ingress into nearby fenlands or remain in shallow Devonian aquifers.

Saline groundwater is defined as having TDS of 10,000-100,000 mg/L, in contrast to brackish (1000-10,000 mg/L), fresh (<1000 mg/L) or brine (>100,000 mg/L) (Davis 1964).

Dissolution trends that configured the Prairie Evaporite and overlying strata in western Canada are recognized as features of the largest known evaporite paleo-

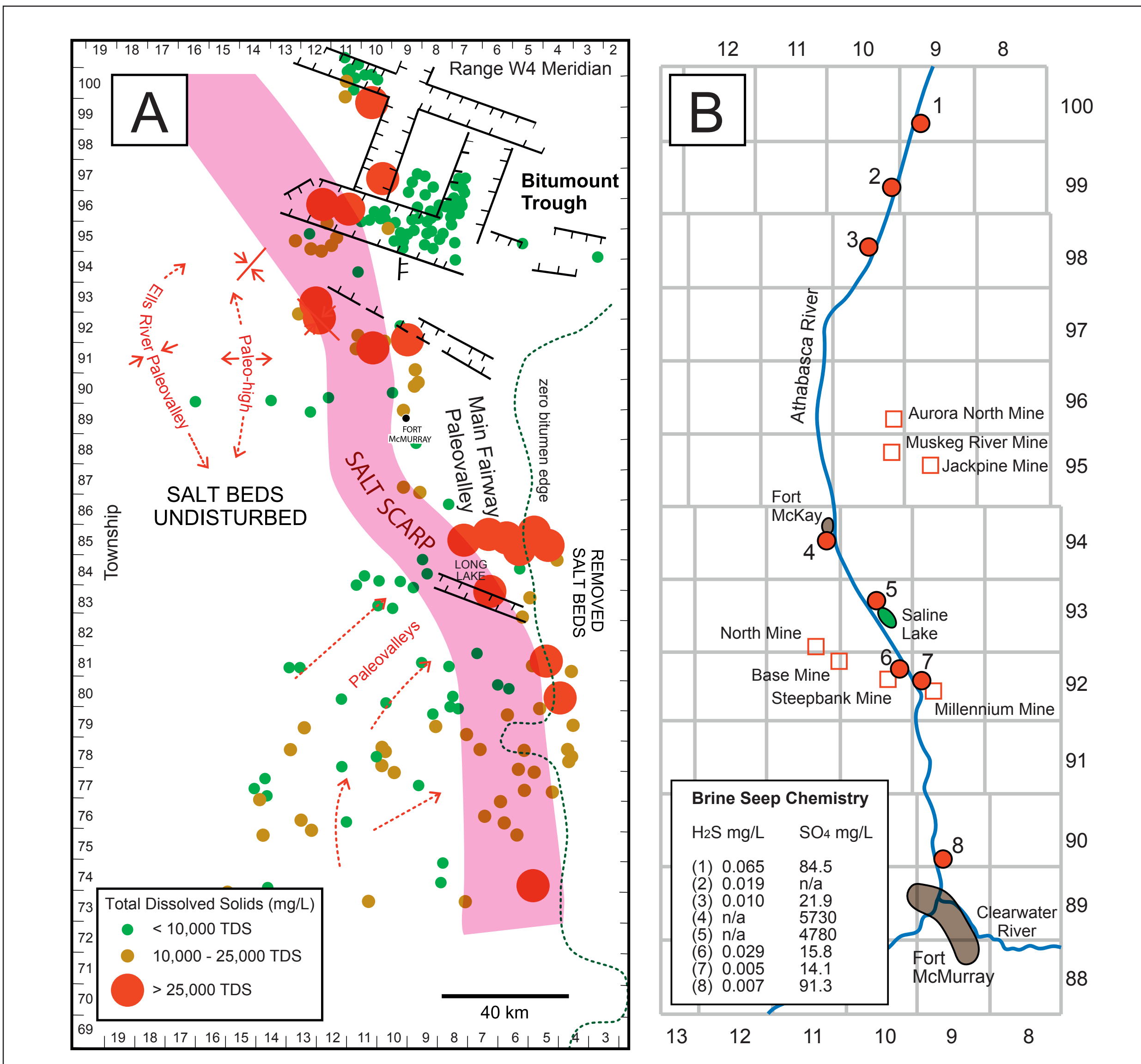

Fig. 3: Dissolved solids measured in groundwater and saline seeps discharged at surface along the Athabasca River Valley, northern Athabasca oil sands deposit. (A) 200 km long trend of elevated TDS up to 100,000 mg/L overlying the salt scarp and salt removal areas to the east, 200 m below. (B) Location of oil sands mines and selected groundwater samples from saline springs and hyporheic zone of channel fill mud along the Athabasca River, north of Fort McMurray. Modified from Gibson et al. (2013), Cowie (2013), Cowie et al. (2015), Birks et al. (2018) and Broughton (2018c).

karst, worldwide (Broughton 2013, 2015). In the study area, this paleo-karst is characterized by salt removal induced subsidence-collapse structures such as the 100 km long Bitumount Trough, sinkhole valleys and sinkholes that overlie a 300 km long segment of the 1000 km long halite-anhydrite dissolution trend developed along the eastern up-dip margin of the Western Canada Sedimentary Basin (Fig. 1). However, application of this paleo-karst terminology may not be entirely correct, *stricto sensu*. A paleo-karst is a buried dissolution feature that is inert or otherwise inactive at present. In contrast, the salt dissolution processes of the study area continue to the present day, and thereby are not entirely inert.

GEOLOGIC SETTING

The rise of the Rockies resulted in the accumulation of multi-km thick Jurassic and Cretaceous strata in the foreland Alberta Basin, which was configured by the eastward advancing Cordilleran deformation front. The overarching WCSB partitioned into the foreland Alberta Basin and the intracratonic Williston Basin by the Bow Island Arch, a northern extension of the Sweetgrass Arch in Montana (Meijer Drees 1986; Wright *et al.* 1994; Hein *et al.* 2013) (Fig. 1).

The 400 m thick Paleozoic strata below the Lower Cretaceous Athabasca oil sands deposit are mostly represented by Devonian formations, including the Elk Point and overlying Beaverhill Lake Groups (Fig. 2). The lower Elk Point Group formations include the Lotsberg salt and overlying Contact Rapids carbonate strata. The middle Elk Point Group is represented by the Keg River and overlying Prairie Evaporite, and covered by carbonate strata of the Dawson Bay Formation (Grobe 2000). The Middle Devonian Prairie Evaporite accumulated as a 100-200 m thick interval of halite beds with secondary anhydrite and calcareous shale beds. This evaporite basin extended from northern and central Alberta (Meijer Drees 1994; Grobe 2000; Hauck *et al.* 2017), across southern Saskatchewan and southwestern Manitoba (Holter 1969; McTavish & Vigrass 1987), and into northeast Montana and western North Dakota (LeFever & LeFever 2005).

The Laurentia and Gondwana paleocontinents were separated by the Rheic Ocean during the Paleozoic. Plate movements resulted in compressional and extensional tectonism of the Antler orogeny, resulting in this area of proto-North American to collide to form Pangaea (Van der Voo 1988; Mossop & Shetsen 1994). During the Middle Devonian, a southward extending arm of the Panthalassic Ocean embayed the north equatorial margin of Laurentia, resulting in a shallow inland sea that extended across present-day western Canada and into northeastern Montana and western North Dakota (Fig. 1).

The 400 km long Presqu'ile barrier reef developed at the northern seaward end of the shallow inland sea during the Givetian Stage of the Lower-Middle Devonian. This resulted in a barred evaporite basin (Holter 1969; Meijer Drees 1986; Broughton 2017a, 2018a, 2020). Reconstruction of the Middle Devonian paleogeography suggests the barred inland sea of the Elk Point Basin was positioned at an equatorial latitude of 10° to 20° south. Research on fluid inclusions suggest that brine evaporation cycles were controlled by temperatures up to 39 °C (Chipley 1985; Chipley & Keyser 1989, 1991).

The Upper Devonian carbonate formations of the Beaverhill Lake Group subcrop at the pre-Cretaceous unconformity onto which McMurray Formation (Aptian) strata were deposited (Hein *et al.* 2013; Schneider *et al.* 2014). The Cretaceous section, including the bitumen-saturated sands of the McMurray Formation, are exposed along the Athabasca River Valley. The principal reservoir rock of the Athabasca oil sands in northeast Alberta consists of the Lower Cretaceous McMurray Formation, which accumulated on a karstic Devonian limestone paleotopography (Fig. 2). Late Cretaceous hydrocarbon flows into multi-km scale point bar sand deposits were subsequently biodegraded *in situ.* The resulting ultra-heavy oil, 6-8° API, cemented the unconsolidated sand beds into a regional bitumen platform known as the Athabasca oil sands deposit.

The Athabasca River Valley in northeast Alberta overlies a segment of the Assiniboia PaleoValley, which developed parallel to the underlying salt removal trend (i.e. the salt scarp) in Middle Devonian substrate (Broughton 2016a, b, 2017a, 2018a, Grobe 2000; Hauck *et al.* 2017). Catastrophic floods of 13,000 and 10,000 years ago emanated from the glacial Lake Agassiz, which extended across most of southern Saskatchewan (Smith & Fisher 1993). Flood waters reconfigured the course of the Clearwater River in northeast Alberta by joining with the Athabasca River at Fort McMurray. Quaternary deepening of the Athabasca River Valley followed the underlying trend of the ancestral Assiniboia River Valley in this area of northeast Alberta. Drainage was northward towards to the Arctic Ocean (Murton *et al.* 2010).

OBSERVATIONS

SALT REMOVAL STAGES IN THE MESOZOIC AND CENOZOIC ERAS

Trends resulting from regional salt dissolution and collapse of overlying strata developed along the eastern up-dip margin of the WCSB and across the southern Saskatchewan area of the northern Williston Basin (Fig. 1). These salt removal trends constitute the largest known evaporite karst on Earth (Broughton 2017a, b, 2018a). Depositional patterns of the McMurray Formation point bars, the principal Athabasca oil sands reservoir rock, were significantly impacted by the dissolution trends that developed in Prairie Evaporite strata, 200 m below. Removal of up to 130 m of salt section was initiated during the Middle Jurassic-Early Cretaceous Cordilleran orogeny and continued during Aptian deposition of the McMurray Formation strata onto the karstic Devonian limestone paleotopography (Broughton 2013, 2015). Saline seep discharges at the surface along the Athabasca River Valley indicate that salt dissolution in the Prairie Evaporite occurs at present (Gibson *et al.* 2013; Birks *et al.* 2018, 2019).

CORDILLERAN SALT DISSOLUTION TRENDS AND COLLAPSE STRUCTURES

Craton deformations controlled the development of two distinctive salt dissolution trends in the Alberta Basin foreland and the northern Williston Basin (Fig. 1) (Broughton 2017b, 2018a). The earliest salt removal patterns developed across the northern Williston Basin, impacting southern Saskatchewan and adjacent areas of eastern Montana and western North Dakota (DeMille *et al.* 1964; Christensen 1967; Holter 1969; Christensen *et al.* 1982; Christensen & Sauer 2002; LeFever & LeFever 2005). As much as a 200 m thick interval of Prairie Evaporite salt beds was removed across the northern Williston Basin, commencing in the Late Devonian and becoming more widespread towards the end of the Paleozoic with Antler tectonism (Broughton 2017a; Smith & Pullen 1967). These events were followed by regionally extensive dissolution patterns during Laramide structuring (Holter 1969; Broughton 2018a; McTavish & Vigrass 1987).

The northern area of the Athabasca deposit overlies a 300 km long segment of the 1000 km long and 150 km wide dissolution trend developed along the up-dip eastern margin of the WCSB. This trend extends from northeastern Alberta, across southeastern Saskatchewan and into southwest Manitoba (Meijer Drees 1994; Bachu & Underschultz 1993; Hein *et al.* 2013; Broughton 2013, 2015, 2016a, b, 2017a, 2018a, b). The partial to complete removal of as much as a 130 m thick interval of halite-anhydrite beds across the study area in northeast Alberta commenced with the Cordilleran development of the Alberta Basin foreland and corresponding uplift of northeast Alberta. Dissolution trends in the Middle Devonian strata below the area of the Athabasca deposit were multi-staged, responsive to uplift of the eastern foreland area and concurrent with surface erosion of post-Upper Devonian strata (Fig. 2).

Salt dissolution tectonism has been widely documented as having a major influence on configuration of the pre-Cretaceous paleotopography, which was subsequently buried and configured further as the sub-Cretaceous floor below the Lower Cretaceous Athabasca oil sands deposit (Hein *et al.* 2013; Broughton 2013, 2015; Hein 2017; Barton 2016; Barton *et al.* 2017; Baniak & Kingsmith 2018). The salt dissolution events continued into the Aptian concurrent with overlying deposition of the McMurray Formation strata on the karstic Late Devonian limestone topography (Broughton 2013, 2015, 2016a, b, 2017a, b, c).

Sinkholes, breccia pipes and syndepositional trends indicate a widespread dissolution stage towards the end of the lower McMurray Formation deposition, and continuing during the middle and upper interval depositions (Broughton 2013, 2015; Baniak & Kingsmith 2018). There is no stratigraphic evidence preserved for salt removal during the Albian deposition of the overlying Clearwater Formation. Most of the post-McMurray strata of the study area have been eroded by Pleistocene glaciation.

Salt removal patterns are interpreted to have been responsive to movements of Precambrian blocks during craton deformations that configured the Alberta and Williston Basins of the WCSB (Smith & Pullen 1967; Kent 1974; Brown & Brown 1987; McTavish & Vigrass 1987; Broughton 2013, 2018a). Differentially displaced craton blocks, individual or linked as chains, resulted in NW-SE and NE-SW lineaments that are discernable on multiple Phanerozoic depositional surfaces (Smith & Pullen 1967; Kent 1974; McTavish & Vigrass 1987; Brown & Brown 1987; Broughton 2015, 2016a, b). These help to define 10s km long syndepositional trends. Seismic traces of faults rooted in the Precambrian are difficult to trace into the post-Devonian stratigraphic column because of the masking effects by salt beds and signals dissipated within the evaporitic strata (Broughton 2015, 2016a, 2017c). The orientations of syndepositional trends provide indirect evidence of underlying salt removal patterns having been generated as linear dissolution fronts that advanced to the NW and to the NE (Smith & Pullen 1967; Broughton

2013, 2018a). Subsequent coalescing resulted in broader areas of complete salt removal (Broughton 2013, 2015).

These salt dissolution trends follow multi-km to 10s km long reef patterns of the underlying or partially juxtaposed Keg River (Alberta Basin) and equivalent Winnipegosis Formation (Williston Basin). These reefs developed along the margins of reticulate basement blocks only a few hundred meters below. During the Paleozoic and Mesozoic, flows of meteoric-charged groundwater were along porous margins of these Keg River-Winnipegosis reef trends, and overlying dolostone beds of the lower Prairie Evaporite. During regional basin deformation events, these relatively fresh groundwater flows were into laterally offset and overlying salt beds. Basin loading effectively directed groundwater flows up-section to the northeast toward basin margins (Bachu & Underschultz 1993; Bachu 1995; Bachu *et al*. 1993).

Evaporite karst structures of the study area:

(1) Salt solution scarp. This 300 km long and 10-20 km wide trend of partial removal of the salt interval in the Prairie Evaporite occurs 200 m below the Athabasca deposit (Figs. 1, 3). This structural flexure below the length of the Athabasca deposit separates areas of complete salt removal to the east from undisturbed areas to the west (Meijer Drees 1986; Bachu *et al*. 1993; Hein *et al*. 2000, 2001, 2013; Broughton 2013, 2015; Hein 2015; Birks *et al*. 2018; Hauck *et al*. 2017; Barton *et al*. 2017). The westward migration of the salt dissolution scarp to the north of Fort McMurray resulted in parallel dissolution trends

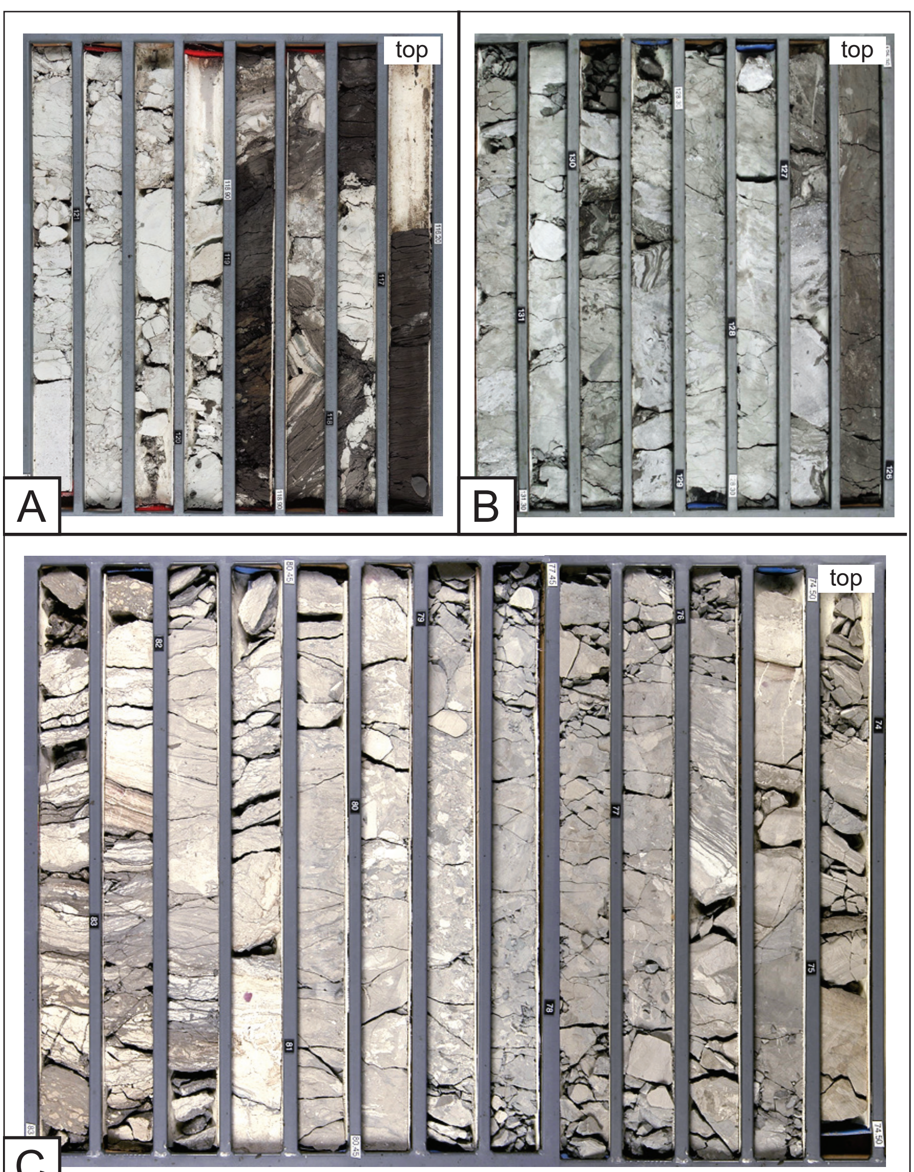

Fig. 4: Salt dissolution collapse breccia of the Waterways Formation (Upper Devonian) limestone and lower McMurray Formation (Aptian) at sites along the Bitumount Trough. Core box slats are 75 cm. Modified from Broughton (2013, 2015).

that were responsive to differing mineral solubility rates. These trends are: (1) eastern areas with complete removal of all halite and anhydrite beds; (2) partial removal of all halite beds with preservation of anhydrite; (3) complete removal of halite and partial removal of anhydride; (4) westward areas not affected by dissolution, resulting in a mostly complete salt section. This accumulation of the lower interval of the McMurray Formation along this segment of the Assiniboia PaleoValley in northeast Alberta northward of Fort McMurray was above the underlying trend of complete halite and partial anhydrite removal described by Schneider & Grobe (2013), Schneider *et al.* (2013, 2014) and Broughton (2020), and below the subsequent Quaternary position of the Athabasca River Valley.

The pre-Aptian position of the salt solution scarp was N-S. During the deposition of the McMurray Formation, the N-S orientation of the dissolution front northward of the town of Fort McMurray migrated to the NW to its present position below the Athabasca River Valley (Broughton 2015, 2016b, 2017a, b, 2018a, c). In contrast, the position of the dissolution scarp was relatively stable southward of the McMurray Formation type section at the town of Fort McMurray (Broughton 2018c, 2019). It is noteworthy that the eastern trailing margin of the salt scarp northward of Fort McMurray (Twp. 88-100) overlies the trace of the Precambrian Sewetakun Fault (Hackbarth & Nastasa 1979). It is possible that movements along this played a role in activating the dissolution front and directing groundwater flows along overlying Phanerozoic fracture trends until the W-NW scarp migration stabilized at the current position.

(2) Bitumount Trough. The 100 km long V-shaped Bitumount Trough is the largest known salt collapse structure. It underlies the area of the northern area of the Athabasca oil sands deposit. The collapse-subsidence development of the Bitumount Trough mostly occurred during deposition of the lower interval of the McMurray Formation. Development of the adjoined Central Collapse structure followed migration of the underlying scarp further to the northwest during depositions of the middle and upper intervals (Broughton 2015; Barton *et al.* 2017; Baniak & Kingsmith 2018). The Trough and the adjoined Central Collapse developed during deposition of the McMurray Formation, resulting from the W-NW migration of the salt scarp below the northern Athabasca deposit. Differential subsidence of km-scale Middle-Upper Devonian fault blocks, responsive to underlying salt removal, configured the sub-Cretaceous unconformity surface that floors the deposits of the McMurray Formation. The western area of the trough overlies the salt scarp and the eastern area extends over areas with mostly complete salt removal.

(3) Sinkholes and breccia pipes. Westward migration of the partial dissolution front, i.e. the salt scarp, was responsible for differential subsidences of km-scale fault blocks of overlying strata, and complete salt removal areas east of the trailing edge (Broughton 2013). This structuring resulted in distribution of multi-km long and 10s m thick limestone breccia zones and pipes (Fig. 4). Sinkholes resulting from salt removal in the substrate are recognized at several stratigraphic horizons (Broughton 2013).

Limestone-walled sinkholes, commonly 10-20 m to as much as 70-90 m deep, developed on the pre-Cretaceous karstic carbonate paleotopography of Waterways Formation, Beaverhill Lake Group (Middle-Upper Devonian). These sinkholes were subsequently filled and covered over by unconsolidated fluvial sands of the lower McMurray Formation. Many of the sinkhole and breccia pipe structures were reactivated toward the end of lower McMurray Formation deposition. As a result, breccia pipe-sinkhole complexes cross-cut lower McMurray Formation strata, but were usually terminated upon deposition of middle interval strata (Broughton 2013, 2015, 2017a, b, c).

Multi-km long linear chains of 10-130 m diameter lower McMurray sinkholes, partially eroded on the Holocene topography, are aligned NW-SE and NNE-SSW along salt-removal induced fracture lineaments emanating upward to the surface (Haug *et al.* 2009, 2014).

HOLOCENE SALINE SEEPS: DISTRIBUTION AND CHEMISTRY

Saline seeps discharge at many sites along the Athabasca River Valley, northward of Fort McMurray, and along the confluence with the Christina River (Fig. 3). These river valleys incised McMurray Formation strata of the Bitumount Trough, often exhuming strata down to the underlying erosion-resistant Devonian limestone (Hein *et al.* 2013; Broughton 2013, 2015; Hein 2017). Dissolved solids (TDS) and isotope chemistry indicate that spring waters are largely meteoric-sourced with variable contributions by glacial meltwater having been in contact with the underlying Devonian salt beds. Flows migrated up-section along Middle-Upper Devonian breccia zones (Fig. 4).

The elevated salinity measurements recorded for spring waters resulted from subglacial and proglacial meltwater flows into the shallow subsurface with the hydraulic drive responsive to basin deformation and loading associated with the 1.5 km thick Laurentide ice sheet (Grasby & Betcher 2000; Grasby *et al.* 2000; Grasby & Chen 2005; Grasby 2006; Haug *et al.* 2009, 2014; Broughton 2017b). Meltwater flows in contact with the buried Prairie Evaporite salt scarp rejuvenated dissolution only

200 m below the McMurray Formation oil sands. The meltwaters, mixed with dissolved salts, ascended to the surface upon withdrawal of the ice sheet as isostatic rebound occurred and the pre-Pleistocene basin hydrodynamics reasserted. The groundwater discharged as saline seeps and springs along topographic lows of river valleys, particularly along exposures of the sub-Cretaceous unconformity (Birks *et al.* 2018), but also remained in the shallow subsurface as formation water (Mahood *et al.* 2012).

Calculated annual discharge of saline groundwater to the Athabasca River amounts to 3.1 x 10^6 m^3, which equates to TDS of 64 million kg/year (Gue 2012). A similar annual discharge of saline groundwater for the Clearwater River was calculated at 3.2 x 10^6 m^3 or 66 million kg/year. Saline spring discharges into the Athabasca River have Na:Cl ratios closer to 1 (Grasby & Chen 2005; Gue *et al.* 2015; Gue *et al.* 2017), which are indicative of salinity having originated from halite dissolution. Salt dissolution trends elsewhere across western Canada were similarly reactivated by glacial meltwater flows into the subsurface, altering the groundwater chemistry and resulting in reactivation of older dissolution trends and collapse structures in both northeast Alberta (Ford 1998; Broughton 2016b, 2017a, 2018a, b) and southern Saskatchewan (Christiansen 1967, 1971; Christiansen *et al.* 1982).

There is a significant range in TDS chemistry across the Athabasca deposit (Fig. 3). Brackish to saline springs of the study area have TDS measurements between 7,000 and 52,000 mg/L (Hitchon *et al.* 1969; Ozoray *et al.* 1980; Grasby & Chen 2005; Gue *et al.* 2015). Measurement indicate a median Cl concentration of 9,800 mg/L and δ^{37}Cl values ranging from 0.2 to 1.0‰. Low δ^{18}O and δ^2H values and high salinities of the spring waters are indicative of salt dissolution sourced from the Prairie Evaporite salt scarp by glacial meltwater (Grasby & Chen 2005). Spring waters that discharge into the Athabasca and Clearwater rivers have δ^{18}O values as low as -23.5‰, suggestive of a water mixture containing as much as 50-75% Laurentide glacial meltwater (Gue 2012; Gue *et al.* 2015, 2017). For example, 10 saline springs sampled along the banks of the Athabasca and Clearwater rivers have δ^{18}O water chemistry indicating that most of the springs are composed of at least 26% glacial meltwater, often 40-60%, but a couple measured as much as 75% meltwater (Gue 2012). Of these, 8 recorded TDS measurements between 13,000 and 24,000 mg/L.

The highest TDS measurements were from water samples collected at stratigraphic intervals overlying the

Fig. 5: Brine spring along the eastern bank of the Athabasca River, near the Mildred Lake Mine. It discharges into La Saline Lake, resulting in a calcareous tufa deposit (Photo: A. Gue).

salt scarp and the eastern trailing margin (Cowie 2013; Cowie *et al.* 2014, 2015; Broughton 2017a, b, 2018c). Measurements of 100,000 mg/L to as much as 270,000 mg/L have been recorded in formation water samples recovered from McMurray Formation strata overlying the salt scarp (Jasechko *et al.* 2012; Cowie 2013; Birks *et al.* 2018, 2019), particularly where collapse breccia provided direct vertical communication pathways. Groundwater salinities from Devonian strata decrease rapidly from approximately 100,000 mg/L above eastern trailing edge of the salt scarp to values of less than 1000 mg/L at distances of 10 km eastward from the trend (CEMA 2010a; Jasechko *et al.* 2012; Birks *et al.* 2018).

It is noteworthy that Quaternary salt dissolution trends in the study area result in saline/brine seeps to the surface, but do not generally result in post-glacial collapse structures of any significant size (>km^2). These are inconsequential compared to the numerous 10s-100s km^2 Pleistocene collapses recognized across the southern Saskatchewan area of the northern Williston Basin (Holter 1969; Christiansen 1967, 1971; Christiansen *et al.* 1982). Nonetheless, deformations of McMurray strata have been caused by extremely over-pressured glacial meltwater in the vicinity of the Muskeg River Mine in the northern Bitumount Trough (Broughton 2018b). These unusual pressures resulted in subglacial hydrofracturing and resulted in several hydrodynamic blowout structures, such as 4-5 m dimeter open chimneys that cross-cut the rigid bitumen platform and extended upward to the plugs of the surficial cover. These are smaller examples of the Howe Lake blowout structure described by Christiansen *et al.* (1982).

Migrations of Devonian-sourced saline flows up-section to the surface occur as: (1) springs discharged along the banks of the Athabasca River into the waterway, often forming saline lakes off-bank; (2) infiltration of bottom muds along the river channels emanating from sources below; (3) seeps into fens and wetlands peripheral to the river valley; (4) formation waters observed with mine observation wells into Devonian strata below the McMurray Formation oil sand reservoirs.

(1) Springs. Saline seeps that discharge into the Athabasca River emanate from numerous sites along the sub-Cretaceous unconformity exposed along the Athabasca River Valley. Seeps are also observed along the Clearwater River valley eastward of confluence with Athabasca River at Fort McMurray. The following are examples of springs with markedly high TDS measurements.

Example A: La Saline spring. Multiple discharges flow into La Saline Lake, an oxbow along the east bank of the Athabasca River, opposite of the Mildred Lake Mine on the west bank (Figs. 3B, 5). The water collects in a shallow pool, and subsequently flows down an embankment to La Saline Lake. TDS measurements from the spring are typically 73,200 mg/L (Ca 1830 mg/L; Mg 456 mg/L; Na 25,600 mg/L; SO_4 4780 mg/L; Cl 40,200 mg/L (Hitchon *et al.* 1969; Birks *et al.* 2018). Other researchers report seasonally dependant measurements with a wide range of TDS measurements, such as 44,700-51,800 mg/L (Grasby 2006; Gue 2012). A calcareous tufa deposit, 100s m across (Fig. 5), developed along the southeast bank of the lake (Borneuf 1983). Microbial sulfate reduction occurred near surface, resulting in spring water affected by methanogenesis and methane oxidation (Fig. 6). Crusts and muds with elemental sulfur are recognized at

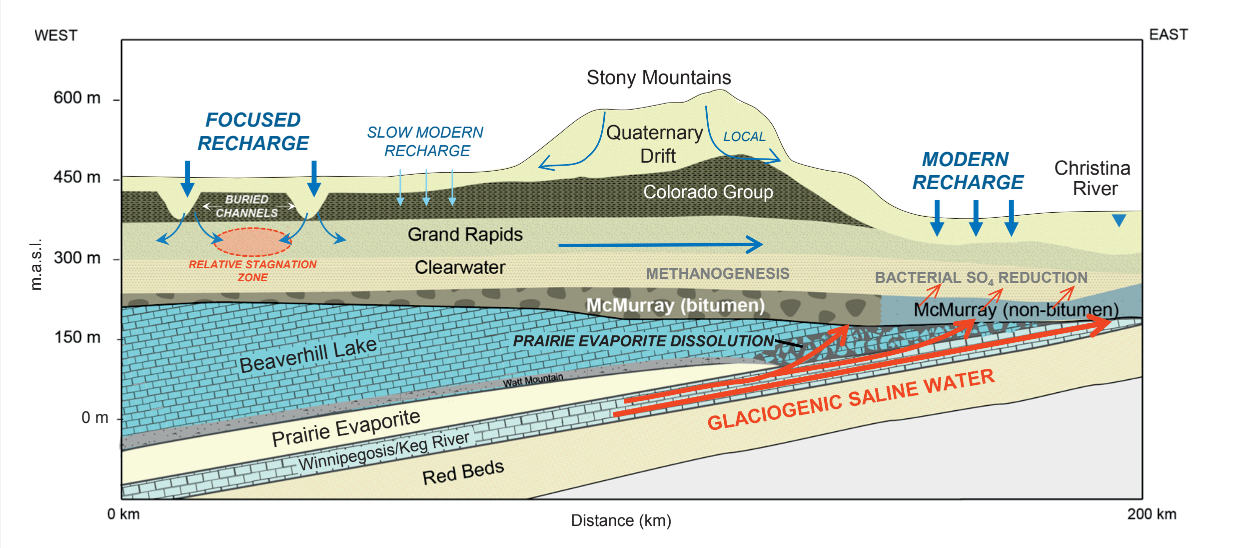

Fig. 6: Schematic cross-section of glaciogenic saline groundwater flow up-section along collapse breccia of the Prairie Evaporite salt scarp, 200 m below, resulting in surface discharges along river valleys. Modified from Birks et al. (2019).

the spring. The dissolved solids of the spring are diluted upon mixing into the lake water, for example 260 mg/L SO_4 in lake water. The sulphate content of the La Saline spring water is 2-8x the level of other springs along the Athabasca and Clearwater River valleys (Gue 2012; Gue *et al.* 2015, 2017).

Example B: Fort McKay spring. This intermittent brine flow emanates from a well casing on the west bank of the Athabasca River at the town of Fort McKay (Fig. 3B). A very high TDS analysis of 214,000 mg/L has been reported: Ca 1730 mg/L; Mg 447 mg/L; Na 79,200 mg/L; SO_4 5730 mg/L; Cl 126,300 mg/L. Recently, the flow diminished to a trickle and measured only 5320 mg/L (Gue 2012).

(2) River bottom muds. Seeps with elevated TDS have been observed to infiltrate channel bottom mud of the Athabasca River (Broughton 2016b; Birks *et al.* 2018). Samples of pore water were collected from channel mud at 1 and 3 m depths below the mud/water interface at sites along the Athabasca River, north of the town of Fort McMurray (Fig. 3B: sites 1-3, 6-8). Increased salinities for the channel fill mud are characteristic, but diluted by fresh river water. The up-hole mud samples indicate mixing with the Athabasca River water, in contrast with bottom hole samples having geochemical and isotope signals more consistent with infiltration of saline groundwater into the channel mud from underlying sources. These salinity measurements of river bottom mud are diluted and have lower values measured than saline springs discharged along the river valley (Fig. 3B: sites 4-5).

(3) Fens and wetlands. Most saline seeps of the study area are discharged at the level of the sub-Cretaceous unconformity where exposed along the Athabasca and Christina river valleys. Stratigraphically and topographically higher discharges also occur, and permeate fenlands and wetlands of the study area. For example, saline seeps into fenlands have been observed along the erosional edge of the Cretaceous Grand Rapids Formation (Stewart & Lemay 2011; Wells & Price 2015a, b). Cl/Br ratios and $\delta^{18}O$ and $\delta^{2}H$ isotope measurements indicate halite dissolution as the source for these 10,000 mg/L TDS seeps (Stewart & Lemay 2011).

(4) Formation waters. A regionally widespread network for 10s km of saline groundwater aquifers extends below the sub-Cretaceous unconformity, and is characterized by seepages up-section along collapse breccia conduits (Mahood *et al.* 2012; Broughton 2018c, 2019). Observation wells are used to evaluate potential geo-hazard risk of the regional saline groundwater flow below the oil sand mines. These 100-200 m deep observation wells into intervals of Upper Devonian carbonate strata record groundwater movements and salinities approximately 100 m below pit operations. For example, at the southwest corner of the Muskeg River Mine on the east bank of the Athabasca River (Twp 95, Rge 9-10), an uncontrollable flood of saline water was released from a Devonian aquifer into a mine pit known as Cell 2A (Cooper 2011). Removal of the bitumen sand interval was sufficient to release overburden pressure on the pit floor, which consists of Devonian limestone of the Waterway Formation (Stoakes *et al.* 2014). The saline formation water flow emanated from a multi-m long fissure in the limestone pit floor, flooding and eventually filling the mine excavation. Analysis of the Cell 2A water indicated TDS of 38,000 mg/L. This chemistry is consistent with formation water samples that measured 40,000-70,000 mg/L recovered from observation wells drilled into the underlying collapse breccia portion of the Prairie Evaporite, which is at a level 100 m below the pits of the Muskeg River Mine.

INTERPRETATION: UNUSUAL DEPOSITS OF THE MCMURRAY FORMATION

EVIDENCE FOR MIGRATIONS UP-SECTION OF DEVONIAN FORMATION WATER TO CRETACEOUS DEPOSITS

Episodic removal of up to 130 m of Middle Devonian salt beds occurred during overlying deposition of the McMurray Formation, but evidence is scant for tracing the ultimate disposition of voluminous brines that must have been produced. There are 3 deposits of the McMurray Formation that are indicative of voluminous brines produced in the Devonian subsurface and ascended to the surface concurrent with the deposition of the McMurray Formation. These Devonian formation water flows up-section infiltrated sand beds along the margins of the Assiniboia River Valley and some discharged at the surface. These facies are now observed in the subsurface or were partially exposed by the expansion and deepening of the Athabasca River Valley following Pleistocene flooding.

The 3 deposits are: (1) a drainage-line silcrete emplaced at the top of the lower interval; (2) calcite-cemented sand intervals; (3) biofacies of widely distributed brackish-water trace-fossils, mostly burrows, considered diagnostic of middle interval beds. These lithofacies and biofacies are interpreted to have originations during the Early Cretaceous, and are attributable to saline seeps to the surface or near surface. The collective association of these 3 depositional events has not been spatiotemporally linked previously to the multi-staged dissolution process that resulted in Quaternary saline seeps discharged along the Athabasca River Valley.

SILCRETE OF THE LOWER MCMURRAY FORMATION

The Beaver River Sandstone is a discontinuous quartzite bed up to 1.7 m thick that occurs as narrowly distributed facies at the uppermost level of the lower McMurray Formation (Fig. 7). This 10s km long drainage-line silcrete was discontinuously emplaced at a horizontal level along the disconformable contact with the overlying middle interval beds. These erosion resistant beds are distributed as caprocks along the Athabasca River Valley (Figs. 7, 8). This quartzite interval was partially exposed and eroded as Late Pleistocene glacial meltwater floods enlarged and deepened the river valley. Partial erosion sourced innumerable quartzite boulders distributed along the floor of the Athabasca River Valley, and concentrated on the valley floor of the Bitumount Trough.

The silicified interval consists of light grey orthoquartzite with a bulk composition of 98-99% quartz. The matrix ranges from 75% to 95% quartz and 5-25% quartzite pebbles. The original porosity is estimated at approximately 25-30%, and is consistent with other sand reservoirs of the formation. Silicified microfossils are observed with SEM, consisting of branching hollow tubular bacterial sheaths with diameters of 3-4μm (Broughton 2020).

Silicification of the unconsolidated sands occurred during deposition of the uppermost beds of the lower McMurray Formation accumulated along this segment of the Assiniboia PaleoValley. This diagenesis has been interpreted as responsive to dissolution of halite and anhydrite beds in the underlying Prairie Evaporite. The diagenetic model proposes by Tsang (1998) and Broughton (2020) asserts that sulfate-rich brines resulted from the dissolution of gypsum/anhydrite beds of the underlying Prairie Evaporite and migrated up-section to the lower McMurray Formation sand beds accumulated along the margin of the Assiniboia River Valley. Microbial sulfate redox occurred near the surface and altered the chemistry of the ascending brines. This resulted in dispersed pools of strongly acidic groundwater with sufficient acidity to induce widespread corrosion of the quartz sand grains and markedly increase silica saturation. A pH shift would have occurred as the acidic groundwater seeps mixed with meteoric-charged oxygenated groundwater at the onset of middle interval deposition, triggering erratic silica cementation that formed the drainage-line silcrete along the margins of the Assiniboia PaleoValley, now exposed by the overlying trend of the Quaternary Athabasca River Valley (Broughton 2020). Similar seeps to the surface with strongly elevated sulfur or sulfate content can be observed at springs along the Athabasca River Valley, such as La Saline Lake (Gue 2012; Gue *et al*. 2015, 2017).

The quartzite was used as toolstone material by indigenous groups that date back at least 10,000 years. Hundreds of archeological sites consisting of toolstone excavation pits and arrow head manufacturing sites are known along the floor of the Bitumount Trough and elsewhere along the river valley (Fenton & Ives 1982, 1984,

Fig. 7: Late Pleistocene expansion of the Athabasca River Valley partially exposed Beaver River silcrete that developed near the top of the lower interval of the McMurray Formation. Late Pleistocene deepening of the Athabasca River Valley resulted in partial erosion of the exposed silcrete. Caprocks and quartzite boulders are dispersed along the floor of the river valley. This example of a 1.7 m-thick silcrete caprock is located adjacent to the Quarry of the Ancestors (Photo: P. Broughton).

1990; Ives & Fenton 1983, 1985; Kristensen *et al*. 2016). Clusters of exaction pits are known as the Quarry of the Ancestors and the Beaver River Quarry (Fig. 8).

CALCITE-CEMENTED SAND INTERVALS OF THE LOWER MCMURRAY FORMATION

The lower interval of the McMurray Formation includes poikilotopic calcite-cemented sand intervals, commonly 0.2-1.5 m thick, but also can occur as clusters as much as 8-10 m thick (Fig. 9). Most of these cemented sand intervals are distributed within the sand deposits that infill the Bitumount Trough. Broughton (2021) has interpreted these calcite-cemented sand intervals as being spatiotemporally linked to salt removal patterns along the Prairie Evaporite salt scarp. Sinkhole fills consisting of collapse breccia often include blocks of previously cemented sand. This is consistent with cementation having occurred during lower McMurray deposition, concurrent with subsidence of the Bitumount Trough. Networks of cement-healed fractures and breccia are also observed extending from the level of the sub-Cretaceous unconformity upward for 10s m towards the top of the lower McMurray interval (Broughton 2021).

The dissolution induced collapse-subsidence of overlying Upper Devonian carbonate strata resulted in concurrent migrations up-section of Ca-bicarbonate saturated Devonian formation water to the lower McMurray Formation fills of the Bitumount Trough. Precipitations of calcite cement in Cretaceous sediments are interpreted as having been the result of migrations up-section of bicarbonate-saturated Devonian formation water. This cementation process is consistent with the range of positive values for the $\delta^{18}O$ isotopes of +22.2‰ to +24.3‰ for cemented sands of the Athabas-

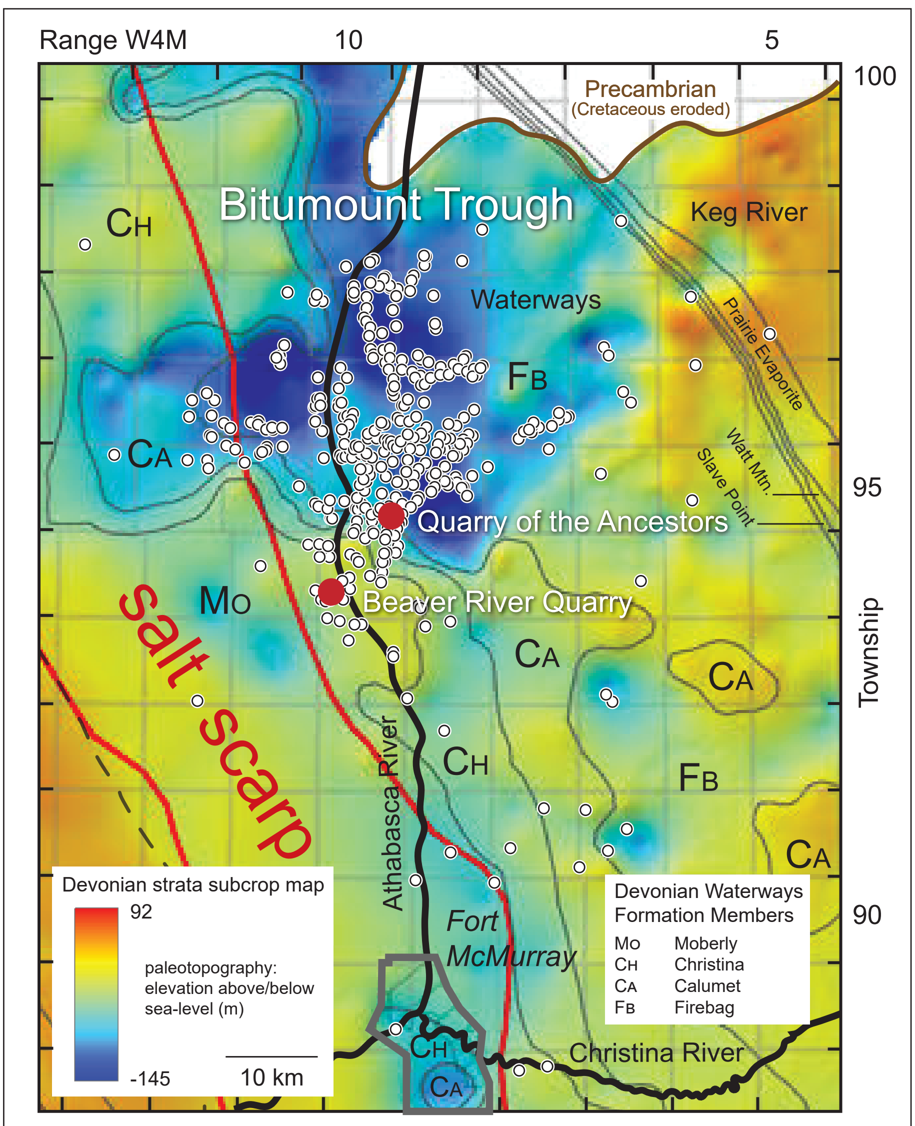

Fig. 8: Outcrops of the Beaver River Sandstone and erratically dispersed quartzite boulders are observed along the floor of the Athabasca River Valley. Clusters of outcrops occur across the floor of the Bitumount Trough. The trend of the drainage-line silcrete follows the eastern margin of the Prairie Evaporite salt scarp, 200 m below. Quarry of the Ancestors and the Beaver River Quarry were sources of the quartzite for use as toolstone. Modified from Broughton (2015), Kristensen et al. (2016) and Hauck et al. (2017).

ca deposit described by Dimitrakopoulos & Muehlenbachs (1987), albeit based on limited data from only 5 samples. In contrast, there has been extensive research on the linkage between Paleozoic carbonate strata and cemented intervals of overlying Cretaceous strata for deposits of the Alberta Basin to the west of the study area. Measurements of elevated oxygen isotope values, $\delta^{18}O$ ~ +23% in calcite cements result from infiltrations of Cretaceous strata by ascending bicarbonate-saturated Palaeozoic formation waters, particularly near the base of the Mesozoic section. This is indicative that carbonate-saturated fluids reached equilibrium with average Palaeozoic carbonate strata (Longstaffe 1984; Connoly *et al.* 1990a, b). These studies record calcite cements of the Cretaceous strata having elevated oxygen isotope values consistent with migrations up-section of formation fluids from karstic limestone trends. Sandstone pore water emplaced above Palaeozoic carbonate strata typically measure substantially higher $\delta^{18}O$ values of +7‰ to +9‰ or higher. Longstaffe *et al.* (1992) report oxygen isotope values for calcite cement in overlying Cretaceous strata have elevated $\delta^{18}O$ range of +12‰ to +21‰. The strongly positive isotope values of the underlying Palaeozoic carbonates were in equilibrium with cements of overlying Cretaceous sands (Connolly *et al.* 1990a, b; Longstaffe *et al.* 1992; Longstaffe 1994; Kriste 2000). The responsiveness of calcite having oxygen-isotope exchange with formation waters during dissolution and re-precipitation have been documented by many researchers (Longstaffe *et al.* 1992).

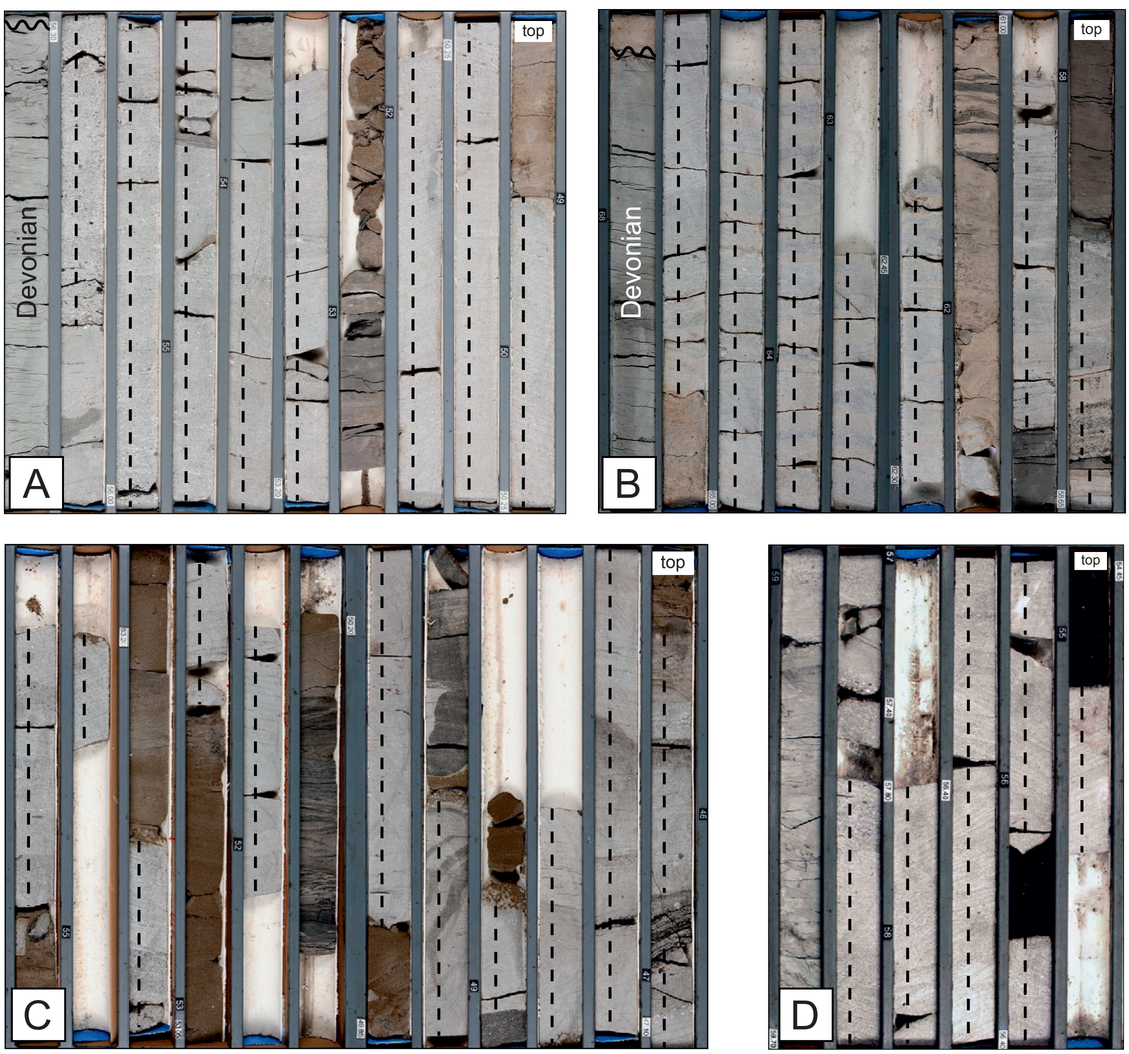

Fig. 9: Multi-meter thick interval of calcite-cemented beds (dash-lines) within the lower McMurray Formation. Well cores of the Bitumount Trough: (A) 1AB/01-05-97-08W4M; (B) 1AC/09-08-97-08W4M; (C) 1AA/16-33-96-08W4M; (D) 1AA/16-36-97-08W4M. Core box slats are 75 cm.

BRACKISH-WATER TRACE-FOSSILS OF THE MIDDLE MCMURRAY FORMATION

The depositional environment of the middle McMurray Formation is controversial with rival paleogeographic models extensively debated. Differing interpretations have been proposed for the 300 km long Early Cretaceous inland depositional system at the northern end of a continental-scale river system that approached the now-eroded shoreline of the Boreal Sea. Interpretations of the middle McMurray Formation sedimentology broadly follow two different models or a third variant. These irreconcilable models that attempt to explain the depositional environments of the middle interval of the McMurray Formation are known as the "McMurray Conundrum" (Blum & Jennings 2016; Broughton 2018c, 2019).

(1) Fluvial Model. Deposits accumulated along a northward flowing axial channel belt of the Alberta foreland, paralleling eastern margin of the Cordillera deformation front. This fluvial model explains the highly sinuous axial fluvial channel architecture, which consists of looping meanders with multi-km long point bars, counter point bars, and downstream meander scrolling (Hubbard *et al*. 2011; Fustic *et al*. 2012; Durkin *et al*. 2017a, b). This highly sinuous fluvial channel architecture with bank-full depths of 30-40 m is at the scale of a giant river system such as the Mississippi River, which is used as a modern analogue. However, this river system model cannot account for the pervasive distribution of brackish-water trace-fossils, and cannot be compatible with a 10s m thick salt wedge necessarily extending 100s km upstream to sustain the brackish-water zoology that colonized the 2-7 km long and 10-40 m thick point bars. The channel architecture may be interpreted as definitively fluvial in character, but the widespread brackish-water fossils are admittedly enigmatic. The model is not compatible with the development of a 20-40 m thick salt wedge extending for as much as 200-300 km upstream as to submerge km-scale point bars with brackish-water to permit habitation by crustaceans.

(2) Estuary Model. The depositional model asserts that an estuary characterized by a fluvial-tidal transition zones extending 100s km inland can explain the distribution of the brackish-water zoology far inland (Gingras *et al*. 2016, 2019). However, this estuarine paleogeography cannot readily account for the highly sinuous and looping meander channel architecture extending for 100s of km inland.

(3) Salt Tectonism Model. A third model that asserts that brine seeps to the surface occurred during deposition of the middle McMurray Formation and were discharged into the channel deposits along the Assiniboia River Valley (Broughton 2018c, 2019). This alternative, albeit controversial, to the two widely accepted but irreconcilable depositional systems proposes that removal of the 80-130 m thick salt section across 1000s km^2 resulted in voluminous brine seeps that migrated up-section to channel sand bars during deposition of the middle interval (Broughton 2018c; Hein & Dolby 2018). Channel muds constrained leakage of the ascending brines into the current along the river bottom. This salt dissolution seep model can provide an explanation for the enigmatic distribution of brackish-water trace-fossils in the channel muds, otherwise difficult to account for by the fluvial channel belt model. Accordingly, a brief transgression southward by a tongue of the Boreal Sea transported marine/brackish-water larvae inland along the tide-impacted backwater length of the river at the onset of middle interval deposition. This brackish-water zoology was sustained along the fluvial channel belt by saline seeps that elevated salinity levels in channel muds, but without altering the chemistry of the river water column as the fluvial system dominance reasserted. The brackish-water invertebrates rapidly evolved diminutive body forms as they adapted to new terrestrial food sources along these fluvial channels. This salt tectonism model precludes the necessity for a 10s m thick salt wedge to have extended 100s km inland and cover over 10-40 m thick fluvial point bars colonized by burrowing crustaceans adapted to brackish-water environments. Nonetheless, this salt dissolution-brine seep model would also be consistent with the estuary model.

DISCUSSION AND CONCLUSIONS

HOLOCENE SALINE SEEPS AS ANALOGUE FOR APTIAN BRINE SEEPS

Mannville Group strata in deeper areas of the Alberta Basin record elevated oxygen isotope values for early diagenetic calcite cements, resulting in further increases in $\delta^{18}O$ values during burial diagenesis as pore water were being equilibrated with the underlying carbonate beds. These positive values were maintained upon migration to overlying Mannville Group strata, and fixated by Cretaceous calcite cementation before impact by ingress of meteoric-charged groundwater and glacial meltwater, which substantially alter isotope values to a negative range. This model contrasts with interpretations that the dissolution of aragonite shell debris resulted in calcite precipitations that cemented marginal marine to deltaic clastic sediments. The use of stable isotope measurements has been instrumental in confirming the role of up-section migrations of carbonate-saturated formation fluids.

Quaternary geochemical trends (Fig. 3A) are interpreted to mirror earlier Cretaceous dissolution patterns, but do not necessarily provide evidence regarding the disposition of the voluminous brine that must have resulted. The large volume of produced brine would have to be accounted for either by surface discharge or distribution elsewhere in the basin subsurface, or both. There is only indirect stratigraphic evidence that the regional salt dissolution events, known to have occurred during deposition of the McMurray Formation, resulted in saline or brine seeps to the surface. That migrations up-section of chloride and sulphate-saturated Devonian formation water did in fact occur are indicated the occurrences of: (1) silcrete at the top of the lower interval; (2) calcite-cemented sand intervals; (3) brackish-water trace-fossils distributed along the channel belt of the middle interval.

Holocene saline seeps and springs discharged along the Athabasca River Valley are interpreted as a modern analogue for dissolution trends that would have resulted in voluminous brine seeps similarly discharged at the surface during deposition of the McMurray Formation. The geo-hydraulic drives of these Early Cretaceous and Quaternary saline to brine flows up-section somewhat differ, but both were responsive to basin loading either by the Cordilleran deepening Alberta Basin depocenter to the southwest, or by weight of the Pleistocene ice sheet with isostatic rebound upon withdrawal. Both processes resulted in meteoric-charged groundwater coming in contact with the Prairie Evaporite salt scarp only 200 m below. Both the Early Cretaceous and Quaternary groundwater flows mixed with dissolved salt and subsequently migrated up-section to the surface along karstic breccia collapse structures that cross-cut Upper Devonian strata aquitards and if present, the bitumen-saturated sand aquiclude of the overlying McMurray Formation (Broughton 2013, 2015; Cowie 2013). These flows up-section may have occurred intermittently during the interval between McMurray Formation deposition and the Laurentide ice cover, but this remains uncertain because the stratigraphic evidence has been eroded.

Spatial linkages between Pleistocene-Holocene and Aptian salt removal stages that resulted in saline and brine seeps up-section are indicated by the eventual stationary alignment of the dissolution front (salt scarp) below the Assiniboia PaleoValley and the superimposed Athabasca River Valley. The W-NW migration of the salt scarp during deposition of the McMurray Formation eventually stabilized and remained at a stationary position into the Quaternary below the Athabasca River Valley. This is suggested by the lack of any further post-McMurray migration westward because no larger-scale collapse structure developed during the Quaternary.

Salt volume removal during the Pleistocene and Holocene across the study area was relatively insignificant in contrast to large scale (100s km^2) Pleistocene collapse events across southern Saskatchewan, such as formations of the Saskatoon and Regina Lows (Christiansen 1967; Christiansen & Sauer 2001, 2002). Salt scarp alignment below the Assiniboia River Valley is consistent with the trend of elevated TDS measurements of groundwater and spring waters (Fig. 3A). The distribution of dissolved salts in the groundwater follows the Holocene position of the salt scarp and trailing edge of complete salt removal to the east (Grasby & Londry 2007) and is consistent with salt removal patterns during McMurray Formation deposition (Cowie 2013; Cowie *et al.* 2014, 2015; Broughton 2017a, b, 2018a, b). Strongly elevated dissolved solid (TDS) trends of surface discharged springs along the Athabasca River Valley are consistent with salt removal patterns along the salt scarp at the time of McMurray Formation deposition. Regional collapses occurred during deposition of the McMurray Formation, such as the development of the Bitumount Trough (Broughton 2013, 2015).

These geographic and geochemical relationships suggest an alignment that would be favorable for including brine seeps to the surface. That Aptian migrations up-section of Devonian formation waters did happen are suggested by the emplacement of the drainage-line silcrete along the margins of the Assiniboia PaleoValley, which is consistent with boundaries of the overlying Athabasca River Valley. These seeps also controlled emplacement of calcite-cemented sand intervals and the distribution of brackish-water trace-fossils. The emplacements of these lithofacies and biofacies followed the major elevated salinity trend above the salt scarp. The multi-staged regional dissolutions of 10s m thick Middle Devonian salt beds were thereby concurrent with deposition of the uppermost lower and middle-upper intervals of the McMurray Formation (Grasby & Londry 2007; Broughton 2013, 2015), and resulted in saline seeps to the overlying depositional surfaces (Hein & Dolby 2018; Broughton 2019, 2020).

These seeps may have been only stages of intermittently continuous dissolution of the Prairie Evaporite from the Cordilleran tectonism to the present day.

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