Mackenzie–Peel Platform and Ellesmerian Foreland Composite Tectono-Sedimentary Element, northwestern Canada

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Abstract: The Mackenzie–Peel Platform Tectono-Sedimentary Element (TSE), and the overlying Ellesmerian Foreland TSE, consist of Cambrian–Early Carboniferous shelf and slope sedimentary deposits in Canada’s northern Interior Plains. In this chapter, these elements are combined into the Mackenzie–Ellesmerian Composite TSE. The history of the area includes early extensional faulting and subsidence in the Mackenzie Trough, passive-margin deposition across the Mackenzie–Peel Platform, local uplift and erosion along the Keele Arch, subsidence and deposition in the Ellesmerian Foreland, possible minor folding during the Ellesmerian Orogeny, and folding and faulting in Cretaceous–Eocene time associated with the development of the Canadian Cordillera. Recorded petroleum discoveries are within Cambrian sandstone (Mount Clark Formation), Devonian carbonate strata (Ramparts and Fort Norman formations) and Devonian shale (Canol Formation). Additional oil and gas shows are documented from Cambrian–Silurian carbonate units (Franklin Mountain and Mount Kindle formations), Devonian carbonate units (Arnica, Landry and Bear Rock formations) and Late Devonian–Early Carboniferous siliciclastic units (Imperial and Turtle formations). Petroleum exploration activity within the area has occurred in several phases since 1920, most of it associated with the one producing oilfield at Norman Wells.

Canada’s northwestern Interior Plains are underlain by sedimentary rocks deposited on Archean and Paleoproterozoic crystalline basement of the Canadian Shield (Cook and MacLean 2004). The Mackenzie–Ellesmerian Composite Tectono-Sedimentary Element (CTSE) comprises an unmetamorphosed Paleozoic succession that can be subdivided into the ‘Mackenzie–Peel Platform’ and the ‘Ellesmerian Foreland’, which in turn is overlain by Mesozoic strata of the ‘Cordilleran Foreland’. The ‘Mackenzie–Peel Platform’ Tectono-Sedimentary Element (TSE) incorporates the ‘Anderson Plain Platform – Eastern’ and ‘Anderson Plain Platform – Western’ sedimentary successions of Grantz et al. (2011). The term ‘Mackenzie–Peel Platform’ is used here because it unites regional-scale stratigraphic packages and reflects the palaeo-geographical terminology commonly applied to the region. ‘Mackenzie Platform’ originally encompassed the region of Lower Paleozoic shelf or platform strata between the Canadian Shield and the deeper-water ‘trough’ units now preserved in the northern Cordillera (Lenz 1972). This usage was favoured for Cambrian–Silurian strata by Cecile and Norford (1993), Cecile et al. (1997) subsequently subdivided the Late Cambrian–Middle Devonian platform into the Lac des Bois and Blackwater platforms; these terms are not used in this report. The Devonian succession north of 64° N is also referred to as ‘Peel Platform’ (e.g. Moore 1993; equivalent to the ‘Peel Shelf’ of Morrow 2012). The deeper-marine Middle Devonian–Early Carboniferous siliciclastic strata represent an Ellesmerian Foreland TSE, preserved beneath the sub-Mesozoic unconformity in the same region. Therefore, the Mackenzie–Peel Platform TSE and the Ellesmerian Foreland TSE jointly form a CTSE; for brevity, the term ‘Mackenzie–Ellesmerian CTSE’ (ME CTSE) is used.

Age

Cambrian–Early Carboniferous. A major regional unconformity separates the Mackenzie–Ellesmerian CTSE from underlying early Neoproterozoic and older strata. Units at the base of the Paleozoic succession have been dated as Cambrian Series 2 (MacNaughton et al. 2013). The transition from the Mackenzie–Peel Platform TSE to the Ellesmerian Foreland TSE is placed at the onset of siliciclastic deposition in late Givetian (late Middle Devonian)–early Frasnian (early Late Devonian) time (Morrow 1999). The top of the Ellesmerian Foreland TSE was dated as Tournaisian (Early Carboniferous) by Norris (1997). This succession is unconformably overlain by Jurassic and Cretaceous strata of the Cordilleran Foreland (Dixon 1999). Additional biostratigraphic age constraints within the succession are documented by Aitken et al. (1973), Norford and Macqueen (1975), Morrow (1991), Pope and Leslie (2013), Gouwy et al. (2017), Pedder (2017) and Uyeno et al. (2017).

Geographical location and dimensions

The Mackenzie–Ellesmerian CTSE underlies the NW Interior Plains of Canada’s mainland Northwest Territories, northeastern Yukon and western Nunavut (Fig. 1; Enclosure A). The ME CTSE is approximately 950 x 500 km, with its long axis orientated NNW–SSE. The area includes the Peel Plateau, Peel Plain, Anderson Plain, Colville Hills, western Horton Plain, Great Bear Plain, Franklin Mountains and Mackenzie Plain physiographical regions.

Principal datasets

Wells

As of 2016, there are 632 petroleum wells intersecting Paleozoic strata within the ME CTSE area (Fig. 2; Enclosure F). Of these, 382 are development wells, all completed within the Norman Wells Field, and another 250 are exploration wells drilled throughout the region. Of the exploration wells, approximately 60 wells penetrate the full Paleozoic succession. Most wells were aimed at conventional targets but, since 2011, exploration for shale oil and gas in the Mackenzie Plain has contributed to the completion of five vertical and two horizontal exploratory wells (Terlaky 2017).

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Seismic data

For the northern Interior Plains and northern Mackenzie River Valley, there are more than 1400 seismic reflection profiles on public record with the National Energy Board of Canada (https://www.canada.ca/en/national-energy-board.html). These lines were acquired by more than 30 companies from 1960 to 2010. The highest density of lines is found along the Mackenzie Plain and around the Colville Hills (Fig. 2; Enclosure F).

Outcrop studies

Across the low-lying plains of the ME CTSE area, outcrop exposures are concentrated along stream banks and canyons with vegetation and/or surficial materials typically covering bedrock between stream valleys. These outcrops have mainly been accessed by helicopter over the last 50 years. Road access is limited to the Dempster Highway passing through Inuvik in the extreme NW of the region, and the Mackenzie Valley winter road connecting communities along the Mackenzie River Valley (Fig. 1). In the Colville Hills and Franklin Mountains, additional bedrock exposure is found on ridges and cliff faces where vegetation is sparse or absent. Within and east of the Colville Hills and Franklin Mountains, in areas dominantly underlain by carbonate rocks, karst features are present and bedrock is locally exposed in sinkholes and related features. For an overview of outcrop-based stratigraphic work in the ME CTSE area see Fallas et al. (2015a), and for an overview of available maps see Fallas et al. (2015b).

Tectonic setting, boundaries and main tectonic/erosional/depositional phases

The ME CTSE is a shelf and platform succession formed on stable continental crust (Enclosures B, C, and D), and has been categorized as a discrete, long-lived, stable TSE (Grantz et al. 2011; Enclosure E). To the west in the Canadian...
Cordillera, rifting and continental break-up of Rodinia and Pannotia in the Neoproterozoic (Scotese 2009) initiated subsidence on the NW Laurentian margin. Subsequent deposition of sedimentary successions began upon a peneplain of deformed Proterozoic intracratonic sedimentary basins developed on thinned continental crust on the northwestern margin of the Canadian Shield (Cook et al. 1999). The tectonic history and major depositional and erosional intervals of the ME CTSE are summarized in Figure 3.

The platform records passive-margin deposition that follows rifting to the west (Cecile et al. 1997). The western margin of the carbonate platform is delineated by a transition into shale-dominated strata of Selwyn Basin and Misty Creek Embayment preserved in the western Mackenzie Mountains, as well as the Richardson Trough of the Richardson Mountains. However, the deformed western margin of the platform, preserved in the Mackenzie Mountains and Richardson Mountains, is excluded from this CTSE. To the NE, the Mackenzie–Peel Platform passes into the Arctic Platform where Lower Paleozoic carbonate strata dip NE towards the Arctic Islands and units have been mapped using Arctic Islands terminology (see Okulitch 2000). To the east it is bounded by a preservational zero edge against the Canadian Shield. The eastern boundary of the Ellesmerian Foreland deposits corresponds to the Horn River Group preservational zero edge shown in Figure 2. The Mackenzie–Peel Platform extends south to approximately 60° N, where it passes into the MacDonald Platform. Ellesmerian Foreland siliciclastic deposits pass into mixed carbonate and shale deposits of the Great Slave Plain SE of Mackenzie Plain (Morrow 2012).

Palaeogeographical maps for the Cambrian–Silurian Mackenzie Platform can be found in Cecile and Norford (1993). Morrow (2012) provided palaeogeographical maps for the Devonian Mackenzie and Peel platforms. Cambrian depositional patterns were strongly controlled by a network of tectonic highs (arches and domes) and lows (deposcentres and graben). The region’s Cambrian tectonic history was reviewed by MacLean (2011), who considered it to commence with early Cambrian regional subsidence, recorded by deposition of the Mount Clark Formation (Cambrian Series 2). This was
followed late in Cambrian Series 2 and during Series 3 by protracted subsidence, locally enhanced by extensional faulting, including development of a graben system, notably beneath Mackenzie Plain (Mackenzie Trough), recorded by deposition of the Mount Cap and Saline River formations. By the late Cambrian (Furongian), arches within the CTSE were flooded and covered by carbonates of the Franklin Mountain Formation, establishing a stable carbonate platform across the region (Turner 2011). Regional uplift during the Middle–Late Ordovician and the Silurian–Early Devonian produced major unconformities atop the Franklin Mountain Formation and Mount Kindle Formation, respectively (Norford and Macqueen 1975). Relationships exposed in the Franklin Mountains and Colville Hills reveal locally enhanced erosion of the Mount Kindle Formation and Franklin Mountain Formation along the uplifted Keele Arch from mid-Silurian to Early Devonian time (MacLean et al. 2014). Following a latest Silurian–Middle Devonian phase of shallow-marine carbonate deposition, the platform was incrementally drowned by siliciclastic sediment derived from the Ellesmerian Orogen during the Late Devonian–Early Carboniferous (Morrow 2012). Depositional and erosional phases between the Early Carboniferous and Jurassic left no stratigraphic record, and are therefore unconstrained.

Within the Mackenzie Plain, Franklin Mountains and Colville Hills the entire Paleozoic succession of the ME CTSE is involved in Laramide fold and thrust deformation of Cretaceous–Eocene age associated with the northern Canadian Cordillera (Cook 1983; Cook and MacLean 1999). Inversion of Cambrian-age normal faults as reverse faults during Laramide deformation is documented in the Colville Hills and eastern Franklin Mountains (MacLean et al. 2014).

**Underlying and overlying rock assemblages**

**Age of underlying consolidated basement or youngest underlying unmetamorphosed rock unit**

Across much of its extent, the Mackenzie–Peel Platform lies with angular unconformity upon stratigraphic units ranging in age from Paleoproterozoic to earliest Neoproterozoic (Tonian). These include the Hornby Bay (Paleoproterozoic), Dismal Lakes and Coppermine River (Mesoproterozoic) groups exposed NE of Great Bear Lake (Fig. 1), the Shaler Supergroup (early Neoproterozoic) exposed in the Melville Hills/Brook Inlier, and the Mackenzie Mountains Supergroup (early Neoproterozoic) exposed in the eastern Mackenzie Mountains (Enclosure D). Details of the older subsurface stratigraphy were documented in the Colville Hills and eastern Franklin Mountains (MacLean et al. 2004). To the east, the Paleozoic succession is non-conformable upon Precambrian crystalline basement of the Canadian Shield.
Age of oldest overlying rock unit

A regional unconformity separates deposits of the ME CTSE from an overlying Mesozoic siliciclastic succession. In most areas, the oldest overlying unit is Early Cretaceous sandstone of the Martin House or Langton Bay formations. Within the Franklin Mountains, isolated exposures of Cretaceous strata overlying Paleozoic carbonates belong to the Late Cretaceous Slater River Formation (MacLean et al. 2014). In northern Anderson Plain, the oldest known overlying units are isolated deposits of Late Jurassic Husky Formation preserved near the Arctic Ocean coastline (Dixon 1999).

Tectonic subdivision and internal structure

The ME CTSE underlies the northwestern Interior Plains of Canada and is involved in the eastern Foreland Belt deformation of the Cordilleran Orogen within the Mackenzie Plain and the Franklin Mountains. Following Grantz et al. (2011), that portion of Paleozoic platformal or foreland strata that is involved in the more intense deformation of the Mackenzie Mountains and Richardson Mountains in the Cordilleran Orogen is not included in this summary (Enclosure E). Paleozoic strata across this region are generally flat lying or dip gently towards the mountains (SW) or Mackenzie Delta (NW); see Figures 4 and 5. Deformation associated with the development of the Canadian Cordillera during Late Cretaceous–Eocene time has created folds and faults involving Paleozoic strata within the Mackenzie Plain, Franklin Mountains and the Colville Hills (Cook 1983). Figure 6 shows the general style of structures NE of the Mackenzie Mountains, with widely spaced, detached folds and thrusts dominating the region from the Peel Plateau to the eastern Franklin Mountains (B–D) and locally reactivated Cambrian normal faults in the Colville Hills (E–G). Larger structures are also visible in Figures 4 and 5 as local structural highs on the base of the Cambrian or base of the Devonian. The deeper detachment level for structures in the Mackenzie Mountains (c. 10 km:

![Fig. 4. Depth–structure map on the base of Cambrian strata based on public-domain well and seismic data, as interpreted by MacLean (2012); the contour interval is 100 m, deepening from red to blue. Labels are placed so that the negative sign is aligned with the labelled contour. The Cambrian zero edge lies at the boundary between the Precambrian and the Paleozoic.](https://example.com/fig4.jpg)
Fig. 6) rises beneath the Mackenzie Plain to lie within Saline River Formation evaporitic strata of the Cambrian succession 2–3 km beneath the Franklin Mountains, showing how structures in the Franklin Mountains are directly linked to the Cordillera. This area differs from the southern Canadian Cordillera by having both foreland-vergent and hinterland-vergent thrust faults, which are likely to be related to the highly ductile detachment layer (see Harrison 1995 for similarly divergent salt-detached structures). Steeply dipping structures in the Colville Hills involve Proterozoic strata beneath the Cambrian evaporitic strata and are interpreted to have developed independently of structures in the Franklin Mountains, although the timing is also Late Cretaceous–Middle Cambrian time. Reactivation of the Proterozoic–Cambrian structure during Ellesmerian or subsequent Laramide (Cretaceous–Eocene) deformation of the northern Canadian Cordillera is a likely explanation for the location and orientation of the syncline at the surface.

For further details regarding the structural style across the Franklin Mountains, see Cook (1983). Structural relationships in the Colville Hills are discussed in MacLean and Cook (1992).
The Cretaceous carbonate). The age of the basal beds of the Mount Clark (shale, commonly dark in colour, with lesser sandstone and sandstone and minor shale) and the Mount Cap Formation (red shale, evaporites and carbonates), overlain gradationally by the Franklin Mountain Formation (dolostone with an increase in water depth led to deposition of the shale-clastic claystone and dolostone). The age of the basal beds of the Mount Clark Formation is not well constrained, although the common presence of intense bioturbation argues for a Cambrian age. The contact between the Mount Clark and Mount Cap formations, although locally sharp, is a diachronous facies boundary (Dixon and Stasiuk 1998; MacNaughton et al. 2013); it is not known to be older than Cambrian Stages 3 or 4 (Bonia–Olenellus Zone). Regionally, the uppermost part of the Mount Cap Formation is at least as young as Cambrian Stage 5 (Glossopleura Zone: Aitken et al. 1973; MacNaughton et al. 2013). In terms of traditional subdivisions, these are Lower–Middle Cambrian; strata and are present throughout the TSE, with a zero edge where they crop out against the Canadian Shield to the east or abut against the ancient Mackenzie Arch system to the west (Aitken et al. 1973). The Mount Clark Formation was deposited in shoreline to shallow-marine settings and records initial flooding on the peneplain of Proterozoic strata (Dixon and Stasiuk 1998). A subsequent increase in water depth led to deposition of the shale-dominated Mount Cap Formation.

The second sequence consists of the Saline River Formation (red shale, evaporites and carbonates), overlain gradationally by the Franklin Mountain Formation (dolostone with an upper interval of cherty or siliceous dolostone). The basal unconformity of this sequence has been documented in the subsurface (Dixon and Stasiuk 1998) and in outcrop in the eastern Mackenzie Mountains (Aitken et al. 1973). Age constraints are sparse but the sequence probably extends from late in Cambrian Stage 5 to Early Ordovician. These units

**Sedimentary fill**

**Total thickness**

The thickness of Paleozoic strata across the Mackenzie–Ellesmerian CTSE varies from a zero edge adjacent to the Canadian Shield to the east or abut against the ancient Mackenzie Arch system to the west (Aitken et al. 1973) and in outcrop in the eastern Mackenzie Mountains (Aitken et al. 1973). The contact between the Mount Clark and Mount Cap formations, although locally sharp, is a diachronous facies boundary (Dixon and Stasiuk 1998; MacNaughton et al. 2013); it is not known to be older than Cambrian Stages 3 or 4 (Bonia–Olenellus Zone). Regionally, the uppermost part of the Mount Cap Formation is at least as young as Cambrian Stage 5 (Glossopleura Zone: Aitken et al. 1973; MacNaughton et al. 2013). In terms of traditional subdivisions, these are Lower–Middle Cambrian; strata and are present throughout the TSE, with a zero edge where they crop out against the Canadian Shield to the east or abut against the ancient Mackenzie Arch system to the west (Aitken et al. 1973). The Mount Clark Formation was deposited in shoreline to shallow-marine settings and records initial flooding on the peneplain of Proterozoic strata (Dixon and Stasiuk 1998). A subsequent increase in water depth led to deposition of the shale-dominated Mount Cap Formation.

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**Lithostratigraphy/seismic stratigraphy**

The Cambrian–Silurian lithostratigraphic succession of Mackenzie–Peel Platform TSE has been summarized in a number of publications (Tassonyi 1969; Aitken et al. 1973; Norford and Macqueen 1975; Pugh 1983, 1993; Aitken 1993; Cecile and Norford 1993; Dixon and Stasiuk 1998; Pyle and Jones 2009; Sommers et al. 2020). It can be considered in terms of three large-scale unconformity-bounded depositional sequences (Figs 3 and 7), described here in ascending order.

The basal sequence is entirely of Cambrian age. In ascending order, it consists of the Mount Clark Formation (quartz sandstone and minor shale) and the Mount Cap Formation (shale, commonly dark in colour, with lesser sandstone and carbonate). The age of the basal beds of the Mount Clark Formation is not well constrained, although the common presence of intense bioturbation argues for a Cambrian age. The contact between the Mount Clark and Mount Cap formations, although locally sharp, is a diachronous facies boundary (Dixon and Stasiuk 1998; MacNaughton et al. 2013); it is not known to be older than Cambrian Stages 3 or 4 (Bonia–Olenellus Zone). Regionally, the uppermost part of the Mount Cap Formation is at least as young as Cambrian Stage 5 (Glossopleura Zone: Aitken et al. 1973; MacNaughton et al. 2013). In terms of traditional subdivisions, these are Lower–Middle Cambrian; strata and are present throughout the TSE, with a zero edge where they crop out against the Canadian Shield to the east or abut against the ancient Mackenzie Arch system to the west (Aitken et al. 1973). The Mount Clark Formation was deposited in shoreline to shallow-marine settings and records initial flooding on the peneplain of Proterozoic strata (Dixon and Stasiuk 1998). A subsequent increase in water depth led to deposition of the shale-dominated Mount Cap Formation.

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**Fig. 6.** Structural cross-section from the Mackenzie Mountains to the Colville Hills showing the folding and faulting style affecting the Mackenzie–Ellesmerian CTSE; the section is expanded from Cook and MacLean (1999) using map relationships and available seismic reflection data. See Figure 1 for the location of the cross-section.

**Fig. 7.** Well cross-section illustrating the stratigraphic relationships within the Paleozoic strata. The gamma-ray log from each well is shown in black. Faulted structures are shown schematically. See Figure 1 for the cross-section location.
are of regional extent. Development of a restricted basin, related in part to the rise of a network of tectonic ridges to the west, led to deposition of the evaporite-rich Saline River Formation (Dixon and Stasinski 1998; MacLean 2011). The Franklin Mountain Formation records deposition on a regionally extensive but environmentally stressed carbonate platform following inundation of most of the arches (Norford and Macqueen 1975; Turner 2011).

The third sequence consists entirely of carbonates of the Mount Kindle Formation. This unit commonly is siliceous or chert-bearing and locally is richly fossiliferous. It encompasses strata of Late Ordovician–Early Silurian age and is separated from underlying strata by a regional disconformity. It records an episode of carbonate platform deposition that was characterized regionally by conditions conducive to an abundant and diverse macrofauna (Norford and Macqueen 1975; Pope and Leslie 2013). Widespread post-Mount Kindle erosion created a regional unconformity between the Mount Kindle and overlying Devonian formations. It is essentially Lochkovian in age and is separable from underlying strata by a regional disconformity. It records an episode of carbonate platform deposition that was characterized regionally by conditions conducive to an abundant and diverse macrofauna (Norford and Macqueen 1975; Pope and Leslie 2013). Widespread post-Mount Kindle erosion created a regional unconformity between the Mount Kindle and overlying Devonian–Cretaceous strata. Across the Keele Arch, post-Mount Kindle Formation erosion locally removed the entire unit in the eastern Franklin Mountains and Colville Hills (between wells M-47 and L-80 in Fig. 7) (MacLean et al. 2014).

The Devonian succession of the Mackenzie–Ellesmerian CTSE has a long history of study (e.g. Hume and Link 1945) and has been featured in numerous reports (e.g. Bassett 1961; Tassonyi 1969; Pugh 1983, 1993; Muir et al. 1985; Morrow 1991, 1999; Meijer Drees 1993; Moore 1993; Norford and Overlie 1991; Tassonyi 1969; Pugh 1983, 1993; Muir 1985; Morrow 1991, 1999; Meijer Drees 1993; Moore 1993; Norris 1997; Yose et al. 2001; Pyle and Jones 2009). Morrow (2012) synthesized the Devonian stratigraphy of the northern mainland by grouping formations into informal ‘assemblages’ that are either extensive but environmentally stressed carbonate platforms (T–R) or second-order sequences. The following discussion of Devonian lithostratigraphy is summarized by Morrow (2012), except where noted, and the reader is urged to consult that report for details on the relatively complex sequence stratigraphy of the succession.

Lower Devonian strata consist of two informal assemblages. The older Delorme Assemblage in the region west of Great Bear Lake, mainly to the south of Tulita, consists of dolomitic sandstone and siltstone of the Tseto Formation, and correlative dolostone, evaporites and solution-collapse breccias of the Camsell Formation. The Delorme Assemblage is essentially Lochkovian–earliest Emsian in this region. Correlative strata beneath Peel Plain and southern region’s strata include facies of dolostones of the Peel Formation, which may be as old as latest Silurian at their base, overlain by sandy and argillaceous carbonates of the Tatsieta Formation that probably are not younger than Pragian. The Delorme Assemblage is not present beneath Horton Plain, the Colville Hills or the northern Franklin Mountains. The Delorme Assemblage is overlain by the Bear Rock Assemblage, which encompasses the remaining Early Devonian strata of the region. In the Peel and Anderson plains, the succession consists of dolostone of Arnica Formation, overlain diachronously by limestone of Landry Formation. The base of the Arnica Formation may be as old as Pragian in these regions. Stratigraphic relationships are more complex in the region around Norman Wells and in the Colville Hills. At surface, the classic expression of this interval is the pinnacle- and cave-forming solution-collapse limestone and dolostone breccia of the Bear Rock Formation. In the subsurface, the same interval is represented by interbedded dolostone and evaporite of the Fort Norman Formation. Locally, Bear Rock Formation breccia passes laterally into dolostone (without evaporite) of the Arnica Formation. In the Norman Wells region, this succession is overlain by a thin package of Landry Formation limestone. In the Colville Hills, poor exposure inhibits recognition of separate stratigraphic units and, although early mapping assigned all strata to Bear Rock Formation (Cook and Atiken 1971), more recent work (Fallas et al. 2015c; Gouwy et al. 2017) suggests that all the formations just named may be present, although perhaps not mappable. The Colville Hills and Anderson Plain mark the eastern limit of the Bear Rock Assemblage (Figs 1 and 5). The upper surface of the Bear Rock Assemblage records marine regression and subaerial exposure that can be recognized throughout much of western Canada (Morrow and Geldsetzer 1988). Aspects of the lithostratigraphy of the Bear Rock Assemblage are the subject of debate and may require revision (e.g. Gal et al. 2009; but see also Gouwy et al. 2017).

Above the Bear Rock Assemblage, the Hume Formation (Eifelian) makes up the lower part of the Hume–Lonely Bay Assemblage. The Hume Formation consists of fossiliferous limestone, locally with a basal member of shale and limestone (Headless Member). The Hume Formation is sharply overlain by dark-weathering shale of the Hare Indian Formation (early–mid Givetian), including the basal, organic-rich Bluefish Member, and these strata make up the upper part of the Hume–Lonely Bay Assemblage. This succession extends east almost to the Colville Hills, and north and west to the limits of the Mackenzie–Peel Platform TSE.

Locally, as at Norman Wells, reef and off-reef limestone facies of the late Givetian Ramparts Formation (of which the reefal Kee Scarp Member forms the reservoir at Norman Wells) overlie the Hare Indian Formation. Dark, organic-rich mudstones of the Canol Formation (early Frasnian) conformably overlie both the Ramparts and Hare Indian formations. The Hare Indian, Ramparts and Canol formations together make up the Horn River Group. The Canol Formation extends well to the north and west within the CTSE but does not extend as far east as the Delorme Assemblage. The Horn River Group can be combined with overlying shale, siltstone and sandstone (platformal and deeper-marine) of the Imperial Formation to make an additional assemblage ( Slave–Kakisa Assemblage) of Frasnian age in the south and extending into the Fammernian in the Peel and Anderson plains. A Frasnian limestone (Jungle Ridge Member) is present within the Imperial Formation in the Mackenzie Plain region. In the Peel Plateau area, deltaic sandstone and conglomerate of the Tuttle Formation was deposited in late Famennian–Tournaisian time conformably above turbiditic deposits of the Imperial Formation (Allen et al. 2009). Both the Imperial and Tuttle formations are part of foreland clastic wedge deposition (Ellesmerian Foreland TSE) related to the Ellesmerian Orogeny (Lane 2007).

In seismic reflection studies of Mackenzie–Peel Platform and Ellesmerian Foreland strata, the major reflectors do not necessarily correspond with the major lithostratigraphic and sequence stratigraphic boundaries described in the preceding paragraphs. Instead, the major reflectors correspond to the following stratigraphic surfaces: base of Cretaceous/top of the Imperial Formation, top of Ramparts Formation (top of the Hare Indian Formation where the Ramparts Formation is absent), top of the Hume Formation, top of the Saline River Formation, top of the Mount Cap Formation and base of Cambrian. The interval dominated by carbonates from the top of the Saline River Formation to the top of the Hume Formation has few reflective interfaces but the top of the Franklin Mountain Formation and the top of Mount Kindle Formation/base of Devonian are locally recognizable in seismic data.

**Migmatism**

Migmatism is not recorded in rocks of the Mackenzie–Peel Platform or Ellesmerian Foreland but Paleozoic volcanism is well documented further west outside the CTSE area in the correlative Selwyn Basin (Goodfellow et al. 1995).
Heat flow

Heat-flow data for the Mackenzie-Ellesmerian CTSE are limited. Majorowicz et al. (1988) estimated that geothermal gradients for the Mackenzie Plain generally are <30 mK m\(^{-1}\), reaching values between 40 and 50 mK m\(^{-1}\) in that part of the Mackenzie Plain and the Franklin Mountains between the eastern Mackenzie Mountains and Great Bear Lake. They estimated that heat-flow values could vary from 40 to 110 mW m\(^{-2}\) across the larger region covered by the ME CTSE, with values in excess of 80 mW m\(^{-2}\) being found only between the Franklin Mountains and Mackenzie Mountains in the region west of Great Bear Lake. This is consistent with the high heat flow of 84 mW m\(^{-2}\) measured at Norman Wells by Garland and Lennox (1962).

Petroleum geology

Discovered and potential petroleum resources

Discoveries and showings of oil and gas are shown in Figure 3. In the Mackenzie–Ellesmerian CTSE, the conventional hydrocarbon discovery of greatest economic significance to date is the Norman Wells oil and solution gas field, hosted in the Middle Devonian Kee Scarp Member of the Ramparts Formation. Reservoir parameters for the Norman Wells oilfield include a drainage area of 1600 hectares, net pay of 110 m, average porosity of 9.8%, water saturation of 0.1, reservoir temperature of 21°C and reservoir pressure of 4900 kPa (Kempthorne and Irish 1981; Irish and Kempthorne 1987; Kaldi 1989; Mediterranean Drains 2017). The in-place oil volume is 108 MMm\(^{3}\) (679 MMbbl) (Yose et al. 2001). In-place solution gas volume is 6230 MMm\(^{3}\) (220 Bcf) (Canadian Gas Potential Committee 2005).

The Cambrian Mount Clark Formation is reservoir to several hydrocarbon discoveries in the Colville Hills. All examples of the ‘Cambrian clastic play’ of Hannigan et al. (2011) have been single-well discoveries: Tedi Lake K-24 (gas, 1974), Tweed Lake M-47 (gas condensate, 1985), Bele O-35 (gas, 1986), Nogha O-47 (gas, 1986) and Lac Maunoir C-34 (oil, 2004). The Bear Rock Formation (Devonian) is thought to be the reservoir for gas, oil and condensate in the Summit Creek B-44 and K-44 wells, at the eastern edge of the Mackenzie Mountains south of Tulita (Hannigan et al. 2011).

Since 2011, organic-rich shale of the Devonian Canol Formation has been an active exploration target for unconventional oil and gas in the Mackenzie River Valley around Norman Wells. Significant hydrocarbon discoveries have been reported at Dodo Canyon E-76 (2014), Mirror Lake P-20 (2014) and East MacKay 1-78 (oil and gas, 2013). Hannigan et al. (2011) evaluated the conventional hydrocarbon potential of the Mackenzie River drainage system from the provincial–territorial boundary (60° N) northward to, but not including, the Mackenzie Delta/Beaufort region. The Paleozoic strata that make up the Mackenzie–Ellesmerian CTSE as defined in the present report have a total mean in-place potential of 449 MMm\(^{3}\) (2824 MMbbl) of oil and 320 477 MMm\(^{3}\) (11.3 Tcf) of gas, based on the summation of estimates for individual plays and potential plays hosted in these strata. Unconventional hydrocarbon resources are estimated at 23 000 MMm\(^{3}\) (145 Bbbl) of oil for the Canol Formation, and 7300 MMm\(^{3}\) (46 Bbbl) of oil for the Bluefish Member of the Hare Indian Formation (Terlaky 2017).

Current exploration status

Oil seeps on the banks of the Mackenzie River were long known and utilized by the Dene people. The first commercial petroleum discovery on the northern mainland occurred at Norman Wells in 1920. Production was limited until World War II, when the short-lived Canol pipeline connected Norman Wells to Whitehorse in support of the Allied war effort in the Pacific theatre. Following an expansion of the Norman Wells Field, a 900 km pipeline along the Mackenzie Valley was completed in 1986. Norman Wells remains one of Canada’s top producing oilfields. In 2011, the Canol Formation in the central Mackenzie Valley became a target for exploration interest in shale oil and shale gas (Terlaky 2017) but some of these wells have been recently abandoned (2016). The ME CTSE area saw steady drilling activity each year from 1960 onwards but, as of the time of writing (late 2018), no new wells have been drilled since 2014.

Hydrocarbon systems and plays

Herein, we focus on the known discoveries in the Mackenzie–Peel Platform TSE. No known discoveries have been documented in the overlying Ellesmerian Foreland TSE. Additional potential hydrocarbon system elements and conceptual plays are present in both TSEs, and the reader is referred to the extensive account of Hannigan et al. (2011) for details.

Source rocks. Paleozoic source rocks are indicated in Figure 3. Scattered, thin, algal-rich shales are present in the Cambrian Mount Cap Formation in the Colville Hills (Wielens et al. 1990; Dixon and Stasiuk 1998). They vary in total organic carbon (TOC) from 0.5 to 6%, with hydrogen index (HI) values up to 768 mgHC g\(^{-1}\) TOC. These oil-prone source rocks with Type I kerogens range from thermally immature in the central Colville Hills to mature near Tweed Lake (Dixon and Stasiuk 1998). Similar algal-rich shales are present in the Mount Cap Formation beneath the Mackenzie Plain, where they are deeply buried and are likely to be within the gas-generation zone, past the peak of oil generation (Dixon and Stasiuk 1998). Certain gas accumulations in late mature oil zones within the Cambrian strata at Colville Hills may have their source in Proterozoic strata, notably a 75 m-thick shale unit in the Dismal Lakes Assemblage that contains up to 1.4% TOC at maturities above the oil window, but within the gas-generation phase (Snowdon and Williams 1986).

Oil-prone, organic-rich shale in the Middle Devonian Bluefish Member of the Hare Indian Formation beneath the Peel and Anderson plains has an average thickness of about 20 m and may have been the source for bitumen found in the Hume Formation. These rocks are mature to overmature but retain moderate TOC and may remain a potential source for gas. The Bluefish Member is present beneath the Mackenzie Plain, but its geochemical character suggests that it was not a major source for the Norman Wells conventional oilfield (Snowdon et al. 1987; Feinstein et al. 1988). The Bluefish Member has been identified as a potential unconventional shale oil source within the Mackenzie Plain (Terlaky 2017).

Organic-rich bituminous shales of the Middle–Upper Devonian Canol Formation are present beneath the Peel, Anderson and Great Bear plains, in thicknesses between 6 and 122 m. Residual kerogen ranges between 0.58 and 27.14% TOC (Morrow 1999; National Energy Board 2000). HI values range up to 1055 mgHC g\(^{-1}\) TOC. This excellent, oil-prone source rock is likely to have generated hydrocarbons in the Interior Platform area. The Canol Formation is mature in the
Mackenzie Plain and along the eastern edge of the Mackenzie Mountains (Feinstein et al. 1991). At the Summit Creek B-44 discovery, thermally mature potential source rocks occur in the Canol Formation (TOC = 3–5% over 140 m; vitrinite reflectance ($R_0$) = 1.1–1.2%), which is the likely source rock for the discovery (Stasiuk et al. 2006). Upper Devonian bituminous shale of the Canol Formation drapes the Kee Scarp reef at Norman Wells and has been geochemically correlated to the oil accumulation (Snowdon et al. 1987; Feinstein et al. 1988). Similar to the Bluefish Member, Canol strata are within the oil window at present depths beneath Norman Wells. In the Peel Plateau, solid bitumen (albertite) found in outcrop is thought to be derived from the Canol Formation and suggests excellent oil source potential (Link et al. 1989; Terlaky 2017).

Reservoirs. Cambrian quartz-rich sandstone of the Mount Clark Formation hosts gas and oil pools beneath the Colville Hills. Grain size varies from very fine sandstone to conglomerate, sorting is fair to good, and grains are subrounded to rounded (Hamblin 1990). Porosity ranges from 8 to 18% and permeability varies from 1.0 to several tens of millidarcies. Petrophysical well-log analyses reveal a maximum porosity and permeability of 6916 mD (Hu and Petrophysical well-log analyses indicate porosities averaging close to 4%, with maximum values approaching 19%; permeabilities approach 1285 mD (Hu and Hannigan 2009).

Middle Devonian reefs (Kee Scarp Member of the Ramparts Formation) are the producing reservoirs at Norman Wells due to the development of diagenetic chalky microporosity (Kaldi 1989) that ranges from 12 to 20%. Matrix permeability is extremely low, averaging 2.2 mD, but is enhanced by a multi-scaled natural fracture system (Yose et al. 2001). Core porosity and permeability of Kee Scarp and Ramparts rocks averages close to 8.8% and 5.3 mD, respectively, and ranges up to 28% and 3320 mD. Petrophysical log analyses show porosities averaging near 5.3%, maximizing at 20.6% (Hu and Hannigan 2009). Net pay is 8.0–110.0 m. Reefs in the Kee Scarp Member also are potential reservoirs beneath the eastern Peel Plain and Anderson Plain.

Seals. Effective top and lateral seals to oil or gas found in the Cambrian Mount Clark Formation are provided by the overlying Cambrian Mount Cap Formation, a shale-dominated succession up to 200 m thick, and the Saline River Formation, consisting of up to 500 m of shale, halite, anhydrite and dolostone (Dixon and Stasiuk 1998). In the Norman Wells oilfield, top and lateral seals for the Middle Devonian Kee Scarp Member reservoir are provided by shale of the Middle– Upper Devonian Canol Formation. Regionally, shales of the Middle Devonian Horn River Group and the Upper Devonian Imperial Formation also may be effective seals.

Traps. The Norman Wells oilfield is in a stratigraphic trap formed by an atoll-type reef in the Middle Devonian Kee Scarp Member (Fig. 8). The reef is sealed by shales of the Devonian Horn River Group and Canol Formation. Traps in the Colville Hills involve sandstone of the Mount Clark Formation as reservoir, with the Mount Cap Formation shales as seal. Structural traps include the Tedji Lake K-24 gas discovery, drilled on a probable block-faulted anticline (Hamblin 1990), and the discoveries at Tweed Lake M-47 (gas-condensate), Nogha C-49 (gas) and Lac Maunoir C-34 (oil), all drilled into fault-bounded anticlines. Bele O-35 is the lone stratigraphic trap, where gas with minor condensate accumulated in Cambrian sandstone onlapping a Proterozoic topographical high (Fig. 9).
At the eastern edge of the Mackenzie Mountains, the trap for the Summit Creek B-44 discovery (oil, gas and condensate) is a doubly plunging, fault-bounded anticline involving a carbonate reservoir (Fort Norman Formation) imbricated with the Canol Formation source rock. The Canol Formation also seals the reservoir (Fig. 10).

There are numerous other potential trap configurations possible in the Mackenzie–Peel Platform and Ellesmerian Foreland successions. The reader is referred to Hannigan et al. (2011) for a fuller discussion.

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Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

References


