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Canadian Arctic–Beaufort Sea Rifted Margin Tectono-Sedimentary Element, SE Canada Basin

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Abstract

The Canadian Arctic Rifted Margin Tectono-Stratigraphic Element (CARM TSE) is located on the continental shelf and slope that lie to the west of the Canadian Arctic Archipelago and to the north of the Mackenzie Delta. The TSE comprises the rift succession deposited on the eastern and southern margins of the Amerasia Basin, coincident with the opening of this basin. The TSE strata range in age from the latest Triassic (Rhaetian) to Early Cretaceous (Albian). A major unconformity marks the base of the TSE with underlying rocks consisting of moderately to highly deformed Proterozoic and Lower Paleozoic rocks that are regarded as basement. The TSE is overlain by the Canadian Arctic Prograded Margin (CAPM) TSE with the boundary being a significant unconformity in landward areas. Well data are limited to the Beaufort-Mackenzie area and reflection and refraction seismic data indicate that the succession is up to four km thick. The TSE is divided into 4 structural domains with deformation increasing to the north. The Beaufort-Mackenzie Domain is dominated by extensional structures with later contractional structures present in its western portion. The Southern Domain is extensional and characterized by normal faults with tilted fault blocks. The structure of the Central Domain is similar to that of the Southern Domain but may include broad folds formed during the Paleogene Eurekan Orogeny. The succession in the Northern Domain is likely strongly folded and cut by thrust faults of the Eurekan Orogeny. Cretaceous extrusive and intrusive basic rocks, related to magmatism in the northern Amerasia Basin, are present in both the Central and Northern domains. Petroleum source rocks, of both lacustrine and marine origin, may be present in the Jurassic portion of the succession and marine shales in the Lower Cretaceous succession. The potential for structural and stratigraphic traps in widespread sandstone units of alluvial fan to marine slope origin is high. The remote location of the TSE, however, makes it likely it will not be a target for petroleum exploration in the foreseeable future.

Introduction

The Canadian Arctic Rifted Margin (CARM) TSE comprises the uppermost Triassic to Lower Cretaceous succession which was deposited on the southern and eastern margins of the Amerasia Basin during the initiation and opening of the basin by hyperextension of continental crust followed by sea floor spreading. This TSE lies below the shelf and slope of the eastern Beaufort Sea as well as offshore the Canadian Arctic Islands and extends from the USA-Canada border in the south and west to the Canada-Greenland border in the northeast (Fig. 1). It borders the Beaufortian Rifted Margin CTSE (Houseknecht, this volume) in the southwest and underlies the Beaufort-Mackenzie TSE (Chen et al., this volume) in the Beaufort Sea-Mackenzie Delta area and the Canadian Arctic Prograded Margin TSE (Embry et al., this volume, a) along the Canadian Arctic margin northeast of the Beaufort Sea. Rocks underlying the CARM TSE are moderately to highly deformed Neoproterozoic-Devonian strata with associated basement intrusives (e.g., Helwig et al., 2011; Embry and Beauchamp, 2019).

This paper summarizes what is currently known about the geology and petroleum potential of the Canadian Arctic Rifted Margin Tectono-Sedimentary Element (CARM TSE). For purposes of its description in this paper, it is divided into four structural domains (Fig. 1): the Beaufort-Mackenzie Domain (B-MD), covering the eastern portion of the Beaufort Sea including the Mackenzie Delta; the Southern Domain (SD), from Amundsen Gulf to offshore southern Prince Patrick Island; the Central Domain (CD), from offshore central Prince Patrick Island to Peary Channel, and the Northern Domain (ND), offshore Meighen, Axel Heiberg and Ellesmere islands as far as the contiguous Alpha Ridge (Fig. 1). Most of the subsurface data acquired in the TSE, and available for study, lie within the B-MD, with scarce to completely absent subsurface geological data available in the other three domains.

1. Age

Deposits of the CARM TSE are interpreted to range in age from latest Triassic (Rhaetian) to Early Cretaceous (Albian) based on the stratigraphy of the B-MD and the interpreted rifting history of the Amerasia Basin (Dixon, 1996; Embry and Dixon, 1994; Grantz et al, 2011; Embry and Anfinson, 2014).

2. Geographic location and dimensions

The CARM TSE is located along the marine shelf and slope that lie to the west of the Canadian Arctic Archipelago and in the eastern Beaufort Sea-Mackenzie Delta region. The TSE runs for about 2400 km between the USA-Canada political border on the southwest, and the Canada-Greenland political border on the northeast (Fig. 1). It is 200-400 km wide with the southeast margin being mostly on the inner to middle portion of continental shelf and onshore in the vicinity of the Mackenzie Delta. This margin is marked by a system of normal faults which preserve Jurassic to Lower Cretaceous strata (Fig. 1). Due to the paucity of data, the precise location of such a fault system boundary is poorly defined over the portion of the TSE that lies to the north of the Beaufort-Mackenzie region. An uplifted rift shoulder lies landward of the TSE boundary and has been given local names such as Husky Lakes Uplift (HLU; Fig. 1) in the Mackenzie Delta area (cf. Dixon, 1999), Storkerson Uplift and Prince Patrick Island Uplift (SU and PPU; Fig. 1) in the Banks and Prince Patrick islands areas (cf. Miall, 1979), the last probably linking up with what is the Sverdrup Rim (SR) further northeast (e.g., Embry and Beauchamp, 2019). The basinward margin of the TSE is the base of the marine slope. The TSE covers approximately 350,000 square kilometres.

3. Principal data sets

3.1. Outcrop:

Strata of the TSE do not outcrop although correlative strata outcrop to the south of the Beaufort-Mackenzie Domain, mainly in the Richardson Mountains (e.g., Dixon, 1992, 1998; Poulton et al., 1982; cf. Fallas et al., this volume), east of the Central and Northern domains in the Sverdrup CTSE (Embry et al., this volume, b) and east of the Southern Domain in the southern Prince Patrick Island, Eglinton Island and Banks Island area (Miall, 1979; Harrison and Brent, 2006).

3.2. Wells:

Several tens of wells penetrating into or through the CARM TSE were drilled in the southern Mackenzie Delta and along the Tuktoyaktuk Peninsula (Dixon, 1982; Wielens, 1992). These are displayed on Figure 2.

3.3. Seismic:

Numerous industry seismic lines were shot in the Beaufort-Mackenzie Domain of the CARM TSE and maps showing the locations of these lines as well as the lines themselves are available for public viewing at the Canadian Energy Regulator (formerly the National Energy Board) (https://www.cer-rec.gc.ca). Further, deep seismic reflection profiles in this area were acquired by the Geological Survey of Canada in 1986-1989 as part of its Frontier Geoscience Program (FGP). These were all marine profiles, acquired opportunistically within limited ice-free expanses of the Beaufort Sea, with the exception of Profile 86-1, on the Mackenzie Delta (Fig. 1), an interpretation of which was published by Cook at al. (1987). The locations and extant interpretations of other FGP profiles in the BM-D can be found in Dietrich et al. (1989), Stephenson et al. (1994), O'Leary et al. (1995), Stephenson (1996) and Li et al. (2016). These were complemented by a set of (mainly) onshore-offshore seismic refraction profiles acquired in 1987 (Stephenson et al., 1989), including 87-F (Fig. 1). Part of 87-F was coincident with reflection profile 86-1 onshore but it continued for an additional 120 km offshore, northwestwards into the Beaufort Sea, which was ice covered at the time of its acquisition. Later, in 2006-2008, ION Geophysical carried out an extensive seismic reflection acquisition program in the Canadian Beaufort

Sea. Helwig et al. (2011) provided a comprehensive compilation of ION profile locations in the TSE and selected profile interpretations (see also Chen et al., this volume). Finally, a 3-D geometric model of crustal structure and basin architecture of much of the B-MD, in which all of the seismic data mentioned above, integrated with available subsurface geological information and other geophysical information, notably the gravity field, was published by Sippel et al. (2013).

Outside the B-MD, there are limited seismic reflection data. Part of the ION Geophysical 2006-2008 deep seismic reflection grid lies in the SD of TSE, opposite Banks Island and northern Amundsen Gulf (Fig. 1). Interpretations of several of the ION lines are found in Helwig et al. (2011) and Somme (2018). A fragment of one marine seismic reflection line acquired as part of a large, multidisciplinary project throughout the Canada Basin (e.g., Mosher et al., 2012; cf. Chian et al., 2016) crosses into the CARM TSE Central Domain on the outer margin of Sever Spur (CB; Fig. 1).

Onshore-offshore seismic refraction data outside the B-MD were acquired between Prince Patrick and Borden islands (profiles BB and PP; Fig. 1) in the mid-1960s. Results were published by Overton (1970) and Berry and Barr (1971). Nothing further was done until a set of three integrated seismic refraction surveys were shot on the northern Central and southern Northern domains of the TSE from a base established on an offshore ice island in 1985, 1986 and 1990, offshore Ellef Ringnes, Meighen and Axel Heiberg islands (profiles II; Fig. 1). The results of these surveys are summarized in Asudeh et al. (1989), Argyle and Forsyth (1994) and Forsyth et al. (1990a,b;1998). Later, Funck et al. (2011) presented the results of a seismic refraction line shot in 2008 across the shelf and slope close to the northern extent of the II grid in to the north of Nansen Sound (ARTA; Fig. 1) and Jackson et al. (2010) presented the results of a seismic refraction survey shot in 2006 just beyond the northeast border of the TSE, crossing the Lincoln Sea from Greenland to the Lomonosov Ridge (LORITA; Fig. 1).

4. Tectonic setting, TSE boundaries, and main tectonic/erosional phases

The formation of Canadian Arctic Rifted Margin TSE was coincident with the formation of the adjacent Amerasia Basin. The plate tectonic evolution of the Amerasia Basin remains controversial. For the purposes of this paper, a plate-scale model for the development of Amerasia Basin in which a northern Alaska-contiguous Siberia microplate rotated away from the Canadian Arctic Archipelago from latest Triassic through Early Cretaceous suffices, essentially along the lines of the widely cited model of Grantz et al. (2011) and its precursors and, for example, more recent, more detailed rotational/translational models such as that of Hutchinson et al. (2017) and Døssing et al. (2020). The Amerasia Basin is interpreted to have had an initial, latest Triassic-earliest Cretaceous phase of hyperextension of continental crust followed by sea floor spreading in Early Cretaceous (Embry and Dixon, 1994; Grantz et al., 2011; Embry and Anfinson, 2014; Chian et al., 2016). Extensive, mainly basic, volcanism typically associated with a mantle plume, was coincident with the sea floor spreading phase of the Amerasia Basin (Grantz et al, 2011). Volcanism in the Amerasia Basin is interpreted to have occurred as far south as latitude 80 and as far north as the base of the Lomonosov Ridge and was centred on the high-standing Alpha Ridge-Mendeleev Rise complex. The volcanism also occurred on adjacent continental areas (e.g., Embry et al., this volume, b; Fig. 8) and is interpreted to have affected the CARM TSE, where it is adjacent to the area of volcanism in the northern Amerasia Basin (Saltus et al., 2011; Oakey and Saltus, 2016; Anudu et al., 2017).

The base of the TSE is a major 1st order sequence boundary which overlies moderately to highly deformed Proterozoic-Lower Paleozoic rocks (Figs. 3, 4). The TSE formed as a rifted margin on the eastern and southern flanks of the opening Amerasia Basin with the provision of accommodation space driven primarily by extension. Rifting ceased at the end of the Early Cretaceous and the TSE is capped by a widespread, first order sequence boundary of late Early Cretaceous age (Embry and Dixon, 1994) (Figs. 3, 4).

The innermost rift margin of the TSE lies under Tuktoyaktuk Peninsula and the southern Mackenzie Delta and is defined by the Husky Lakes Fault Zone (HLFZ), located in Figure 2 and shown in cross-section in Figure 5. (The HLFZ here is the same structural element referred to as the Eskimo Lakes Fault Zone by Chen et al. [this volume], a name that is no longer in use [cf. Hadlari et al., 2020]). Basinward of the fault zone is the Kugmallit Trough (Fig. 5; see also Figs. 4, 6 in Chen et al., this volume), a half graben-like feature which preserves the thickest accumulation of rift-phase strata of the CARM TSE. The Middle Jurassic to Lower Cretaceous succession is down-faulted (as seen in Figure 5), such that local structural highs are present to the northwest (see, for example, Fig. 2 in Dixon, 1982). Basinward (northwest) of the Kugmallit Trough is another fault zone, the Taglu Fault Zone (not seen in Fig. 5; cf. Chen et al., this volume, Fig. 6), which, although defined by Cenozoic listric faults, appears to be underlain by pre-drift normal faults. Faults of the HLFZ itself apparently sole-out deep within probable Proterozoic strata, based on a deep seismic crustal reflection image (Cook et al., 1987; cf. profile 86-1 on Fig. 1).

Due to the paucity of well data and the lack of detail of the available seismic refraction surveys, there is no reliable information within the TSE that allows an interpretation of its tectonic phases. However, given it is a continuation of the Beaufortian Rifted Margin CTSE of northern Alaska (Houseknecht, this volume), it is reasonable to assume that the CARM TSE had a similar tectonic development as documented in the eastern segment of that CTSE. Furthermore, the tectonic development of the uppermost Triassic-Lower Cretaceous succession in the adjacent Sverdrup Basin CTSE is well known (Embry, 2011; Embry and Beauchamp, 2019; Embry et al., 2019; Embry et al, this volume, b). Based on the tectonic phases of the mentioned CTSEs, it is very likely that parts of the CARM TSE experienced significant tectonic uplift in latest Sinemurian, latest Aalenian, late Callovian, early Hauterivian, late Hauterivian, late Aptian and late Albian as shown in the generalized stratigraphic column (Fig. 3). Further, it is assumed that intervals of normal faulting followed most, if not all, of these intervals of tectonic uplift. Notably, normal faulting is documented to have occurred in the latest Aalenian, late Callovian, late Hauterivian and late Aptian in the southern Prince Patrick Island/Eglinton Island area (Harrison and Brent, 2005). Upper Jurassic strata are present in restricted, small grabens or half grabens such as the Eglinton Graben between Eglinton Island and Banks Island, Banks Basin on Banks Island and in Anderson Basin lying to the southeast of the Mackenzie Delta area (cf. Miall, 1979; Brideaux and Fisher, 1976; Dixon, 1999). These areally restricted, fault-bounded basins are separated from the CARM TSE by tectonic highs (Prince Patrick Uplift, Storkerson Uplift, Husky Lakes Uplift), which form parts of the rift shoulder that lies landward of the CARM TSE (all elements located on Fig. 1).

5. Underlying and overlying assemblages

5.1 Age of underlying consolidated basement, or youngest underlying unmetamorphosed rock unit: The Canadian Arctic Rifted Margin TSE is underlain by Proterozoic-Lower Paleozoic rocks that are moderately to highly deformed. These strata are correlative to those of the Mackenzie-Peel Platform and Ellesmerian Foreland CTSE (Fallas et al., this volume) and the Franklinian CTSE (Dewing and Hadlari, this volume). They are regarded as basement just as described by Houseknecht (this volume) in the adjacent Beaufort Rifted Margin CTSE.

5.2 Age of oldest overlying rock unit: The overlying strata consist of lowermost Upper Cretaceous (Cenomanian) strata at the base of the overlying Canadian Arctic Prograded Margin TSE (Embry et al, this volume, a) and Beaufort-Mackenzie TSE (Chen et al., this volume) (Figs. 3,4,5).

6. Tectonic subdivision and internal structures

The CARM TSE is divided into four general structural domains along strike: the Beaufort-Mackenzie Domain (B-MD), covering the eastern portion of the Beaufort Sea including the Mackenzie Delta; the Southern Domain (SD), from Amundsen Gulf to offshore southern Prince Patrick Island; the Central Domain (CD), from offshore central Prince Patrick Island to Peary Channel, and the Northern Domain (ND), offshore Meighen, Axel Heiberg and Ellesmere islands as far as the contiguous Alpha Ridge (Fig. 1). These domains are distinguished for convenience for discussing variability of the CARM TSE along the Canadian Arctic margin. Other factors include the structural nature of the contiguous Amerasia Basin and a new model of Moho depth within the TSE and contiguous areas (Fig. 1). These are both reflected in the changing orientation of the continental margin as seen in Figure 1 and potential field anomalies along the continental margin (e.g., Forsyth et al.,1990a) as well as with structural trends in the adjacent continental geology (Embry and Stephenson, 2022).

The Moho depth map seen in Figure 1 was newly compiled from the gravity and magnetic modelling by Stephenson et al. (1994), Anudu (2018), Anudu et al. (2016) and Oakey and Saltus (2014; cf. Oakey and Saltus, 2016) along extended versions of all of the indicated seismic lines. These models were in all cases tightly controlled by the seismically-constrained velocity models with which they are largely coincident. In the B-MD a 3-D geometric model of crustal structure and basin architecture published by Sippel et al. (2013), itself based on all available seismic data (cited in section 3.3), integrated with available subsurface geological information and the gravity field, was also utilized. In the ND, passive seismology results and gravity inversion on Ellesmere Island, part of Axel Heiberg Island and their common northern margin (Schiffer and Stephenson, 2017; Stephenson et al., 2017) were used to supplement the offshore seismic data.

The Beaufort-Mackenzie Domain (B-MD) extends from the Canada/USA border on the west to the Amundsen Gulf on the east (Fig. 1). The depth to Moho contours show a moderately uniform shallowing from normal continental crust values to thinned, transitional crustal values in the area of data coverage and at the scale of the mapping. Dixon (1996) and Helwig et al. (2011) provided interpreted seismic sections that illustrate the structure of the CARM succession in the B-MD. The succession is dominated by down-to-the-basin normal faults that were contemporaneous with sedimentation. The faults extend through the entire succession and terminate at the late Albian unconformity which caps the CARM TSE. In the western portion of the domain, the upper part of the CARM succession is deformed by folds and thrust faults (Helwig et al., 2011).

The Southern Domain (SD), running from Amundsen Gulf to offshore southern Prince Patrick Island, has a general NE-SW orientation and depth-to-Moho contours that seem to parallel the shelf edge. It is considered to be structurally similar to the eastern part of the adjacent B-MD. As illustrated in the relevant published reflection seismic sections (Helwig et al., 2011; Somme et al., 2018), ION Line 5690 running across strike offshore of Banks Island shows that the succession is cut by numerous normal faults which segment the TSE into grabens and horsts and results in major thickness differences over short distances (Fig. 4, located on Fig. 1).

The Central Domain (CD) runs from offshore Prince Patrick Island to Meighen Island (Fig. 1) and is characterized by a basinward bulge of depth to Moho. Deeper Moho in this area explains the Sever Spur bathymetric high, which is inferred to be underlain by crust of continental affinity (cf. Hutchinson et al., 2017), and is in keeping with a thinner post-Paleozoic sedimentary succession in this part of the margin (cf. Embry et al., this volume, a). Seismic profile CB (Fig. 1) reveals the presence of (trans)tensional half-grabens on the outer margin of Sever Spur that Hutchinson et al. (2017) interpreted to be coeval with the rifting that formed Canada Basin, and the development of the CARM TSE. Elsewhere, although no other reflection seismic data are available, it is assumed similar rift-generated normal faults are also present, although rifting is less intense given the reduced degree of crustal thinning. This area is interpreted to have been moderately affected by the Eurekan Orogeny based on the extent of Eurekan structures in the adjacent Sverdrup Basin CTSE. However, there are no data that indicate the type of possible Eurekan structures that may be present in the strata of this portion of the TSE.

The Northern Domain (ND) lies offshore of Meighen, Axel Heiberg and Ellesmere islands (Fig. 1) and again has depth-to-Moho contours that parallel the shelf edge except in the area of the TSE that abuts the Alpha Ridge-Mendeleev Rise complex where Moho depth values begin to increase. This domain was strongly affected by the Eurekan Orogeny. It is interpreted that the rift succession will be moderately to strongly deformed by thrust faults and folding.

7. Sedimentary Infill

7.1 Total thickness: The thickness of the basin-fill is estimated to be up to 4 km on the basis of the ION deep seismic reflection results in the Beaufort-Mackenzie and Southern domains (Helwig et al., 2011; Somme et al., 2018). Given the paucity of data, this estimate should be regarded as speculative. Embry et al. (this volume, a) present a Mesozoic-Cenozoic sedimentary isopach map of the Canadian Arctic margin, based on all available geophysical data, with values mostly less than 10 km and not as great as 15 km. Most of the sedimentary column belongs to the overlying CAPM TSE, which has sediment thicknesses up to 10 km (Embry et al., this volume, a), compatible with an estimate of thicknesses of up to 4 km for the CARM TSE.

7.2 Lithostratigraphy/sequence stratigraphy: The strata of the TSE consist of siliciclastic sediments deposited in a variety of environments which evolved through the life of the TSE, including alluvial fan, lacustrine, fluvial, delta plain, delta front, marine shelf, and marine slope. Strata deposited in nonmarine environments may occur in the lowest portion of rift fills in more basinward locations with marine strata much more common throughout most of the TSE.

Based on the contemporaneous stratigraphy of the Sverdrup Basin CTSE, the fault-bounded basins of southern Prince Patrick, Eglinton, and Banks islands and environs as well as the Mackenzie Delta/northern Yukon areas (Embry et al., this volume, b; Harrison and Brent, 2005; Miall, 1979; Dixon et al., 1992; Dixon, 1996; Helwig et al., 2011), the CARM succession can be divided into three major sequences of Rhaetian-Callovian, Oxfordian-Hauterivian, and Barremian-Albian ages (Fig. 3). Large magnitude unconformities of regional extent bound each of these sequences and were interpreted by Embry et al. (2019) to have been generated by episodes of regional tectonic uplift. Other tectonically generated unconformities also punctuate the succession as illustrated on Figure 3.

The strata of the TSE have been penetrated by numerous wells in the B-MD (Figs. 2 and 5) and are best preserved in the subsurface of Tuktoyaktuk Peninsula and the southern part of Mackenzie Delta (Dixon, 1979, 1982, 1991,1992, 1996; Dixon et al., 1989; McNeil et al., 2020; Poulton, 1978). In the subsurface, the thickest rift-phase succession is preserved in the Kugmallit Trough, which is at least 2000 m thick (Fig. 5; also see Fig. 7 in Dixon, 1982). The strata are Early Jurassic to Albian in age and consist of alternating shale-rich and sandstone-rich formations interrupted by a number of major erosional unconformities followed by significant transgressive events, representing phases of uplift and subsidence respectively (Fig. 3).

The two most significant unconformities are of late Hauterivian-early Barremian and late Albian age; both represent major periods of uplift and subsequent subsidence. The former is interpreted as the breakup unconformity marking the start of sea floor spreading in the Amerasia Basin and correlative with major unconformities in northern Alaska and the Sverdrup Basin. The late Albian unconformity marks the end of sea floor spreading and rifting in the Mackenzie Delta region which lies at the apex of the spreading centre. Reflection seismic profiles in the Mackenzie Delta area clearly illustrate the termination of significant normal faulting at the late Albian unconformity (Dixon et al., 1992; Embry and Dixon, 1994) (Fig. 5).

8. Magmatism

A portion of the TSE was affected by basic volcanism typically associated with a mantle plume that was active in the Amerasia Basin during the Cretaceous. The Amerasia volcanism is part of the High Arctic Large Igneous Province (HALIP) and extends from latitude 80°N in the south to the base of the Lomonosov Ridge. Volcanism was concentrated on the Alpha Ridge-Mendeleev Rise complex which is interpreted to consist predominantly of basic volcanics that intruded stretched, thinned continental crust (Forsyth et al., 1986; Buchan and Ernst, 2006; Døssing et al., 2013; Oakey and Saltus, 2016; Jackson and Chian, 2019). Basaltic volcanic flows and associated intrusive sills and dykes of Hauterivian-Maastrichtian age are found in the adjacent Sverdrup Basin (Embry and Osadetz, 1988; Evenchick et al., 2015). Notably, both the northern and southern extent of the volcanic rocks in the Sverdrup Basin (Embry and Beauchamp, 2019) closely matches the northern and southern extent of the magnetically-delineated extent of the HALIP in the Amerasia Basin (Saltus et al., 2011). Consequently, the Northern Domain and the northern part of the Central Domain of the TSE are also likely to contain basalt flows and diabase intrusive rocks. The crustal structure of northernmost Ellesmere Island determined from teleseismic earthquake receiver functions suggests a high velocity lower crustal layer interpreted to represent a magmatic underplate (Stephenson et al., 2018) and Bédard et al. (2021) associated this to the magmatism of the adjacent Alpha Ridge.

No igneous rocks or ash beds are known in the B-MD until the Albian succession where numerous centimetre-scale ash beds are present in the Arctic Red Formation (Fig. 3). The ash beds are interpreted to have been derived from volcanic activity in the Cordilleran fold belt.

9. Heat Flow

Heat flow measurements in the CARM strata of the B-MD are 45-90 mW/m^2 (Jones et al, 1990). Majorowicz and Embry (1998) recorded a heat flow measurement of 44 +/- 11 mW/m^2 from Cenozoic strata in the Crocker I-53 well on Meighen Island (ND). Several legacy heat flow measurements were taken in shallow post-CARM strata (cf. Fuchs et al., 2021) at locations indicated by Ruppel et al. (2019) in the distal offshore part of the Northern Domain of CARM north of Meighen Island and west of Axel Heiberg Island and fall in the range ~50-60 mW/m^2 (cf. Fuchs et al., 2021). Heat flow values on the southern margin of the Alpha Ridge-Mendeleev Rise complex offshore Ellesmere Island but outside the CARM domain are reported to be generally above 60 mW/m^2. In summary, values of 45-90 mW/m^2 can be expected over much of the TSE.

10. Petroleum Geology

10.1. Discovered and potential petroleum resources: The only discoveries in the CARM TSE occur in Lower Cretaceous strata of the B-MD, where gas discoveries are present at the Parsons Lake field (Fig. 2 inset) and in a smaller field at L-28 and oil was discovered at O-13, D-48, I-17 and J-29 (Fig. 2). By far the most significant discovery is the Parsons Lake gas field with about 35.46x109m^3 mean value of marketable gas (National Energy Board, 1998) in a faulted anticline adjacent to the HLFZ (Dixon, 1996).

Given the paucity of data from the TSE, it is not possible to calculate reasonable estimates of the ultimate resource in the TSE. Houseknecht and Bird (2011) have provided estimates for the entire Canadian passive margin. Such estimates are for the entire Canadian margin succession of which the CARM TSE is only a part. In the B-MD, Chen et al. (2007) estimated a mean recoverable oil value of 184x106m^3 for their "rifted margin play group".

10.2. Current exploration status: Currently there is no exploration activity in the CARM TSE. Given the remoteness of the TSE, environmental concerns with offshore areas, and the large, unconventional resources of North America, no exploration activity is expected in the foreseeable future.

10.3. Hydrocarbon systems and plays:

10.3.1. Source rocks: The occurrence and age of any source strata in the TSE are very speculative, given the lack of data. It is possible that organic-rich, lacustrine strata were deposited in grabens during the early phase of TSE development (Rhaetian-Sinemurian) when continuous communication with marine areas did not exist or was intermittent. Organic-rich marine strata may have been deposited in the TSE in Toarcian and Oxfordian-Kimmeridgian, coincident with organic-rich, marine deposition in the Sverdrup Basin CTSE (Embry et al., this volume, b).

Lower Jurassic to Albian strata in the B-MD contain several potential source rocks in the shale-dominant successions (Fig. 3). Potential source rocks include the Middle

Jurassic to lowermost Cretaceous Husky Formation, Valanginian shales in the Parsons Group; (Fig. 3) and the Albian Arctic Red Formation (Dixon, 1996). Although organic geochemistry indicates that the potential source rocks tend to be gas prone some may contain intervals that may be oil prone (e.g., Arctic Red Formation).

10.3.2. Reservoirs: Sandstone units, deposited in a wide variety of depositional environments from alluvial fan to marine slope and with suitable porosity and permeability, are likely present throughout the CARM TSE (Fig. 3).

10.3.3. Seals: Thick shale units are present throughout the succession, especially in the more basinward portion of the TSE. (Fig. 3).

10.3.4. Traps: Traps may be associated with extensional faulting and would include roll-over anticlines and tilted fault blocks. The Central and Northern domains may contain contractional anticlines and these are potential traps. Cenozoic thrust faults in the Northern Domain also may be involved in trap formation. Stratigraphic traps associated with unconformities and rapid, lateral facies changes, involving the shale-out of sandstone units, are also likely present throughout the TSE.

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Figure Captions

Figure 1. Location of the CARM TSE (enclosed by the red line), with its domains (B-MD, SD, CD and ND being Beaufort-Mackenzie, Southern, Central and Northern domains, respectively, in red letters) and seismic profiles (labelled black lines) mentioned (and cited) in the text. The grey box encompassing the Mackenzie Delta (MD) and Tuktoyaktuk Peninsula (TP) area gives the location of the map presented in Figure 2. The white contours describe a new compilation of depth to the Moho (in km) from an integration of seismic constraints with gravity and magnetic modelling, as cited and explained in the text. Although the data distribution is uneven, the first-order trends displayed by this map are considered to be reliably indicative at the scale of the TSE as a whole. Grey lines with labels represent structural highs and basin depocentres formed on the continental side of the the CARM TSE mentioned (and cited) in the text: Husky Lakes Uplift (HLU), Storkerson Uplift (SU), Prince Patrick Uplift (PPU) and Sverdrup Rim (SR), as trend lines with “plus sign” ornament; and Anderson Basin (AB), Banks Basin (BB) and Eglinton Graben (EG), with “open rectangle” ornament.

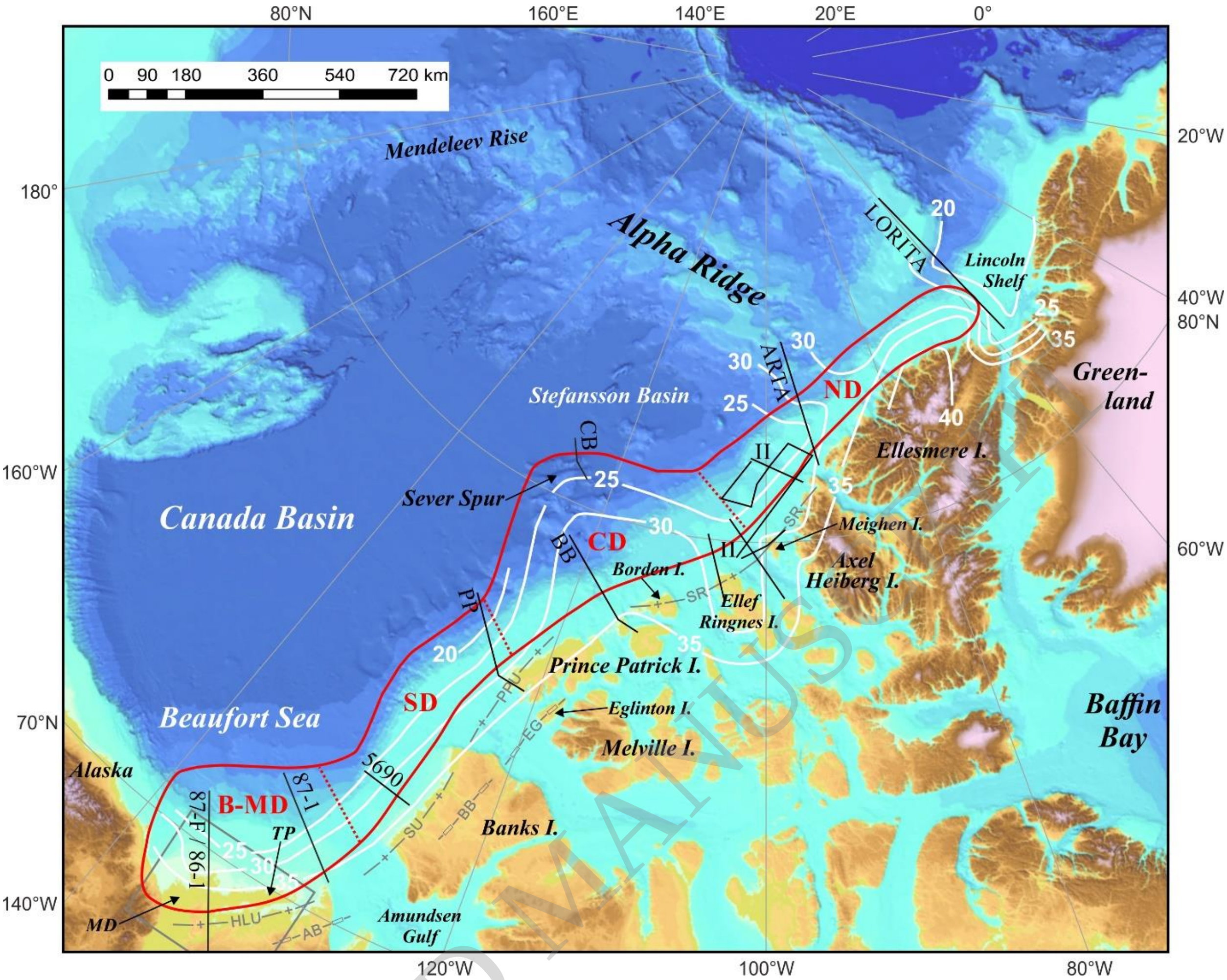
Figure 2. Wells penetrating the syn-rift CARM TSE (specifically its Jurassic-Lower Cretaceous) succession in the Mackenzie Delta-Tuktoyaktuk Peninsula area, modified from Dixon (1982). The inset map shows the environs of the Parsons Lake field in greater detail and the location of the interpreted seismic section seen in Figure 5 (dashed line). The shaded zone in the background of the main map indicates the approximate surface projection of the Husky Lakes Fault Zone (HLFZ), which marks the boundary of the CARM TSE in this area.

Figure 3. Regional lithostratigraphy, tectonic phases and hydrocarbon play elements of the CARM TSE. The stratigraphic nomenclature is that for the Beaufort-Mackenzie Domain, where Rhaetian strata do not occur. The prominent unconformities recognized in the B-MD and in the adjacent Sverdrup Basin CTSE are shown. There is insufficient information available to estimate “charge”.

Figure 4. Fragment of seismic line ION 5690 off Banks Island (located in Fig. 1), modified from the interpretation of Somme et al. (2018), showing the edge of the CARM TSE offshore Banks Island (~50 km). The blue horizon is top Eocene; the green horizon, which caps the CARM TSE, is top Lower Cretaceous, below the overlying CAPM TSE (Embry et al., this volume, a). The red horizon overlies Devonian and older strata and, where the CARM TSE is present, it is fault-disrupted and has an unconformable base. The vertical scale in depth changes somewhat along the section because of the strong lateral velocity contrasts. Comparison with a depth-converted interpretation of the same profile by Helwig et al. (2011), which displays some interpretive dissimilarities, as well as simple calculations based on standard velocity estimates, suggests that the post-Paleozoic succession at the NW end of the section is some 12 km and about 3 km at its SE end. This interpretation along with the original seismic image can be found in Somme et al. (2018; their figure 7) and the original, full ION seismic profile 5690, of which this is a fragment, can be seen in Helwig et al. (2011; their figure 35.11).

Figure 5. Geological interpretation along a reflection seismic section crossing the Husky Lakes Fault Zone (HLFZ), southern Mackenzie Delta at the southern margin of the CARM TSE (cf. Fig. 1), modified from Embry and Dixon (1994). The yellow layer is part of the Beaufort-Mackenzie TSE (Chen et al., this volume; cf. Embry et al., this volume, a) and the green layer represents the CARM TSE overlying older, basement rocks (as in Figure 4). To provide an indication of the depth scale of the cross-section, the basement horizon lies at 3450 m in the A-44 well (Wielens, 1992). Faults are truncated

or show greatly reduced offset at the late Albian unconformity (CU), with some of the post-CU fault offsets interpreted to be related to post-rift tectonic reactivations in the Beaufort Sea (e.g., Lane and Dietrich, 1995). The HLFZ represents the border of the TSE in this location (Fig. 2), which is very near the inferred pivot point for the rotational opening of the Amerasia Basin indicating rifting of the basin ended in the latest Albian. The original seismic image with overlain interpretation can be found in Embry and Dixon (1994); it is approximately coincident to a fragment of deep seismic profile 86-1 (cf. Fig. 1) displayed and analysed by Cook et al. (1987; their Fig. 5).


80°N
160°E
140°E
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0°
0 90 180 360 540 720 km
Mendeleev Rise
20°W
180°
Alpha Ridge
LORITA
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Lincoln Shelf
40°W
80°N
25
35
30
ARTA
30
Green-land
Stefansson Basin
25
ND
40
CB
Ellesmere I.
160°W
II
Sever Spur
25
35
SR
Canada Basin
30
Meighen I.
CD
BB
II
Borden I.
Axel Heiberg I.
60°W
SR
Ellef Ringnes I.
PP
35
20
Prince Patrick I.
SD
Baffin Bay
Eglinton I.
Beaufort Sea
70°N
Melville I.
Alaska
5690
87-1
B-MD
87-F / 86-1
TP
Banks I.
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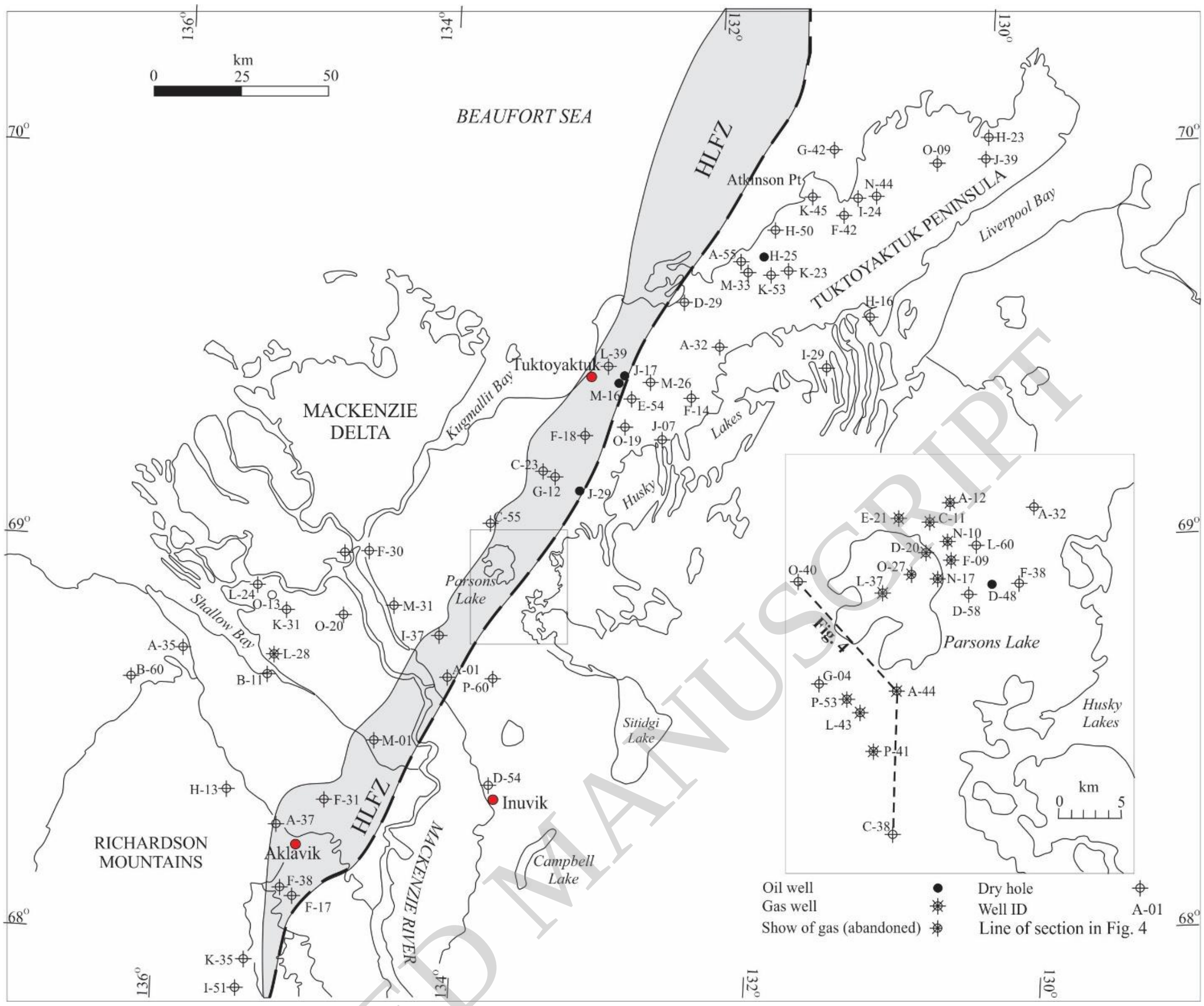
Figure 1


BEAUFORT SEA
HLFZ
MACKENZIE DELTA
TUKTOYAKTUK PENINSULA
Tuktoyaktuk
Inuvik
Aklavik
RICHARDSON MOUNTAINS
MACKENZIE RIVER
Parsons Lake
Husky Lakes
Campbell Lake
Sitidgi Lake
Kugmallit Bay
Liverpool Bay
Shallow Bay
Atkinson Pt
km
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Well ID
A-01
Line of section in Fig. 4
Fig. 4

Figure 2

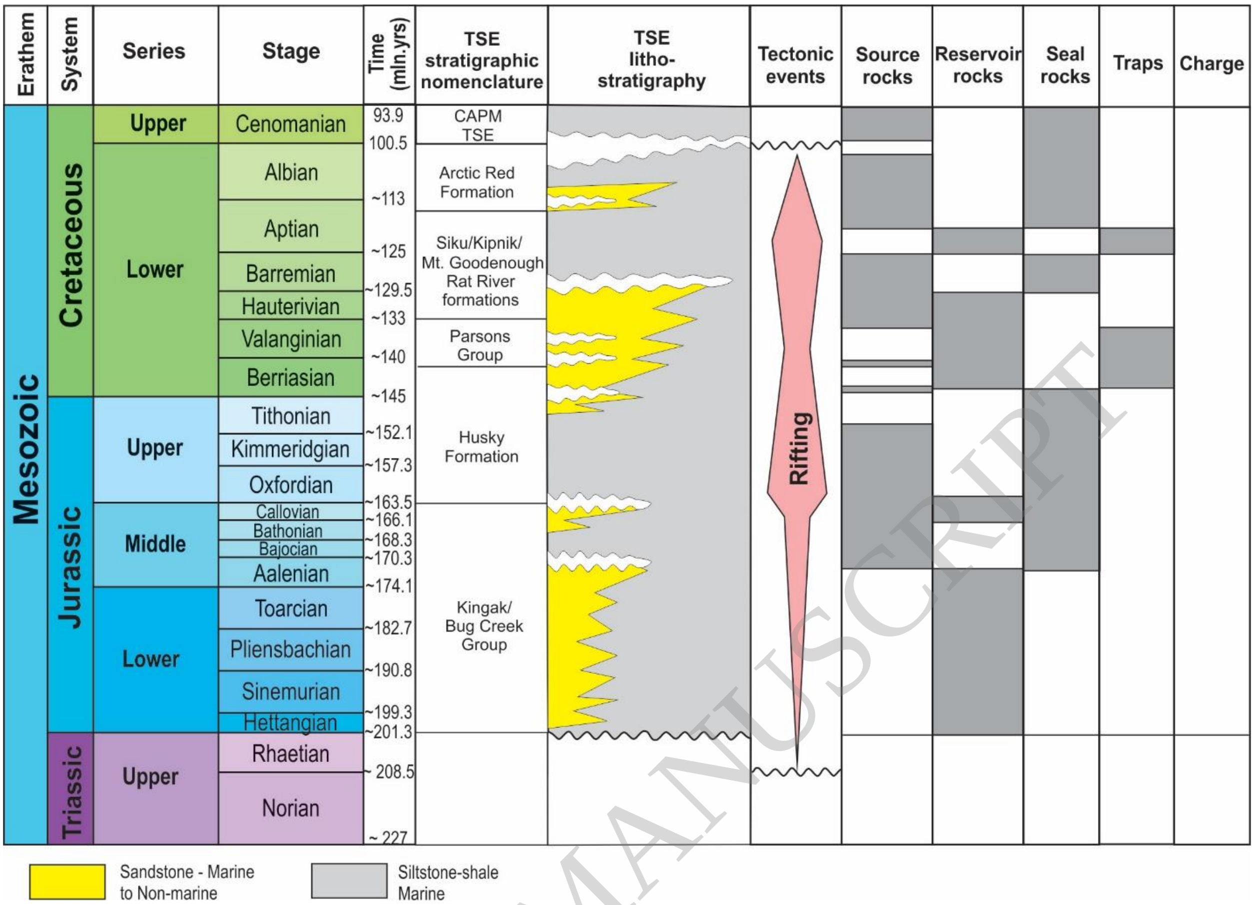
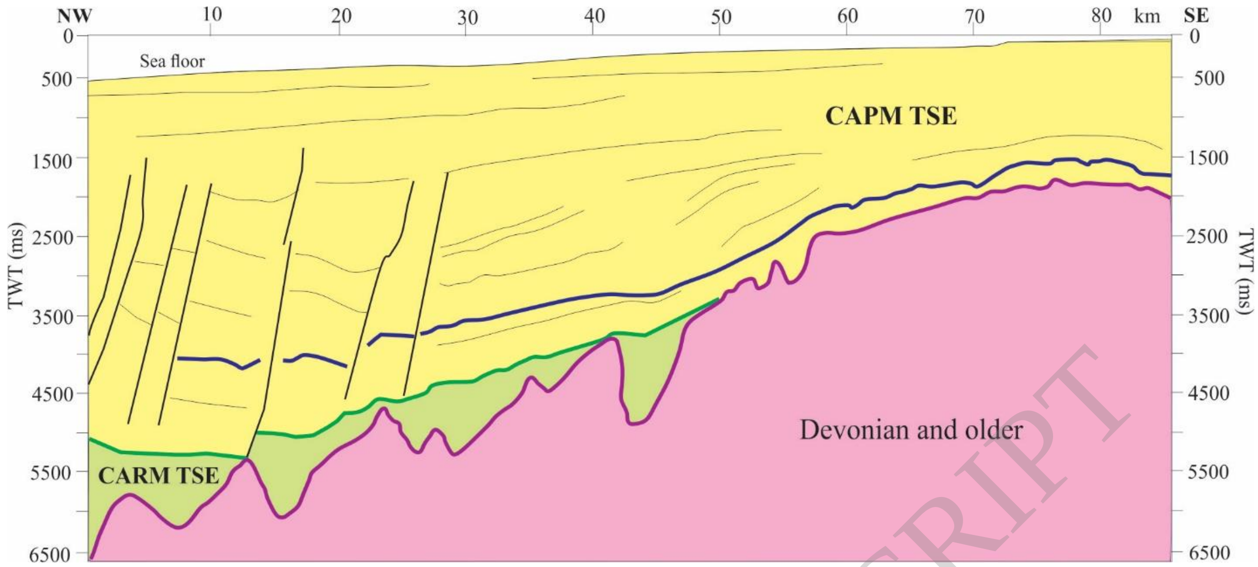

Erathem
System
Series
Stage
Time (mln.yrs)
TSE stratigraphic nomenclature
TSE litho-stratigraphy
Tectonic events
Source rocks
Reservoir rocks
Seal rocks
Traps
Charge
Mesozoic
Cretaceous
Jurassic
Triassic
Upper
Lower
Upper
Middle
Lower
Upper
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Hettangian
Rhaetian
Norian
93.9
100.5
~113
~125
~129.5
~133
~140
~145
~152.1
~157.3
~163.5
~166.1
~168.3
~170.3
~174.1
~182.7
~190.8
~199.3
~201.3
~ 208.5
~ 227
CAPM TSE
Arctic Red Formation
Siku/Kipnik/ Mt. Goodenough Rat River formations
Parsons Group
Husky Formation
Kingak/ Bug Creek Group
Rifting
Sandstone - Marine to Non-marine
Siltstone-shale Marine

Figure 3


NW
SE
10
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km
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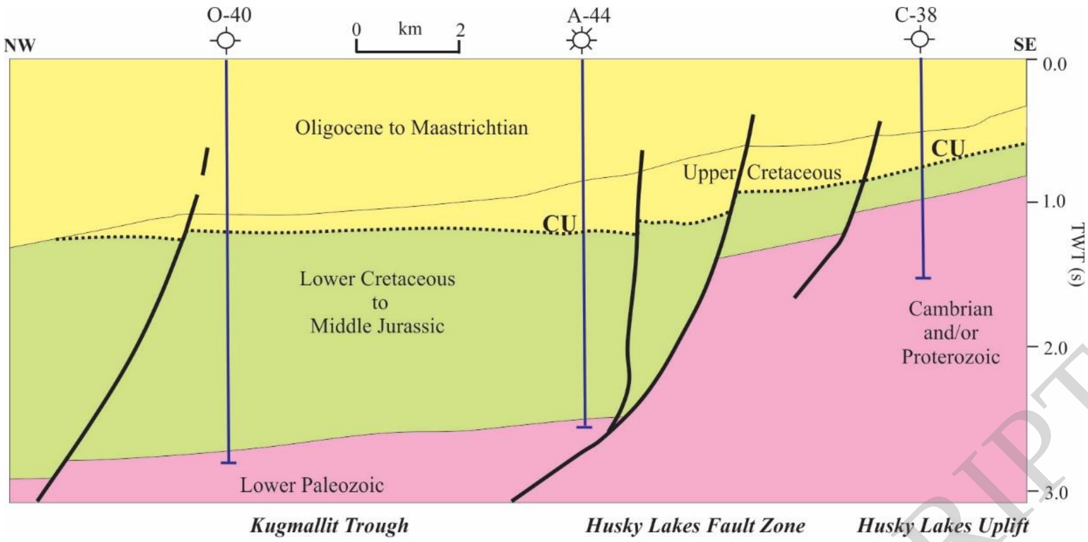
TWT (ms)
Sea floor
CAPM TSE
CARM TSE
Devonian and older

Figure 4


O-40
0 km 2
A-44
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0.0
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TWT (s)
Oligocene to Maastrichtian
Upper Cretaceous
CU
CU
Lower Cretaceous
to
Middle Jurassic
Cambrian
and/or
Proterozoic
Lower Paleozoic
Kugmallit Trough
Husky Lakes Fault Zone
Husky Lakes Uplift

Figure 5