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Geology and Assessment of Undiscovered Oil and Gas Resources of the Northwest Canada Interior Basins Province, Arctic Canada, 2008

Chapter G of
The 2008 Circum-Arctic Resource Appraisal

Professional Paper 1824

U.S. Department of the Interior
U.S. Geological Survey

Cover. Northwestward view across the southern foothills of the Brooks Range along Akmagolik Creek, approximately 150 miles southwest of Prudhoe Bay, Alaska. Exposed rocks are part of the Mississippian–Pennsylvanian Lisburne Group and include a thrust-fault ramp at left. Photo includes two helicopters for scale, a blue-and-white one near the center and a red one at center-right at creek level. U.S. Geological Survey photograph by David Houseknecht.

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By Marilyn E. Tennyson and Janet K. Pitman

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Edited by T.E. Moore and D.L. Gautier

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Chapter G

Geology and Assessment of Undiscovered Oil and Gas Resources of the Northwest Canada Interior Basins Province, Arctic Canada, 2008

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Abstract

The Northwest Canada Interior Basins Province is bounded by the Mackenzie and Richardson Mountains on the southwest and west, by the Eskimo Lakes Arch on the northwest, and by the erosional limit of Paleozoic strata on the east. It lies within the far northwest part of the Paleozoic continent of Laurentia. During early Paleozoic time, it was part of a passive margin formed when the Neoproterozoic supercontinent Rodinia broke apart. A Cambrian marine transgressive sequence gave way to an evaporitic intrashelf basin, succeeded by a westward-building carbonate bank from Late Cambrian through Middle Devonian time. In Late Devonian and early Carboniferous time, the region was buried by a thick succession of south-prograding clastic strata derived from orogenic belts to the northeast and north. A subsequent period of inactivity and erosion persisted until sedimentation resumed as the opening of the Canada Basin initiated an Early Cretaceous marine transgression over much of the region. Later in Cretaceous time, clastic strata derived from Cordilleran uplifts to the southwest began to prograde north, ending with eventual Laramide uplift and deformation in latest Cretaceous and Paleogene time.

Two petroleum systems are known within the province. A petroleum system in Cambrian to Middle Devonian strata, sourced by alginitic Cambrian shales and sealed by Cambrian evaporites, is proven by modest gas discoveries in the Colville Hills; generation is attributed to burial under the Upper Devonian clastic wedge. An Upper Devonian petroleum system, proven by the presence of the 250-million-barrel Norman Wells field at the southern edge of the province, was sourced by organic-rich shale of the Canol Formation. Generation is similarly inferred to have been driven by burial beneath the Devonian clastic wedge, perhaps augmented locally by additional Cretaceous burial. Potential reservoirs include Devonian reefs and sandstones stratigraphically below and laterally equivalent to the source rocks, as well as overlying sandstones in the clastic wedge. Subordinate source rocks could include organic-rich shales within the clastic wedge.

Principal risks to the lower Paleozoic petroleum system include (1) inadequate reservoir volume for a field of the minimum size and (2) petroleum loss by remigration caused by Laramide deformation. One lower Paleozoic assessment unit (AU) was quantitatively assessed, with estimated resources of 0 to 117 million barrels of oil (MMBO), mean 23 MMBO; and 0 to 1,364 billion cubic feet of gas (BCFG), mean 310 BCFG. The principle risks to the Devonian petroleum system were considered to be (1) lack of preservation due to extensive erosion before the Cretaceous, and (2) inadequate reservoir volume, because the best potential reservoir strata, Devonian reefs, may be absent throughout most of the province owing to either lack of deposition or erosion. These risks were sufficiently high that the single AU defined in the Devonian petroleum system was not quantitatively assessed, because the chance of a field of the minimum size, 50 million barrels of oil equivalent, was estimated to be only 0.1.

Introduction

In 2008, the U.S. Geological Survey (USGS) completed an appraisal of undiscovered, technically recoverable conventional oil and gas resources north of the Arctic Circle. Results of that assessment, the Circum-Arctic Resource Appraisal (CARA) include aggregate, probabilistic resource estimates for the entire Arctic region (Gautier and others, 2009, 2011), based on geological evaluation of all the basins wholly or partially north of the Arctic Circle. Basins considered to have at least a 10 percent chance of hosting an oil accumulation larger than 50 million barrels of oil (MMBO) or a gas accumulation larger than 300 billion cubic feet of gas (BCFG) were assessed using the methodology described in Charpentier and Gautier (2011) and Charpentier (2017, this volume, chapter B). This report is a summary of the geologic information and evaluation that underlies the assessment of potential undiscovered oil and gas resources in the Northwest Canada Interior Basins Province.

Northwest Canada Interior Basins Province Description

Province Boundary Definition

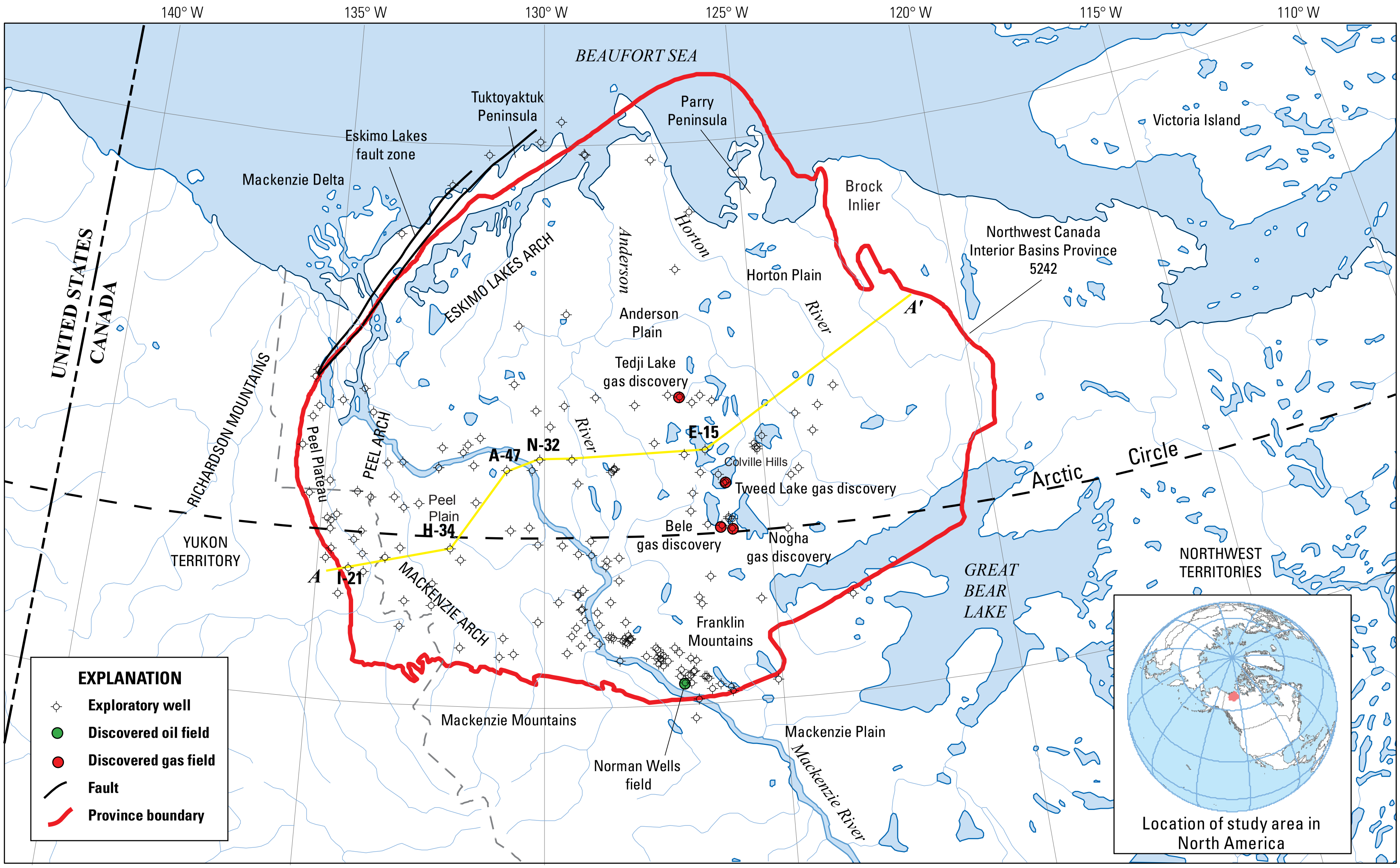
The boundaries of the province (fig. 1) encompass the approximate extent of potentially prospective Cambrian through Devonian strata lying between an extensive area of exposed Precambrian rocks of the Canadian Shield to the east and Laramide-age structural uplifts to the west. The eastern boundary follows the basal contact of Cambrian strata resting on Precambrian rocks, and the southeastern boundary approximately coincides with a slight arch between two Cambrian depocenters delineated by Dixon and Stasiuk (1998): the Good Hope depocenter to the northwest and the Great Bear depocenter to the southeast. West of the Mackenzie River, the boundary follows the northern front of the Mackenzie Mountains (fig. 1), then curves north to coincide with the eastern front of the Richardson Mountains on the west. The northwestern boundary trends northeast along the Eskimo Lakes fault zone, a Mesozoic hinge line on the Tuktoyaktuk Peninsula that separates continental crust on the southeast from extended transitional crust on the northwest. The northern boundary curves around Parry Peninsula along the contact between Proterozoic and Paleozoic strata as delineated by Grantz and others (2009). Geographically, the province includes the plains drained by the Anderson, Horton, Mackenzie, and Peel Rivers, the Peel Plateau west of the Peel River, and the Colville Hills in the east-central part of the province.

Tectonic Overview

Crystalline basement in the study area consists of metamorphosed Paleoproterozoic arcs and orogenic belts that accreted to older Archean cratons between about 2.0 and 1.8 Ga (Whitmeyer and Karlstrom, 2007). Subsequently, several sequences of Mesoproterozoic and Neoproterozoic clastic and carbonate strata, each several kilometers thick, accumulated to a total thickness of more than 10 km (Cook and MacLean, 2004). Between about 725 and 540 Ma, continental crust that lay to the west and north rifted away, forming a passive margin in the northwestern part of Laurentia; the modern identity of this crust is uncertain (Cecile and Morrow, 1997). Immediately west of the Northern Interior Basins Province, in the Richardson Mountains, is the Richardson trough (Lenz, 1972), a north-trending depositional basin filled with lower Paleozoic deepwater clastic strata. This trough was probably a failed rift (Churkin, 1975) between the northwest Canada mainland and the Yukon Platform, a highstanding block at the northwest tip of Laurentia. To the southwest, deeper marine sediments accumulated along the lower Paleozoic continental slope, the Selwyn Basin, which extended southeast from Alaska to northern British Columbia. An arcuate trend of highs, including the Mackenzie, Peel, and Eskimo Lakes Arches (fig. 1), probably represents a rift shoulder that separated transitional crust in the Richardson trough and Selwyn Basin from continental crust of the continental shelf. The marginal arches were intermittently exposed during Early to Middle Cambrian time, leading to deposition of evaporites in the intrashelf basin landward of the arches. In Late Cambrian time, the margin subsided enough to allow a carbonate bank to build over the entire area of the province. Carbonate bank deposition continued through Ordovician, Silurian, and Early and Middle Devonian time. In late Silurian to Early Devonian time the Keele Arch developed near the present location of the Franklin Mountains, but by Middle Devonian time, it had been reduced sufficiently by erosion that sediments were again deposited across its crest (Williams, 1990). Also in Early Devonian time, north-verging folding and thrusting took place in northwest Yukon and adjacent Alaska, an event known as the Romanzof orogeny (Lane, 2007).

Near the end of Middle Devonian time, the carbonate shelf was drowned by a relative rise in sea level and deposition of deepwater clastic strata, which were the distal edge of a voluminous prograding clastic wedge derived from the Caledonian orogeny in northeastern Laurentia. By Late Devonian time, related Ellesmerian compressive deformation was active in the Canadian Arctic Islands to the north, and by early Carboniferous time deformation was underway north of the province, in the area of the modern Mackenzie River delta and northern Richardson Mountains (Lane, 2007). South- and west-prograding marine strata derived from the orogenic belt to the north likely accumulated to thicknesses of a few kilometers at least into early Carboniferous time and probably covered the entire province. Apatite thermochronometry by Ault and others (2009) indicates 3 to 4 km of burial in Devonian to late Carboniferous time in the area east of Great Bear Lake. The nature of Permian through Jurassic deposition in the province, if any, is unknown, although intracontinental sedimentation similar to that in the Sverdrup Basin to the northeast and in Alaska to the northwest is possible.

The region appears to have been tectonically inactive until late in the Mesozoic, by which time much of the clastic wedge and any younger strata had been eroded (Patchett and others, 2004). Rifting and subsidence associated with the opening of the Canada Basin began in Late Jurassic time, allowing deposition of clastic sediments in the present area of the Mackenzie delta (Grantz and May, 1982; Embry, 1990; Dixon, 1999). As rifting culminated in Early Cretaceous seafloor spreading, the entire province subsided below sea level and was blanketed by several hundred meters of transgressive strata, dominantly mudstone (Dixon, 1999). Cordilleran deformation to the southwest began by the end of Early Cretaceous time, providing a new source of clastic sediments that prograded northward across the province (Dixon, 1986, 1992) through most of Late Cretaceous and into Paleogene time. Laramide deformation that began near the end of Cretaceous time caused faulting, folding, and uplift on the flanks of the province in what are now the Mackenzie, Franklin, and Richardson Mountains (Dixon, 1986, 1992; Hadlari and others, 2014). The region has seen no significant tectonism since the end of the Laramide in Paleogene time, although there probably is some seismicity associated with modern plate interactions along the Pacific coast (Hyndman and others, 2005).



Base map from Esri, 2007, used herein under license.
Clarke 1866 Stereographic North Pole

Figure 1. Index map of Northwest Canada Interior Basins Province, Arctic Canada. *A–A′* is line of section shown on figure 3.

Province Stratigraphy and Structural Geology

The oldest sedimentary rocks that are exposed within the province are strata of the Neoproterozoic Shaler Supergroup. These rocks are exposed in the Brock Inlier and the Coppermine area adjacent to the Arctic Ocean and in the correlative Mackenzie Mountains Supergroup (of Young and others, 1979) that crops out in the Mackenzie Mountains along the southwest boundary of the province (Rainbird and others, 1996; Cook and MacLean, 2004) (fig. 1). Seismic data also indicate the presence of correlative rocks of uncertain lithologies throughout the province below Paleozoic strata (Cook and MacLean, 2004). The Neoproterozoic rocks are older than the 723-Ma Natkusiak basalt in the Minto Inlier on Victoria Island, north of the province, and younger than the 1,267±2-Ma basalts of the Coppermine River Group in the same sequence. Both sequences contain detrital zircons in their lower parts with ages of about 1,080 Ma (Rainbird and others, 1996). The Shaler Supergroup predominantly consists of shallow marine carbonates and quartz sandstones capped by a sandstone sequence that was deposited by a large river system originating in the Grenville orogen, across Laurentia to the east (Rainbird and others, 1992, 1997). The west-thickening Mackenzie Mountains Supergroup consists of shallow marine platform stromatolitic and oolitic carbonate, evaporite, quartz sandstone, and shale as much as 4 km thick (Rainbird and others, 1996). Both sequences have been interpreted as having been deposited in embayments within a large intracratonic basin, possibly flanking a regional basement arch or peninsula extending northwest from the vicinity of Great Bear Lake (Rainbird and others, 1996; Long and others, 2008). Younger Neoproterozoic rocks similar to the Windermere Supergroup are absent from the province; latest Neoproterozoic time is represented by an unconformity.

At the base of the Paleozoic succession is a Cambrian transgressive sequence which passes upward into thick platform carbonates of Late Cambrian to Devonian age. The Cambrian Mount Clark Formation (figs. 2, 3) consists of as much as 80 m of fining-upward sandstone and is crossbedded near the base. It is over 200 m thick in the Franklin Mountains, where it crops out in its type area, and thins westward to zero along the Mackenzie–Peel–Eskimo Lakes Arch trend (Dixon and Stasiuk, 1998; Williams, 1990, 1996) and northward toward the Colville Hills, where it is 15 to 60 m thick. The gradationally overlying Mount Cap Formation consists mostly of shale with subordinate dolomite, limestone, and sandstone, and it has a maximum known thickness of almost 200 m. The Cambrian Saline River Formation consists of as much as 500 m of varicolored shale interbedded with anhydrite, halite, and dolomite. These Cambrian strata were deposited within a basin rimmed on the west by the Mackenzie and Peel Arches, which isolated it from open marine water and caused evaporite deposition.

In contrast to the Mount Clark, Mount Cap, and Saline River Formations, the Upper Cambrian to Ordovician Franklin Mountain Formation is present throughout the province. It overlies Precambrian strata of the Mackenzie and Peel Arches with an angular unconformity, but rests disconformably on the older Cambrian strata east of the arches. It is about 375 to 780 m thick and consists of dolomite deposited in various peritidal and subtidal environments during a marine transgression (Morrow, 1999; Dixon and others, 2007). Disconformably above the Franklin Mountain Formation is the Upper Ordovician to Silurian Mount Kindle Formation, which consists of about 200 to 440 m of dolomite deposited on an open marine shelf, as indicated by abundant crinoids and corals (Morrow, 1999). The unconformably overlying uppermost Silurian to Lower Devonian Peel Formation consists of as much as 388 m of dolomite deposited in supratidal to peritidal environments. Above it are the Lower Devonian Tatsieta Formation, typically consisting of about 60 m of muddy dolomitic limestone, and the Arnica and Landry Formations, a sequence of about 500 m of subtidal and intertidal dolomite deposited in a shelf lagoon east of the Mackenzie and Peel Arches.

Middle Devonian strata of the Hume Formation consist of about 90 to 150 m of calcareous shale and fossiliferous shaly limestone, which were deposited during a major transgression that drowned the shallow shelf and allowed westward progradation of open marine carbonates (Morrow and Geldsetzer, 1988; Morrow, 1999; Pyle and others, 2006). Above the Hume Formation is the Bluefish Member of the Hare Indian Formation, a condensed section of organic-rich black shale about 15 m thick. It passes upward into 180 m of calcareous shale and shaly limestone of the Givetian Hare Indian Formation, deposited as west-prograding slope turbidites. The overlying Ramparts Formation consists of fossiliferous limestone and shale with a locally developed reef facies at the top. This reef facies, commonly referred to as the Kee Scarp Member, is the reservoir at Norman Wells field in the southern part of the province, where it reaches a maximum thickness of about 160 m (Kempthorne and Irish, 1981). Reef growth was terminated at the end of Middle Devonian time by abrupt deepening and deposition of a prograding clastic succession, beginning with organic-rich siliceous black shale of the Canol Formation. The Canol Formation, which ranges in thickness to as much as 120 m, is draped over the reefs of the underlying Ramparts Formation in the southern part of the province and deposited directly on the Bluefish Member of the Hare Indian Formation in the northern part. Overlying progradational, coarsening-upward strata of the Upper Devonian to lower Carboniferous Imperial and Tuttle Formations are as much as 1.8 km thick, but may originally have been significantly thicker, as they are truncated by a major unconformity. These strata are foreland basin deposits derived from uplifts to the north produced by Ellesmerian deformation. The Imperial Formation consists of fine-grained sandstone, siltstone, and shale deposited as both turbidites and nearshore facies, and the overlying Tuttle Formation comprises prodeltaic, deltaic, and fluvial sandstone and conglomerate.

Although an unconformity separates the Imperial and Tuttle Formations from the overlying Lower Cretaceous rocks in most of the province, regional considerations and thermal maturity data provide evidence that upper Paleozoic to lower Mesozoic strata were deposited over the area but were subsequently eroded. In the Richardson Mountains and Peel Plateau just west of the province, the lower Carboniferous

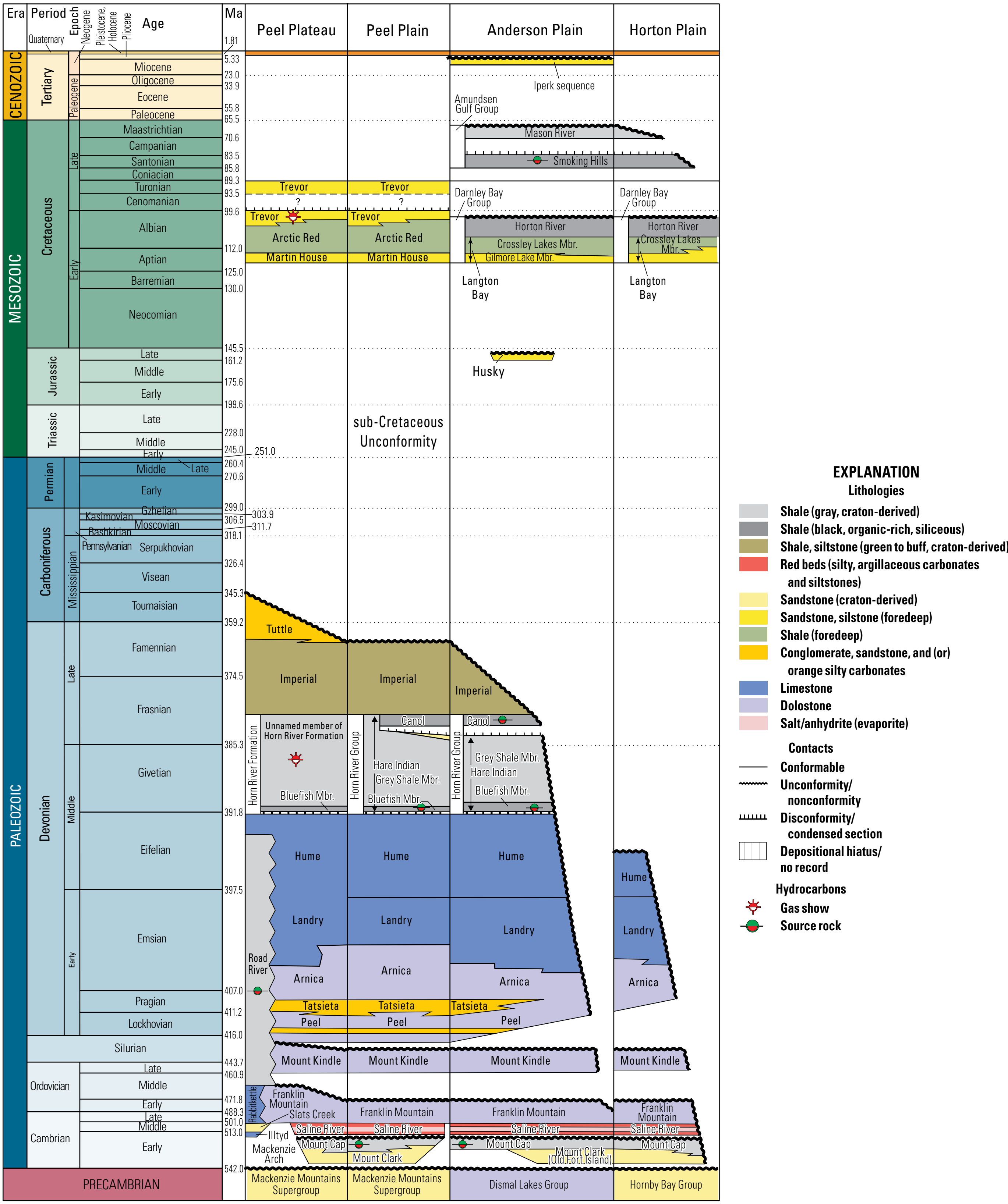


Figure 2. Stratigraphic column of Northwest Canada Interior Basins Province, modified from Pyle and others (2006). Ma, mega-annum; Mbr, Member.

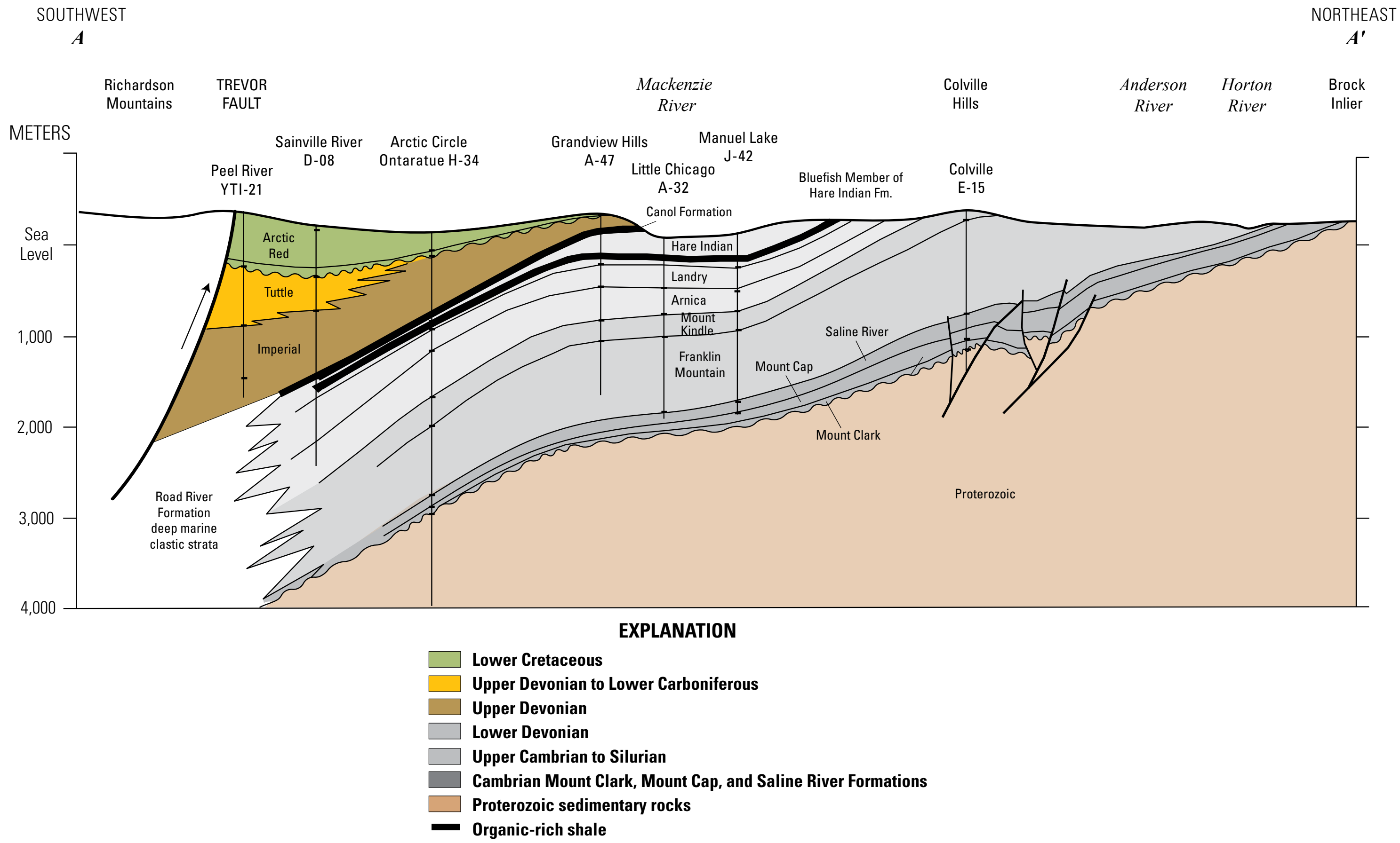


Figure 3. Schematic cross section across Northwest Canada Interior Basins Province. Line of section shown on figure 1. Fm., Formation. Line is about 690 km. Vertical exaggeration is roughly 50x.

Ford Lake Shale (sometimes referred to as the “Ford Lake Formation” in Geological Survey of Canada publications), up to 670 m thick, overlies the Imperial and Tuttle Formations, and it is in turn overlain by Carboniferous limestone of the Hart River Formation (Gordey, 1988). About 150 m of limestone, mudstone, chert, and fine-grained sandstone of the Triassic Shublik Formation are present above the Paleozoic rocks (Norris, 1997). Although Jurassic strata are largely absent from the province, Upper Jurassic rocks were penetrated in one well on the Anderson Plain (Elf Horton River G-02) (Dixon, 1986).

Early in Cretaceous time, a marine transgression associated with the opening of the Canada Basin to the north deposited clastic strata across the eroded Devonian rocks in the northwesternmost part of the province (Dixon, 2004a). The oldest transgressive unit, the Mount Goodenough Formation, of late Hauterivian to Barremian or Aptian age, consists of shelf mudstone. Above it are the inner shelf to nearshore sandstone and shale of the upper Barremian to Aptian Rat River Formation. The overlying Aptian to Albian Martin House Formation is the basal transgressive unit of a major sea-level highstand sequence that was deposited over much of the province in the Albian. In the west, the Martin House Formation consists of as much as 180 m (Pyle and others, 2006) of shelf siltstone, shale, and sandstone with abundant glauconite. To the east on Anderson and Horton Plains, these strata grade to equivalent rocks of the Gilmore Lake Member of the Langton Bay Formation, a fluvial sandstone unit about 60 to 180 m thick, and an overlying upper marine mudstone, the Crossley Lake Member of the Langton Bay Formation, which is about 120 to 300 m thick (Yorath and Cook, 1981). The Albian Arctic Red Formation, locally as much as several hundred meters of mostly mudstone and siltstone, and the equivalent Horton River Formation in the northeastern part of the province, which is as much as 200 m thick (Dixon, 1986), are highstand deposits representing deltaic and shelf environments (Dixon, 1986, 1999; Pyle and others, 2006). The Trevor Formation in the southwestern part of the province is also Albian in age but extends into the Cenomanian as well (Hadlari and others, 2009), and consists of as much as 800 m of north-prograding inner shelf and shoreline sandstone, derived from rising Cordilleran highlands to the south and west (Dixon, 1986, 1997). Its distal equivalent to the north is the Slater River Formation, a unit of thin-bedded dark shale about 300 to 650 m thick. Overlying sandstone, shale, conglomerate, and minor coal of the Little Bear Formation record northward progradation of marginal marine to nonmarine strata during Santonian to Campanian time, followed by a Maastrichtian marine transgression that deposited 60 to 1,000 m of shale of the East Fork Formation (Dixon, 2004b). Farther north near the Beaufort Sea, Campanian organic-rich strata of the Smoking Hills Formation, as much as 100 m thick, are overlain by about 180 m of dark shale of the Campanian to Maastrichtian Mason River Formation (Yorath and Cook, 1981). Only in the southern part of the province along the Mackenzie Mountains front does the stratigraphic section extend into the Paleogene: the Summit Creek Formation, of Maastrichtian to Paleocene age, consists of discontinuous exposures of nonmarine conglomerate, sandstone, tuff, and coal up to a few hundred meters thick (Yorath and Cook, 1981, 1984).

Phanerozoic strata are mostly only mildly deformed, gently dipping regionally southwest toward the Mackenzie and Richardson Mountains where they have been deformed by Laramide tectonism. A regional system of basement arches, the Mackenzie, Peel, and Eskimo Lakes Arches (fig. 1), underlies the western part of the province and separates the Cambrian intrashelf basin on the east from deeper water, more distal strata to the west. In the southern part of the province, a north-south trending tectonic uplift called the Keele Arch or Keele tectonic zone, active in Silurian to Devonian time, was eroded down to Proterozoic rocks in its core and then covered by Middle Devonian and younger strata. A zone of Laramide-age faults and folds in the Colville Hills consists of predominantly north-trending faulted anticlines with a possible strike-slip component, inferred to overlie reactivated Proterozoic structures (Davis and Willott, 1978; MacLean and Cook, 1992).

Petroleum Systems

Two petroleum systems were defined in the Northwest Canada Interior Basins Province. The proven Lower Paleozoic Composite Petroleum System includes strata from Cambrian to Middle Devonian, up to the top of the Hare Indian Formation, and any oil and gas accumulations within them. The principal source rock is Cambrian organic-rich algal shale, but the petroleum system also includes younger potential source units. The Upper Devonian Petroleum System is also proven in the southernmost part of the province, south of the Arctic Circle, where it consists of strata from the uppermost Middle to Upper Devonian Ramparts Formation through the Upper Devonian to lower Carboniferous Tuttle Formation and Ford Lake Shale, along with the oil and gas contained within them.

Lower Paleozoic Composite Petroleum System

Trapped gas and condensate in discovered accumulations in the Colville Hills area, along with oil stains in sandstone of the Mount Clark Formation, demonstrate the existence of a petroleum system in Cambrian strata (fig. 4). The source rocks are almost certainly alginite-rich mudstones that contain organic matter resembling *Gloeocapsomorpha prisca* present in the Cambrian Mount Clark and Mount Cap Formations (Wielens and others, 1990; Dixon and Stasiuk, 1998). Although many samples of the Mount Cap Formation yield less than 1 weight percent total organic carbon (TOC), one well (Colville D-45) penetrated a 10-cm-thick bed with 9.5 weight percent TOC and a hydrogen index (HI) of 768 (Wielens and others, 1990). The organic matter is Type I, with a hydrogen index value of 768 mg hydrocarbon per gram TOC and a Tmax value of 448 °C. Because the organic matter is Type I, which generates petroleum at higher temperatures than Types II and Type III, it is immature for oil generation in the sampled well, indicating that generation of discovered gas took place in a part of the basin that was more deeply buried (Wielens and others, 1990). Dixon and Stasiuk (1998) reported the presence of additional strata with characteristics similar to the bed described by Wielens and others (1990). Maturity increases toward the southwest, where occurrences of alginitic strata that are mature for petroleum generation have been documented (Macauley, 1987; Dixon and Stasiuk, 1998).

Other possible source rocks below the Upper Devonian part of the stratigraphic section are the organic-rich shales of the basal Bluefish Member of the Middle Devonian Hare Indian Formation, along with other shales within the Hare Indian Formation. Southwest of the province, in the Mackenzie Mountains, the Bluefish Member of the Hare Indian Formation has as much as 10 weight percent TOC and averages almost 6 weight percent (Al-Aasm and others, 1996). Shales of the Hare Indian Formation are reported to have as much as 13 weight percent TOC, although average values are typically closer to 3 weight percent (Pyle and Gal, 2009a).

Potential source rocks are marginally mature to mature in the northern and eastern parts of the province, including the Colville Hills area, where mature source strata that generated the discovered gas are inferred to be present in the deepest parts of the relatively shallow Cambrian depositional basin (Dixon and Stasiuk, 1998). Maturity levels increase toward the south and west such that the potential source rocks are mature to overmature in the southwestern part of the province. Near the southwestern boundary of the province, at the Mackenzie Mountains front, the Mount Cap Formation is in the very late oil to gas window and contains evidence of generation of light oil; organic matter is mostly pyrobitumen (Stasiuk, 2005). This area, however, probably had significantly greater burial by Cretaceous strata than in most of the province; reconstruction of thicknesses of Cretaceous and Tertiary rocks by Dixon (2004b) indicates that more than 1 km of Cretaceous and Tertiary strata were deposited near the Mackenzie Mountains front, whereas only 250 to 500 m were apparently deposited over parts of the province farther north and east.

The timing of maturation is poorly constrained because of uncertainties in upper Paleozoic and lower Mesozoic burial history. Source rocks were buried by Upper Devonian to lower Carboniferous strata (Imperial and Tuttle Formations and Ford Lake Shale) of the clastic wedge shed from Caledonian and Ellesmerian uplifts to the north and east, but the depth of burial is unknown. Upper Devonian strata in the western part of the province have preserved thicknesses of more than 1.5 km (Gilbert, 1973). On the basis of chemical signatures in Mesozoic strata in the Sverdrup Basin to the north, which had a predominantly southerly provenance, Patchett and others (2004) estimated

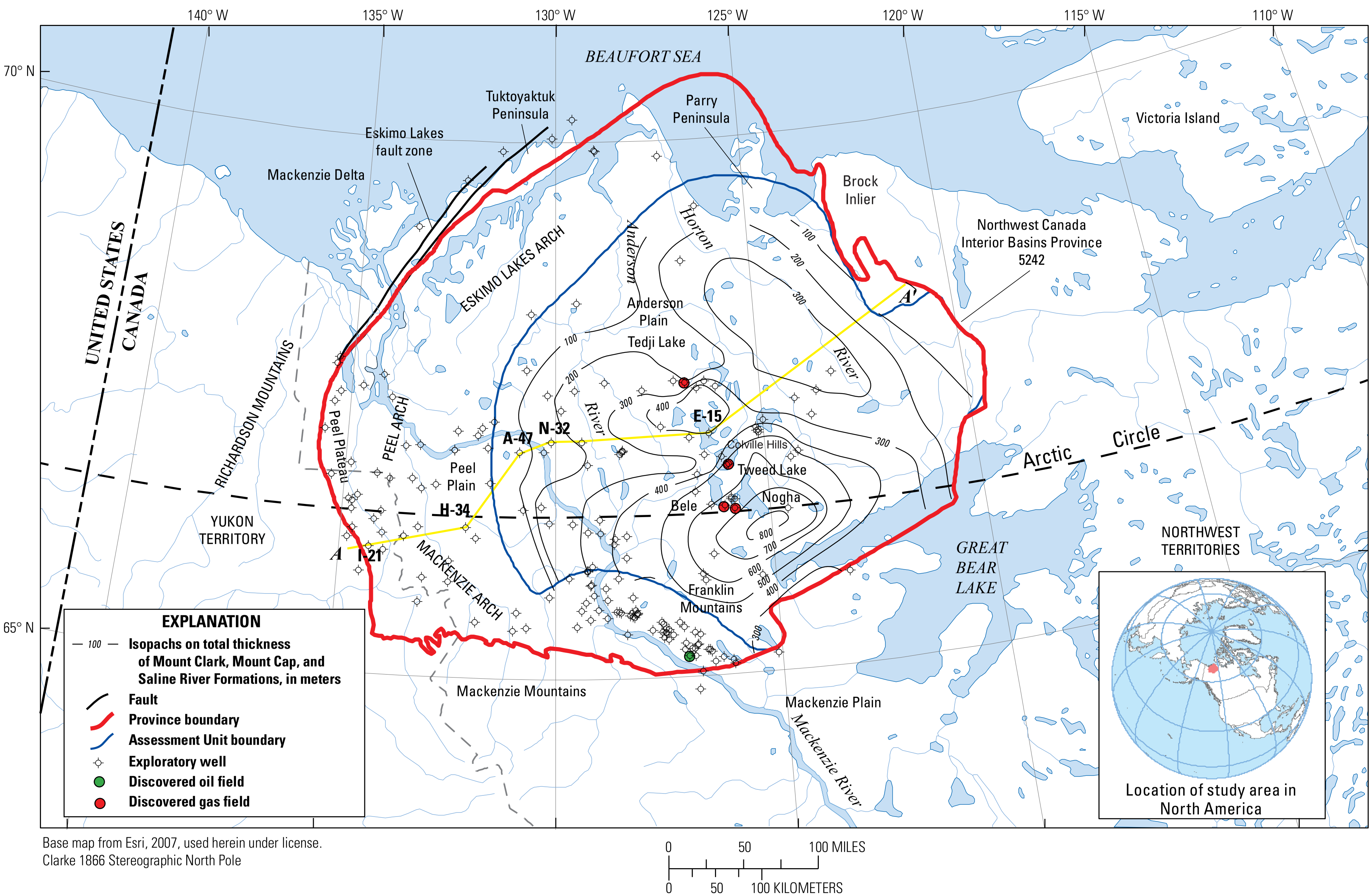


Figure 4. Map of Lower Paleozoic Composite Petroleum System, Arctic Canada. Isopachs showing total thickness of Mount Clark, Mount Cap, and Saline River Formations from Dixon and Stasiuk (1998), in meters.

that more than 2 km of Upper Devonian strata may have been deposited across the northern part of the Northern Interior Basins Province, thining southward. Ault and others (2009) concluded from apatite (U-Th)/He thermochronometry that Precambrian rocks exposed east of the province, just east of Great Bear Lake, were buried by 3 to 4 km of Devonian to Permian strata. There is a marked discontinuity in levels of organic maturity across the unconformity separating Devonian and Cretaceous strata in the western part of the province, which is interpreted as indicating that some 0.7 to 4.7 km of strata were eroded (Link and Bustin, 1989). Thus at least 1 km of section, and possibly significantly more, was probably eroded from the region between Carboniferous and Cretaceous time.

Modeling for this study, using commercial Petromod software, was based on stratigraphic and maturity data (Feinstein and others, 1988; Pyle and others, 2006) for the Atlantic Et Al Ontaratue H-34 well in the west-central part of the province (fig. 4). We assumed deposition of about 2.6 km of the Upper Devonian Imperial Formation, followed by erosion of the upper 2 km between Carboniferous and Early Cretaceous time (fig. 5). This thickness was required in order to match reported vitrinite reflectance data from strata penetrated in the well, using heat-flow values typical of passive margins and foreland basins for most of Phanerozoic time, but with higher heat flow during Late Jurassic and Cretaceous time when rifting and seafloor spreading developed in the Canada Basin to the north. Deposition of about 1,200 m of middle Cretaceous strata (Dixon 1999; 2004b) followed by about 900 m of erosion since 90 Ma was also assumed, as required to match maturity indicators (vitrinite reflectance and pyrolysis) in the Cretaceous rocks. According to the model, generation of oil from organic matter in the Mount Cap Formation began in Late Devonian time, and transformation of organic matter to petroleum was complete by the end of the Devonian. This timing agrees with that inferred by Link and Bustin (1989) and Gal and others (2009a), although it differs from that suggested by Issler and others (2005), who concluded that maturation was Middle Triassic to Early Jurassic in the Fort Norman area south of the province. The modeled well, however, is significantly west of the Colville Hills area, which lay toward the landward edge of the lower Paleozoic shelf and probably was not buried as deeply. This is consistent with the marginal maturity of the organic matter in the Colville Hills area (Dixon and Stasiuk, 1998).

Accordingly, generation of oil from potential source rocks in this petroleum system probably took place during Late Devonian to Carboniferous time (Pyle and Gal, 2009b), and was followed by erosion between late Paleozoic and Early Cretaceous time. Subsequent middle Cretaceous reburial may have increased maturity levels in the western part of the province where Cretaceous strata were thicker. Structural traps for discovered accumulations in the Colville Hills area are of apparent Late Cretaceous to Paleogene age, suggesting that remigration of earlier generated petroleum is likely to have contributed to trap filling. Organic matter that remained after Paleozoic petroleum generation would have generated gas, potentially expelling trapped oil, and trapped oil also may have been cracked to gas (Pyle and Gal, 2009b).

Petroleum generated from alginite source rocks in the Mount Cap Formation evidently migrated along interbedded and underlying Mount Clark Formation sandstones from deeper parts of the depositional basin into Mount Clark Formation traps in shallower parts of the basin. Halite of the Cambrian Saline River Formation and shale within the Mount Cap and Saline River Formations are seals. Mount Cap Formation-derived oil or gas might also have migrated upsection into Ordovician and younger carbonate strata in areas where evaporites are absent or where faults have broken the evaporite seal. Any oil or gas generated from the Bluefish Member of the Hare Indian Formation is most likely to have migrated into underlying limestones in the Hume Formation, as the Hare Indian Formation is predominantly shaly and would likely have blocked upward migration.

A variety of reservoirs and trap types is possible. Discovered accumulations reside in structural traps, which consist of faulted anticlines of Laramide age in the Colville Hills area. Stratigraphic traps are also likely to be present and could include pinchouts of the Cambrian Mount Clark Formation sandstone against Precambrian strata, sealed by shale of the Mount Cap Formation or halite of the Saline River Formation, and oolitic zones, buildups, or fractured or brecciated zones in Cambrian through Middle Devonian carbonate bank strata.

Upper Devonian Petroleum System

Organic-rich shale of the Upper Devonian Canol Formation is the documented source of oil at Norman Wells field in the southernmost part of the province (Snowdon and others, 1987) and is the presumed principal source rock for a petroleum system in the western part of the province (fig. 6). The Canol Formation is generally less than about 100 m thick (Pyle and Gal, 2009a), with TOC values typically ranging from about 2 to 6 weight percent in wells north of the Arctic Circle, with some values almost as high as 9 weight percent; organic matter is predominantly Type II (Snowdon and others, 1987; Link and others, 1989). Organic-rich shales interbedded in the Imperial Formation are also potential source rocks. They have lower TOC than the Canol Formation, mostly ranging between 0.5 and 1.0 weight percent, although they can range up to about 7 weight percent; TOC content increases somewhat toward the west (Pyle and others, 2008; Gal and others, 2009b). Organic matter is predominantly Type III and is thus most likely to have generated only gas.

The Canol Formation is largely absent east of about long 129° to 130° W. in the province owing to erosion. Where present, its organic matter is immature in the east and increases in maturity toward the south and west, approaching maturity near the Mackenzie River. Toward the western boundary of the province, in the area of western Peel Plain and Peel Plateau, organic matter in the Canol Formation is overmature for oil generation (Stasiuk and Fowler, 2002), but in a number of wells, the top of the oil window lies within the Imperial Formation, as indicated by vitrinite reflectance and Rock-Eval data tabulated by Pyle and others (2008).

Generation probably took place in Late Devonian to early Carboniferous time as a result of burial by the Devonian

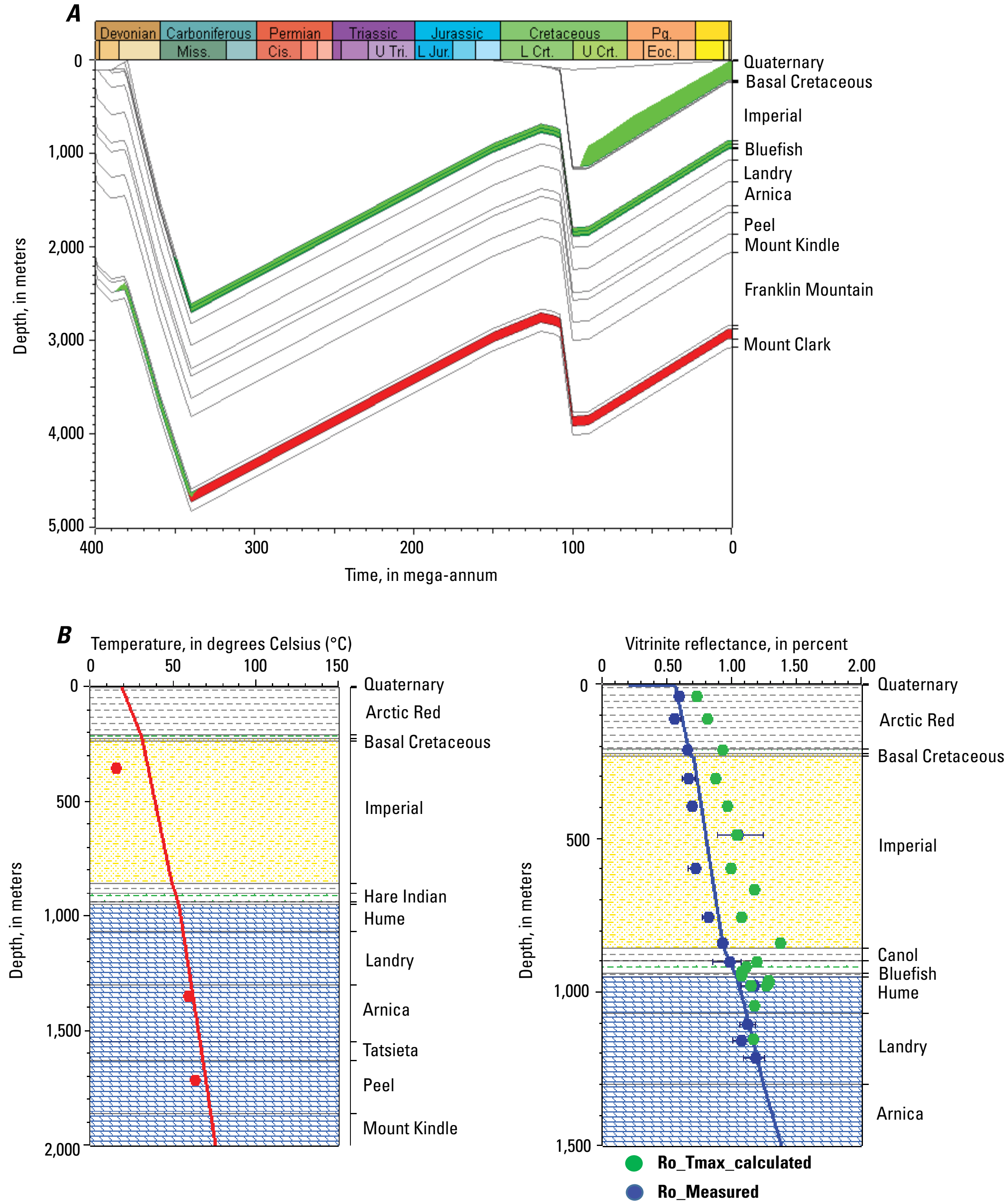


Figure 5. Maturation of petroleum source rocks in Atlantic et al. Ontaratue H-34 well. Well location shown as H-34 on Figure 4 . *A*, Petroleum generation model, produced by commercial Basinmod modeling software. Formation tops from Janicki (2005). Potential source rock units (shown in green [mature for oil generation] and red [mature for gas generation]) include the Cambrian Mount Cap Formation (immediately above the Mount Clark Formation), the Devonian Bluefish Formation and the immediately overlying Hare Indian and Canol Formations, and the Cretaceous Arctic Red Formation. According to the model, Cambrian source rocks generated oil from late Devonian time until maximum burial in Mississippian time, when gas generation began. Devonian source rocks began generating oil near the end of Devonian time. Vitrinite reflectance (Ro) and Tmax values in Cretaceous source rocks at shallow present-day burial depths indicate that they are mature for oil generation, suggesting that oil was generated but that a significant thickness of younger strata (modeled in this case as about 900 m) has been removed by subsequent erosion. Miss., Mississippian; Cis., Cisnerian; U Tri., Upper Triassic; L Jur., Lower Jurassic; L Crt., Lower Cretaceous; U Crt., Upper Cretaceous; Pg., Paleogene; Eoc., Eocene. *B*, Calibration diagram showing plot of temperature versus depth. Red dots show measured temperatures and red line shows temperature profile predicted by the model. Temperature measurements from Atlantic et al. Ontaratue H- 34 well history report. *C*, Calibration diagram showing plot of vitrinite reflectance versus depth. Blue dots show measured vitrinite reflectance values and green dots show Tmax values converted to equivalent vitrinite reflectance values; blue line shows maturity profile predicted by the model. Vitrinite reflectance and Tmax values from Feinstein and others (1988). Formation names shown at right of diagrams.

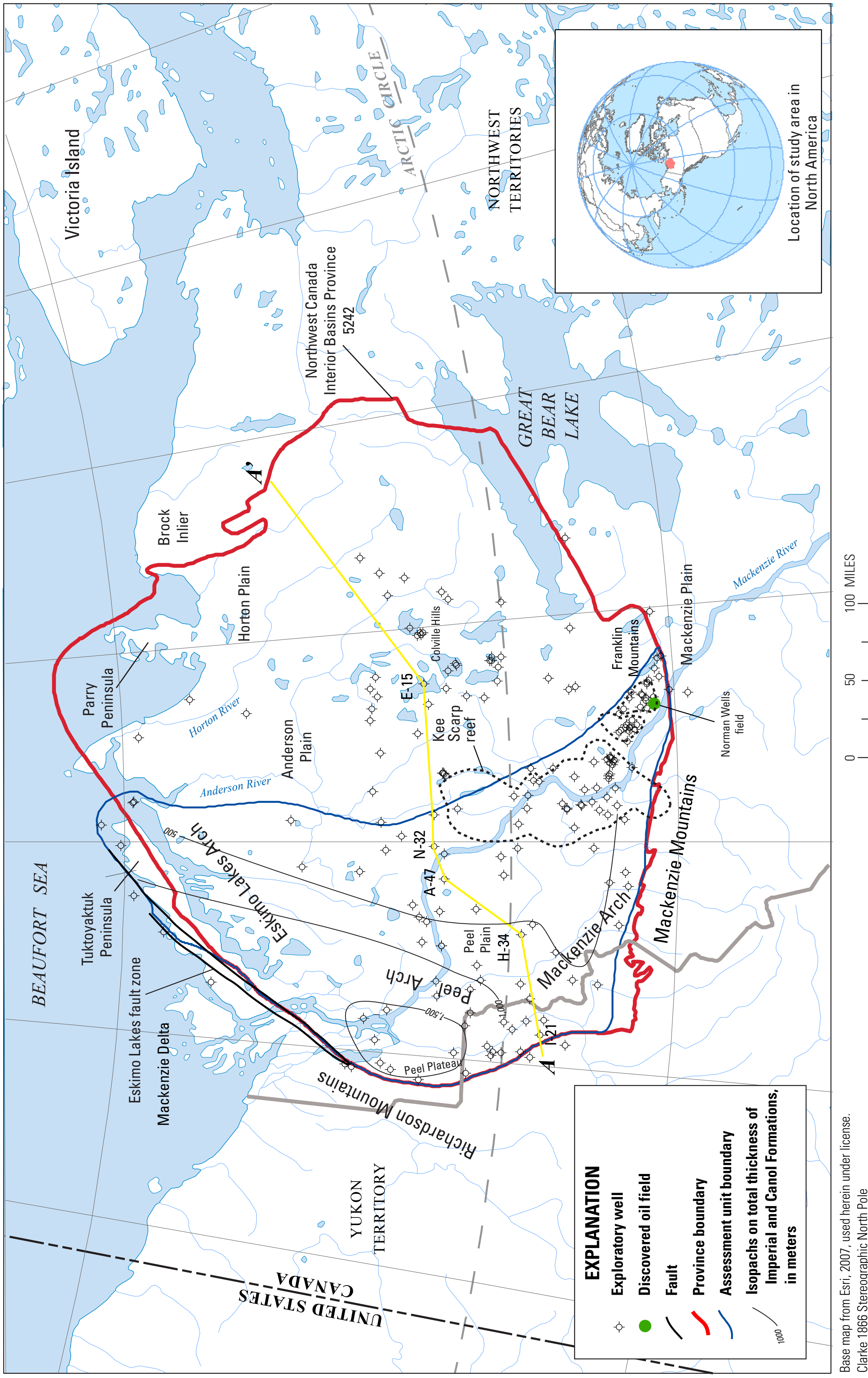


Figure 6. Map of Devonian Petroleum System, Arctic Canada. Isopachs showing total thickness of Canol and Imperial Formations, in meters. Outline of reef facies of Kee Scarp Member of Ramparts Formation from Gilbert (1973).

clastic wedge, as described in the discussion above of model results for the Ontaratue H-34 well. Generation of oil from organic matter in the Canol Formation, according to our model, began in latest Devonian time and continued into early Carboniferous time, resulting in 85 percent transformation of organic matter by about 350 Ma. Modeled additional Cretaceous deposition did not cause further generation.

A recent modeling study by Gal and others (2009a), using different modeling software (Basinmod) and a significantly greater assumed thickness of subsequently eroded Cretaceous strata, concluded that oil generation from Devonian source rocks was Cretaceous in age. Gal and others (2009a) did not model the same well modeled in this study; instead, they modeled several wells slightly farther west, in the Peel Plain. They assumed only about 700 to 900 m of the Devonian Imperial Formation was deposited and subsequently eroded, substantially less than the 2 km assumed in the Ontaratue H-34 well modeled for this study. In contrast, they assumed deposition of 2.6 to 3.5 km of Albian through Upper Cretaceous strata, followed by erosion of all or almost all of the assumed thick Cretaceous strata, beginning in latest Cretaceous or Paleogene time. Accordingly, they concluded that peak generation of oil took place mainly in Late Cretaceous time. The assumed original depositional Cretaceous thickness of 2.6 to 3.5 km, however, is significantly greater than the 250 to 500 m of Albian to Cretaceous strata estimated by Dixon (2004b) in the area of the Ontaratue H-34 well that we modeled.

Petroleum generated from shale of the Canol Formation is known to have migrated laterally and down section into reef limestones of the Kee Scarp Member of the Ramparts Formation at Norman Wells field (Snowdon and others, 1987). It could have also migrated into a sandstone member of the Ramparts Formation correlative with the Key Scarp Member, the Charrue sandstone of Williams (1986b), or upward into sandstone reservoirs in the Imperial Formation.

Several potential reservoirs exist. The Kee Scarp Member of the Ramparts Formation, the reservoir for the Norman Wells field, consists of various reef facies; at Norman Wells field the Kee Scarp Member is a 150-m-thick stromatoporoid reef with associated lagoon, reef flat sand, reef margin, and fore-slope facies; porosity is as much as 24 percent, but permeability is low, generally 2 to 4 millidarcies (mD) (Kempthorne and Irish, 1981; Al-Aasm and Azmy, 1996; Yose and others, 2001). Similar reefal buildups in the southern part of the province have been tested and proven dry, and the trend of reef buildups is missing by erosion northward (Gilbert, 1973; Williams, 1986a,b). Nevertheless, it is possible that reservoirs similar to Norman Wells field remain to be found. The Charrue sandstone of Williams (1986b), a Kee Scarp Member facies present in the area north and west of Norman Wells field, has reported porosity of as much as 14.9 percent in the Richfield Oil Corporation et al. Grandview Hills No. 1 (also known as A-47) well (Gal and others, 2009c) and is a potential reservoir. Sandstone reservoirs in the Imperial and Tuttle Formations may also be present (Gal and others, 2009b), especially in sandstones near the base of the Imperial Formation that could be charged by Canol Formation source rocks.

Assessment Unit Descriptions

Lower Paleozoic Subsalt and Carbonate Platform (52420201)

Exploration Maturity.—Four nonproducing gas accumulations have been discovered, none of which exceeds 300 BCFG.

Boundaries.—This assessment unit (AU) has an area of 165,000 km^2 and is bounded by the approximate limit of the Cambrian Mount Clark, Mount Cap, and Saline River Formations in the subsurface. The northern margin roughly tracks the northern limit of Lower Cambrian strata, known from exploration wells, as shown by Dixon and Stasiuk (1998). On the east, the boundary follows the outcropping contact of Cambrian strata lying unconformably on Proterozoic rocks of the Shaler Supergroup. On the south, it trends along a high that separates the main basin from an adjoining subbasin to the south and along the structural front of the Mackenzie Mountains, where lower Paleozoic strata crop out in folded and faulted Laramide uplifts. The uncertain western boundary lies along the eastern flank of a series of early Paleozoic paleo highs (Mackenzie, Peel, and Eskimo Lakes Arches; fig. 1) that roughly align with the subsurface limit of known miogeoclinal Cambrian strata penetrated in wells. The boundary lies near the Cambrian to Devonian shelf margin facies change from platform strata on the east to basinal sediments of the Road River Group to the west. The AU includes strata from the base of the Paleozoic to the top of the Middle Devonian Hare Indian Formation; overlying strata in the western part of the province were included in the Devonian Reefs and Clastic Wedge AU.

Geologic Analysis of Assessment Unit Probability

Charge.—(0.9) Various sizes have been reported for four gas discoveries in the Colville Hills and it is not certain whether any of the gas discoveries meet the minimum size criterion of 50 million barrels of oil equivalent (MMBOE) required to consider the AU as proven for the purposes of this assessment. As reported by IHS Energy (2007), they are all smaller than 300 BCFG. Other volume estimates range widely. Bele, discovered in 1986, was reported as 82 BCFG by Janicki (2004), 77 BCFG by the National Energy Board (cited by Janicki, 2004), and 169 BCFG by Drummond (2009). Tedji Lake, discovered in 1974, was reported as 31 BCFG by Janicki, 16 BCFG by the National Energy Board (cited by Janicki, 2004), and 52 BCFG by Drummond (2009). Tweed Lake, discovered in 1969, was reported as 112 BCFG by Bever and McIlreath (1992), 122 BCFG by Janicki (2004), 86 BCFG by the National Energy Board (cited by Janicki, 2004), and 355 BCFG by Drummond (2009). Nogha, originally discovered in 1969, but recently delineated with additional drilling, is reported as 257 BCFG by Drummond (2009). These volumes indicate that a petroleum system capable of charging an accumulation of at least 300 BCFG is likely to exist. Oil stains in sandstone of the Mount Clark Formation (Dixon and Stasiuk, 1998) also demonstrate that oil was generated in this petroleum system and so oil accumulations may also be possible. Known source strata are alginite-rich mudstones of the Cambrian Mount Clark and Mount Cap Formations, and potential source rocks include organic-rich mudstones of the Middle Devonian Hare Indian Formation, particularly the Bluefish Member at the base of the formation. Potential Cambrian source rocks are marginally mature to mature in the northern and eastern part of the province, including in the Colville Hills area where mature source strata are inferred to be present in the deepest parts of the relatively shallow Cambrian depositional basin (Dixon and Stasiuk, 1998). Maturity increases toward the southwest, where occurrences of alginitic strata mature enough for petroleum generation have been documented (Macauley, 1987; Dixon and Stasiuk, 1998). Source rocks probably experienced adequate burial for generation by Upper Devonian to lower Carboniferous strata. Burial by Cretaceous strata (Aptian and younger), now partially eroded, may have provided the additional thermal exposure needed to generate petroleum or to crack oil to gas, especially in the western part of the AU.

Rocks.—(0.6) Although transgressive sandstone of the Lower Cambrian Mount Clark Formation is a proven reservoir within this AU, it is quite thin, with pay thicknesses of only a few meters (7.5 m at Bele, 4 m at Tedji Lake, and about 10 m at Tweed Lake, according to Janicki [2004]). Porosity ranges up to 14 percent in discovered accumulations (Janicki, 2004), although it is as high as 24 percent in some cores from wells in the Colville Hills area (Pyle and Gal, 2009b). Permeability varies between 8 mD in the Tweed Lake gas accumulation (Kolisnik and others, 2003) and 112 mD in other discovered accumulations (Janicki, 2004; Pyle and Gal, 2009b). The modest reservoir thicknesses combined with generally poor reservoir properties lend significant doubt as to whether accumulations larger than 50 MMBOE are present. Other possible reservoirs in this AU are various Upper Cambrian, Ordovician, Silurian, and Lower to Middle Devonian carbonate platform units, notably the Bear Rock Formation brecciated dolomite (equivalent to the Arnica Formation) and possibly fractured cherts interbedded in the carbonate succession. Reservoir quality in the carbonate platform units, however, is considered unlikely to be adequate for an accumulation greater than 50 MMBOE, because of generally poor porosity and permeability as well as the marginal likelihood of effective migration pathways from the principal potential source rocks to the carbonate platform strata.

Discovered accumulations occupy structural traps formed in Late Cretaceous and Paleogene time during Laramide tectonism. These traps have been interpreted as reactivated Proterozoic features (Cook and MacLean, 2004). Stratigraphic traps are likely to be present as well, including updip pinchouts against basement highs and facies transitions.

Evaporite and mudstone of the Saline River Formation and dolomitic shales of the Mount Cap Formation seal accumulations in the Lower Cambrian section. Tight zones and interbedded shales in the Ordovician to Lower Devonian carbonate platform succession would be potential seals for accumulations in those strata.

Timing and Preservation.—(0.6) Time of maturation of source rocks was probably Late Devonian to early Carboniferous, during burial by the Upper Devonian clastic wedge. Subsequent Cretaceous reburial, following erosion during late Paleozoic to Mesozoic time, may have slightly increased maturity levels, especially in the southwestern part of the province where Cretaceous strata were thicker. Any organic matter that remained after Paleozoic petroleum generation would likely have generated gas, potentially expelling oil from traps. Trapped oil also would probably have been cracked to gas (Pyle and Gal, 2009b). Structural traps are of apparent Late Cretaceous to Paleogene age, indicating that remigration of earlier generated petroleum probably occurred, and that there is a substantial risk of petroleum loss during remigration.

Extensive erosion, poorly dated between Carboniferous and Early Cretaceous time, also puts most accumulations generated by Devonian burial at high risk for loss. If petroleum was generated during Devonian burial, accumulations higher in the stratigraphic section, particularly in Silurian to Devonian carbonate strata, may have been breached during erosion, leaving only small amounts of late-generated gas to be trapped in Laramide structures. Bitumen in the Colville D-45 well suggests that an oil accumulation was lost there (Dixon and Stasiuk, 1998). The numerous seeps and bitumen deposits in the region may represent remnants of oil accumulations rather than evidence of a presently active petroleum system.

Analogs used in this assessment

Numbers of Fields.—The analogs chosen to assess this AU were depositional systems on rifted passive margins and carbonate shelves and structural settings including craton-interior and passive-margin basins. The median field densities for these types of settings range from about 0.06 to 0.19 accumulations per square kilometer, suggesting about 10 to 30 fields as the median for the distribution when multiplied by the area of the AU, about 165,000 km^2. Because the level of exploration in this AU is relatively high, however, even 10 undiscovered accumulations larger than 50 MMBOE seemed unlikely, and 10 undiscovered accumulations was instead taken as the maximum for the distribution. The median for the distribution of numbers of undiscovered accumulations was estimated to be two, again because the results of exploration to date have not been encouraging.

Sizes of Fields.—Although median sizes for analogous AUs in the analog database are typically slightly over 100 MMBOE, the median size in this AU is likely to be somewhat smaller because of the modest size of discoveries made to date, and so median sizes of 70 MMBO and 420 BCFG were chosen. The maximum field size was similarly considered to be significantly smaller than those in similar settings in the analog database, and so 200 MMBO and 1,200 BCFG were chosen as the maximum possible field sizes, yielding 78 MMBO as the expected mean for the largest oil field and 504 BCFG as the expected mean for the largest gas field.

Proportions of Oil and Gas Fields.—Because only gas accumulations have been discovered, gas accumulations were estimated to compose 70 percent of the undiscovered population at the mode, ranging from 30 to 100 percent of the undiscovered population.

Ancillary Properties and Coproduct ratios.—Global averages from the analog database were used for ancillary properties and coproduct ratios.

A Monte Carlo simulation using the input data described above resulted in estimates of undiscovered oil volume ranging from 0 to 117 MMBO, with a mean of 23 MMBO, and gas volume ranging from 0 to 1,364 BCFG, with a mean of 310 BCFG (table 1).

Devonian Reefs and Clastic Wedge (52420101)

Exploration Maturity.—One oil accumulation greater than the minimum size has been discovered: Norman Wells field (south of the Arctic Circle; 250 MMBO).

Boundaries.—The AU has an extent of 124,000 km^2. Its boundaries are defined by the presence of upper Middle to Upper Devonian strata. The northern margin approximately tracks the northern limit of Upper Devonian strata known from exploration wells. On the east, the boundary follows the eroded eastern edge of the Imperial and Canol Formations. On the south and west, it trends along the structural front of the Mackenzie and Richardson Mountains. The northwestern boundary follows the subsurface extent of known Upper Devonian strata penetrated in wells and is roughly parallel to the Eskimo Lakes fault zone.

Stratigraphically, the AU extends from the base of the Canol Formation to the unconformity or erosional surface at the top of the Upper Devonian to lower Carboniferous Imperial or Tuttle Formations or Ford Lake Shale.

Geologic Analysis of Assessment Unit Probability

Charge.—(0.9) Shale of the Upper Devonian Canol Formation, the documented source of oil at Norman Wells field in the southernmost part of the province (Snowdon and others, 1987), probably generated oil widely throughout the AU during burial by the Imperial and Tuttle Formations, and perhaps by the now-eroded upper Paleozoic and Mesozoic strata. Additional generation from Cretaceous burial may also have taken place in the southwestern part of the province. Numerous shows, bitumen occurrences, and instances of oil staining (Osadetz and others, 2005; Pyle and Gal, 2009a) suggest that an active petroleum system was once widely present in Devonian strata. Organic-rich shales interbedded in the Imperial Formation are also potential source rocks.

Rocks.—(0.5) Kee Scarp-type reef limestones of the Ramparts Formation and pinnacle reefs on the drowned Hare Indian platform are the most promising reservoirs, but their existence north of the Arctic Circle is uncertain. Sandstones of the Imperial and Tuttle Formations are also potential reservoirs, although no discoveries have been made in them, and their reservoir properties are not particularly good (for instance about 5 to 15 percent porosity, but only 1 mD permeability in the Imperial Formation [Gal and others, 2009b]). Stratigraphic traps, such as the Kee Scarp reef at Norman Wells field, are the only type likely to be present, because structural traps did not form until the Late

Table 1. Summary of assessment results, lower Paleozoic subsalt and carbonate platform, assessment unit 52420201.

[MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids; Probability, probability of at least one accumulation equal to or greater than 50 million barrels of oil equivalent. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated and so on for F50 and F5. Fractiles are additive under the assumption of perfect positive correlation. N/A, not applicable]

Accumulation type	Probability (0–1)	Undiscovered resources											
		Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Oil	0.28	0.00	0.00	147.69	29.56	0.00	0.00	304.13	53.89	0.00	0.00	12.67	2.25
Gas	0.32	N/A	N/A	N/A	N/A	0.00	0.00	1,423.53	332.82	0.00	0.00	74.93	17.05
Total	0.32	0.00	0.00	147.69	29.56	0.00	0.00	1,727.67	386.70	0.00	0.00	87.60	19.30

Accumulation type	Probability (0–1)	Largest undiscovered accumulation (MMBO or BCFG)			
		F95	F50	F5	Mean
Oil	0.28	57.67	73.01	114.14	77.74
Gas	0.32	366.90	476.66	739.27	504.41

Cretaceous, too late to trap oil or gas generated during middle Paleozoic burial. Laramide-age traps, however, could have trapped oil or gas that was remigrated out of stratigraphic traps during deformation. Seals within the Imperial and Tuttle Formations are most likely to be interbedded shales.

Timing and Preservation.—(0.2) Time of maturation of source rocks is poorly constrained between Late Devonian and middle Cretaceous time. Modeling suggests oil generation by early Carboniferous time, assuming 2.5 km of Late Devonian burial. Extensive erosion between the Devonian and the Early Cretaceous (Aptian), however, puts most accumulations generated by Devonian burial at high risk of not being preserved, especially in the upper part of the sequence where both the Kee Scarp Member and potential reservoirs in the Imperial Formation lie. If petroleum was generated during Devonian burial, stratigraphically higher accumulations may have been breached during erosion between late Paleozoic and Cretaceous time, leaving only relatively small amounts of late-generated gas to be trapped in Laramide structures. The numerous seeps and bitumen deposits in the region probably represent the remnants of oil accumulations that were lost to erosion, either between the Carboniferous and the Early Cretaceous, or during and following Laramide deformation. Accordingly, this AU was considered to have very little chance of holding a surviving accumulation larger than 50 MMBOE.

The assigned probabilities result in an overall AU probability of 0.10. Because a probability greater than 0.10 was required for quantitative assessment, no quantitative assessment was made.

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Appendixes

Appendixes are available online only, and may be accessed at https://doi.org/10.3133/pp1824G.

Appendix 1. Input Data for the Lower Paleozoic Subsalt and Carbonate Platform Assessment Unit.

Appendix 2. Input Data for the Devonian Reefs and Clastic Wedge Assessment Unit.

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