GEOLOGICAL SURVEY OF CANADA

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A Guide to the Hydrocarbon Potential of the Northern Mainland of Canada

J. Dixon[1], D.W. Morrow[1], and B.C. MacLean[1]

2007

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INTRODUCTION

The northern mainland area that has petroleum potential consists of the northern Yukon and most of the Northwest Territories (NWT) west of the Shield. The Phanerozoic succession is divisible into two principle terrain types, the undeformed to mildly deformed platform underlying the plains area of the NWT and the fold and thrust belt of the Cordillera in the western part of NWT and underlying most of the Yukon (Fig. 1). Underlying the Phanerozoic rocks throughout most of the area is a thick, highly deformed, Proterozoic sedimentary to metasedimentary succession. In the southern part of the interior plains area, metamorphic and igneous rocks of the Precambrian basement underlie the Phanerozoic in the east, with sedimentary and metasedimentary rocks to the west. The Phanerozoic succession overlies the Precambrian with a profound unconformity everywhere, except in a few areas within the Mackenzie Mountains.

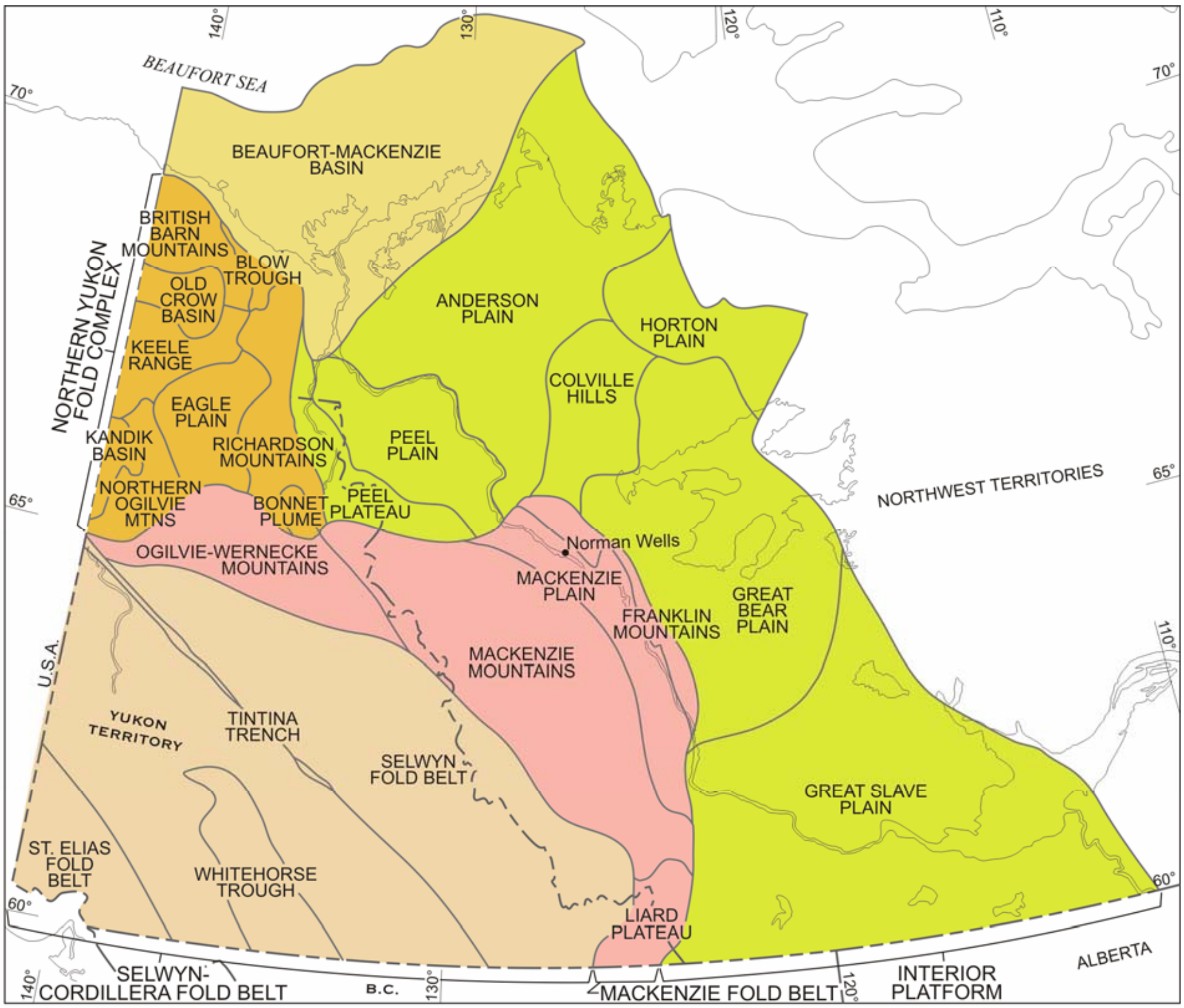

Figure 1. Physiographic and geologic elements, Northwest Territories and northern Yukon.

The northern mainland is divided into five geological provinces and the petroleum potential of each will be discussed separately (Fig. 1). The subdivisions include:

Interior Platform
Beaufort-Mackenzie Basin
Northern Yukon Fold Complex
Mackenzie Fold Belt
Selwyn-Cordillera Fold Belt

Within this area the most significant discoveries are in the Beaufort-Mackenzie Basin, the large gas fields in the Liard Plateau of Mackenzie Fold Belt, the Norman Wells oil field in Mackenzie Plain, plus lesser discoveries in folded strata of Mackenzie Plain, the Colville Hills of the Interior Platform, and in Eagle Plain within the Northern Yukon Fold Complex.

INTERIOR PLATFORM

Geology..............................	Proterozoic sedimentary rocks, Cambrian to Upper Devonian and Cretaceous to Lower Tertiary strata
Proven source rocks...........	Algal-rich shale in the Cambrian Mount Clark-Mount Cap transition. Devonian Canol Formation (calcareous shale) and Bluefish Member of the Hare Indian Formation, and Upper Cretaceous Slater River Formation (shale)
Reservoir rocks....................	Cambrian sandstones, lower Paleozoic carbonates, Middle Devonian reefs, Cretaceous sandstones
Discoveries.........................	Gas in Cambrian sandstone, oil in Lower/Middle Devonian carbonates, gas in Cretaceous sandstone.
Hydrocarbon potential.........	Low to moderate

Introduction

The Interior Platform underlies the plains area of the NWT, and includes only a small part of the eastern Yukon, i.e., northern parts of Great Slave Plain, Great Bear Plain, Anderson Plain, Horton Plain, Colville Hills, Peel Plain, and Peel Plateau.

Geological Setting

Cambrian to Upper Devonian strata underlie most of the Interior Platform, with a thin veneer of Albian rocks throughout much of the area and locally preserved Upper Cretaceous and Lower Tertiary rocks (Fig. 2). Underlying the Phanerozoic is a very thick succession of deformed Proterozoic sedimentary and low-grade metasedimentary rocks. South of Bulmer Lake, in southern Great Bear Plain and northern Great Slave Plain, igneous and metamorphic rocks of the Precambrian Basement underlie Phanerozoic strata with metasediments and sedimentary rocks west of longitude120° 30’W.

Proterozoic sedimentary strata are 13-16 km thick and are known principally from reflection seismic; only a few wells have penetrated these rocks. A seismic stratigraphy has been identified and correlations to outcrops of the Proterozoic in the Coppermine area and Mackenzie Mountains has been attempted by Cook and MacLean (2004).

The Cambrian succession generally is characterized by a basal transgressive sandstone (Mount Clark/Old Fort Island formation) gradationally overlain by interbedded shale, sandstone and thin carbonates of the Mount Cap Formation. These, in turn, are unconformably overlain by the Saline River Formation, a succession of interbedded shale, carbonate and evaporites (anhydrite and halite). The Cambrian sandstones appear not to extend across Peel Plain and are absent under most of Great Slave Plain (Dixon and Stasiuk, 1998). Gradationally succeeding the Saline River Formation is a thick succession of platform carbonates, dominated by dolostone, that extend from the Upper Cambrian to the Middle Devonian and which contain a number of regionally extensive unconformities. In the western Peel Plain and Plateau the carbonates pass laterally into basinal shale of the Road River Group. Most of the carbonates are dolostone, with some developments of anhydrite in the Devonian Bear Rock Formation. In parts of the Middle Devonian succession shale and limestone deposits formed (Arnica Formation, Hare Indian Formation, Hume Formation, and Ramparts Formation). Carbonate deposition ended in the late Middle Devonian with the widespread deposition of the Canol shale, followed by deposition of syntectonic clastics of the Imperial Formation.

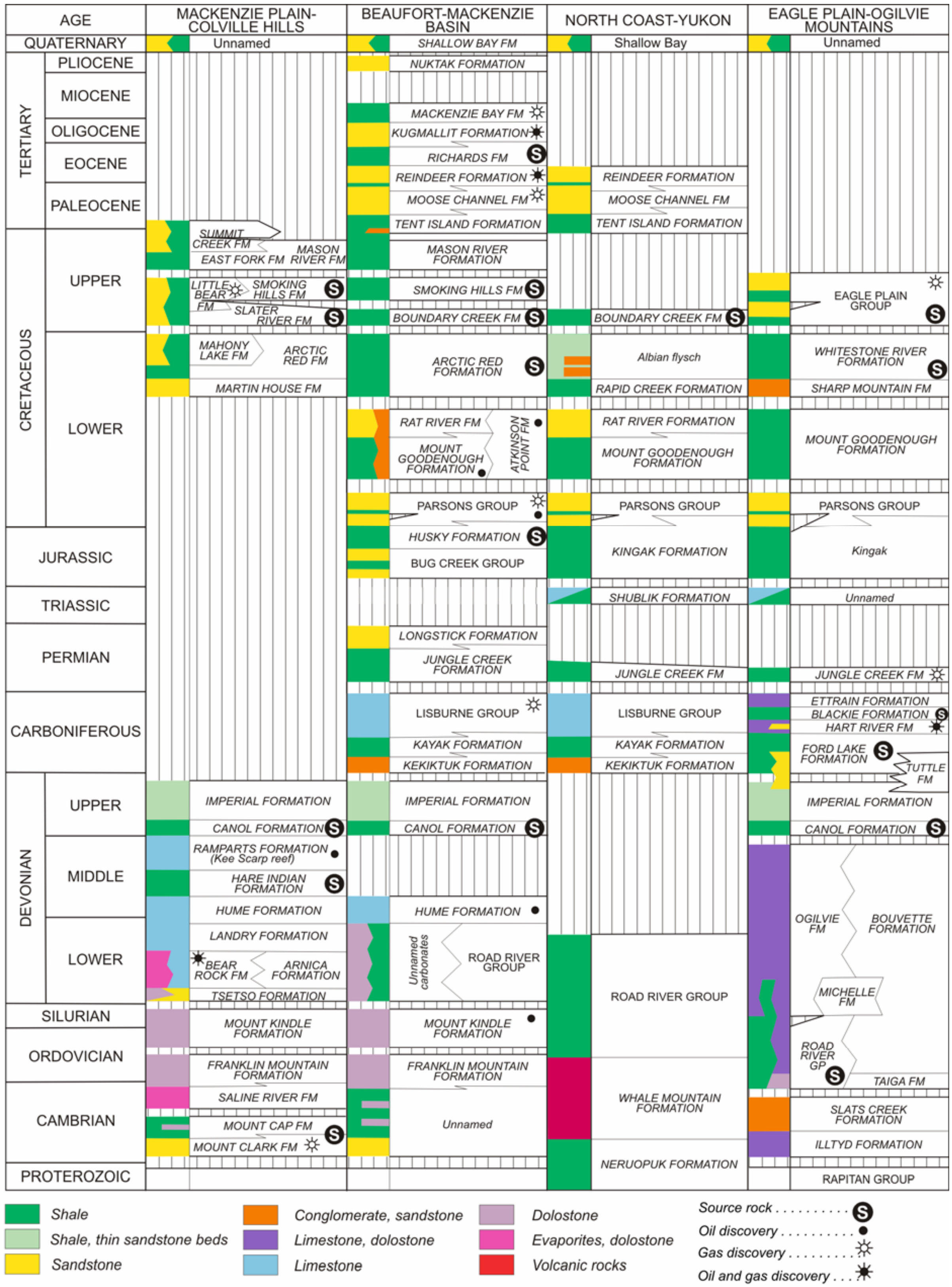

Figure 2: Correlation chart of Phanerozoic strata in the northern mainland.

Carboniferous to earliest Cretaceous strata are absent from most of the Interior Platform, with some Carboniferous possibly preserved in the westernmost part of Peel Plateau and Peel Plain. Albian strata rest unconformably on Paleozoic rocks throughout the area. The Albian is a shale-dominant succession (Arctic Red Formation) with an extensive, thin basal sandstone (Martin House Formation). Upper Cretaceous strata are preserved in Anderson Plain (Mason River Formation -shale), the Peel Plateau (Trevor Formation - interbedded sandstone and shale, and Boundary Creek Formation - organic-rich shale), and some thin Pliocene beds on Anderson Plain (Iperk Sequence - sand and gravel).

Proterozoic strata are folded and thrust faulted but the overlying Phanerozoic is generally only mildly deformed into very broad, open synclines and anticlines, with the overall succession dipping and thickening to the west and southwest (Fig. 3). Some minor normal faults are present throughout the area. In the Colville Hills, Phanerozoic rocks are more intensely deformed. Here, Early Tertiary deformation has created a number of tight, thrust faulted anticlines (Cook and Aitken, 1971, 1973), which in Colville Hills are underlain by large Proterozoic structures (Maclean and Cook, 1992). Others have interpreted the Colville Hills structures as strike-slip features (Davies and Willott, 1978). The same deformation extends into Peel Plateau, where thrust faulted anticlines extend into Albian and Upper Cretaceous strata.

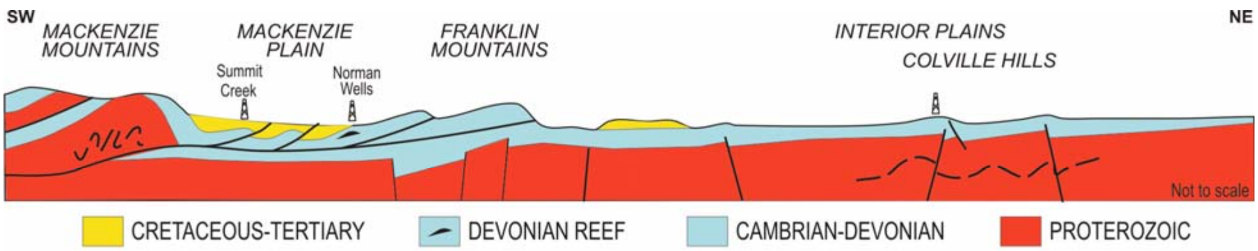

Figure 3. Schematic geologic cross section through Mackenzie Plain to the Colville Hills (no scale). Cambrian graben under the Franklin Mountains based on seismic interpretations (MacLean, 2007).

Exploration History

Most exploration wells are concentrated in the Great Slave Plains with a lower density of drilling in the Colville Hills, Peel Plateau and Plain and in the Anderson and Horton Plains. The most significant discoveries in the northern part of the Interior Platform are in the Colville Hills, where gas and some condensate have been recovered from Cambrian strata in four wells (Tedji lake K-24, Tweed Lake M-47, and Bele O-35). The Tedji Lake K-24 well was completed in 1974 and the Tweed Lake M-47 in 1985 and Bele O-35 in 1986. There was also a significant gas show in Nogha O-47, drilled in 1986.

In the southern part of the Interior Platform in Great Slave Plain several important discoveries have been made. The gas discovery in 1968 within porous limestone and dolostone of the Middle Devonian Sulphur Point Formation at the HB Cameron A-05 well eventually led to the recent development of the mixed oil and gas field at Cameron Hills, which commenced production in 2002 from nine wells. This production comes from several intervals within the Middle Devonian (Keg River, Sulphur Point and Slave Point formations). A large gas discovery also was made in 1961 in reefal, shelf edge limestone of the Slave Point Formation at the Sun Netla C-07 (F-07) well in the southwestern part of Great Slave Plain. In the Cretaceous, a significant gas discovery was made in 1989 at the Arrowhead B-41 well, also in the southwestern part of Great Slave Plain.

Minor gas shows have been reported from many wells in Peel Plateau, the most significant being at the Tree River H-38 well. A significant occurrence of heavy oil (20° API) was discovered in 1971 in the Ordovician Franklin Mountain Formation at the East MacKay B-45 well in Mackenzie Plain. Also, gas shows in the southern part of Great Slave Plain and several smaller gas fields (Celibeta H-78, Grumbler G-63, Tathlina N-18 and the Rabbit Lake field) were discovered in the period between 1960 and 1980 in the Devonian Keg River to Slave Point interval (Gal and Jones, 2003).

Seismic coverage is extensive in parts of Great Slave Plain (MacLean, 2007), limited in parts of Great Bear, Anderson and Horton plains, sparse to moderate in western Peel Plain and the Peel Plateau, and more extensive in Colville Hills and eastern Peel Plain (available through the National Energy Board, Calgary). In general the density of coverage that is publicly available is very low throughout the entire area.

Source Rocks

There are at least five known potential source rocks:

1. Scattered, thin beds of algal-rich shale in the Cambrian Mount Clark-Mount Cap succession (Wielans et al., 1990; Dixon and Stasiuk, 1998),
2. Middle Devonian Bluefish Member of the Hare Indian Formation and the Horn River and Muskwa formations (Feinstein et al., 1988),
3. The Middle, to possibly Upper Devonian, Canol shale (Feinstein et al., 1988, 1991),
4. The basal part of the Upper Cretaceous Slater River Formation (and equivalents), and,
5. The Triassic Toad and Grayling formations, the Lower Cretaceous Garbutt Formation (Leckie et al., 1991) and the Upper Cretaceous Boundary Creek and Smoking Hills formations (Snowdon, 1990).

Other potential source rocks may be present in the lower Paleozoic Road River Group (Stasiuk, pers. comm.) and in Albian shale (Snowdon, 1990), but there are insufficient data to determine the significance of these. Only the Cambrian, Canol and Bluefish source rocks are known to have been correlated to pooled hydrocarbons. The limited distribution and thickness of Cambrian source rocks is a constraint on the volume of hydrocarbons generated. Typically source rocks occur as millimetre to a few centimetres thick laminae and beds that occur at several stratigraphic horizons within the upper Mount Clark and lower Mount Cap formations. Middle Devonian Canol strata are more extensive and occur as a potentially continuous stratigraphic interval a few metres to 122 m thick. It subcrops under western Anderson Plain and eastern Peel Plain and dips gently westward to southwestward under Peel Plain and Peel Plateau. The Triassic Toad-Grayling and the Lower Cretaceous Garbutt have some source rock potential and are both in close proximity to oil shows in the Chinkeh Formation in British Columbia near the border with the Northwest Territories. Slater River shale and equivalent strata occur in parts of Mackenzie Plain and Peel Plateau. Smoking Hills strata are present only under a small area of Anderson Plain and are 20 to 50 m thick. Both Upper Cretaceous units are generally high in organic carbon (up to 12 % by weight) and contain type II marine kerogen.

The lower Paleozoic Road River shale may contain source intervals but so far none have been identified. However, there have been few geochemical analyses of these rocks. Albian strata likewise have not been studied extensively but several zones with high gamma-ray counts may indicate the presence of potential source rocks.

Very little geochemical data is available from the widespread lower Paleozoic platform carbonates but to-date no potential source rocks have been identified from this succession. Only in western Peel Plain and Peel Plateau are there significant shale tongues of the Road River Group interbedded with the carbonates and these may have some potential.

Snowdon and Williams (1986) mention the possibility that Proterozoic sedimentary strata at Belot Hills M-63 have elevated TOC contents (up to 1.4%) and show T_{max} values possibly within the early dry gas zone of maturity.

Reservoir Rocks

The basal Cambrian sandstones of the Colville Hills, fractured carbonates of the Lower/Middle Devonian Bear Rock (or equivalent) Formation, the Devonian reefal and dolomitized Keg River to Slave Point interval across the southern Great Slave Plain following the subsurface edge of the Presqu'ile Barrier or along its back barrier facies contact with the Muskeg evaporites, the Cretaceous Chinkeh sandstones in southwestern Great Slave Plain, There are common occurrences of bitumen in Cambrian sandstones, in the basal Cretaceous sandstones across Great Slave Plain, and in most lower Paleozoic carbonates, indicating that oil was once present.

Other potential reservoirs include:

1. Vuggy or fractured dolostone in the extensively developed lower Paleozoic platform carbonates (possibly at Tree River H-38),
2. Platform carbonate to shale transitions in the lower Paleozoic succession of Peel Plain and Plateau,
3. Isolated, "pinnacle" reef mounds of the Horn Plateau type developed along the upper surface of the Devonian Lonely Bay or Nahanni formations (Gal and Jones, 2003),
4. Porous, shelf edge facies transitions to basinal shale of upper Devonian and Carboniferous platform carbonates (Jean Marie, Kakisa, Tetcho, Kotcho and Flett formations; Gal and Jones, 2003),
5. Secondary porosity (leaching, dolomitization) in Devonian and Carboniferous platform carbonates (Jean Marie, Kakisa, Tetcho, Kotcho and Flett formations; Gal and Jones, 2003), and in solution-collapse breccias (Bear Rock Formation),
6. Sandy turbidites in the Devonian Imperial Formation,
7. Conglomeratic sandstones of the Carboniferous Tuttle Formation in Peel Plateau,
8. The basal sandstone of the Albian succession (Martin House Formation), and,
9. Sandstones in the Albian to Santonian of Peel Plateau (Dixon, 1999).

Maturation and Generation

Thermal maturity of Cambrian source rocks is marginally mature to mature in the north Colville Hills with a trend that shows increasing maturity towards the south (Dixon and Stasiuk, 1998). Throughout most of the Interior Platform sediment thickness and burial is moderate, consequently any source rocks in these areas would likely be immature to marginally mature. However, as the succession thickens towards the west and southwest thermal maturity likely increases, with overmature strata in the lower Paleozoic succession under parts of Peel Plain and Peel Plateau.

Oil and gas have been generated from Cambrian source rocks (e.g., Tweed Lake A-67, ~ 0.9-1.0% Ro vitrinite equivalent) and the extensive occurrence of bitumen in Cambrian sandstones indicates that oil generation occurred. However, the recovery of gas and condensate from the sandstones at Tweed Lake A-67 within a late mature oil zone suggests that most of the gas likely migrated from elsewhere (Dixon and Stasiuk, 1998), possibly from the south and west.

Devonian Horn River source rock shale ranges widely in maturity across Great Slave Plain from submature at the top of the oil window east of 119 degrees longitude to overmature in the dry gas generation zone west of about 123 degrees longitude (Stasiuk and Fowler, 2002).

Lower Cretaceous source rocks (Garbutt Formation) are submature to mature near the top of the oil window across the southern Great Slave Plain (Stasiuk et al., 2002). Upper Cretaceous Slater River and Smoking Hills strata contain type II kerogen with high levels of organic carbon, up to 12% by weight. Low levels of thermal maturity (Snowdon 1990) and limited areal distribution indicate that these strata are unlikely to be effective source rocks.

Migration and Accumulation

Bitumen in the Cambrian sandstones of the Colville Hills area points to an initial phase of oil generation and migration derived from surrounding source rocks, followed by flushing by gas and condensate (e.g., Tedji Lake gas discovery with extensive bitumen stained sandstone). Extensive bitumen, possibly pyrobitumen, in Cambrian sandstones of the Good Hope A-40 well could be evidence for thermal cracking and gas generation from an initial oil reservoir and migration of the gas to the north and west, into the Colville Hills area. This well sits in one of the depocentres of the Cambrian basin and presumably is located in a thermally mature zone, according to the maturity trends identified by Dixon and Stasiuk (1998).

The unconformity surface on which the Cambrian sandstones rest has significant topographic relief and sandstones pinchout against topographic highs and probably provided traps for the initial liquid hydrocarbons. Tertiary age structures may have enhanced such traps or created new traps into which hydrocarbons remigrated. Shale in the Mount Cap and Saline River formations, and evaporites of the Saline River Formation are seal rocks.

Gas in the numerous Devonian gas fields and shows within the Presqu'ile Barrier across Great Slave Plain was probably generated further west from lower Paleozoic source rocks, such as the Horn River and Muskwa shales. This gas migrated eastward, updip through the barrier in Mesozoic to Cenozoic time. Oil-phase hydrocarbons are present in some fields, such as Cameron Hills, where eastward gas migration failed to flush locally generated, less mature oil from reservoirs.

Exploration Plays

Cambrian Sandstone Reservoirs:

1. Early Tertiary age thrust faulted anticlines.
2. Up-dip pinchout of sandstones against paleotopographic highs.
3. Enhanced traps combining types 1 and 2.

Paleozoic Platform Carbonates:

1. Up-dip pinchout of porous intervals.
2. Fault traps.
3. Carbonate to shale transition and possible development of shelf-edge reefs or biostromes in western Peel Plain, Peel Plateau, and along the Presqu'ile Barrier in Great Slave Plain.
4. Dolomitization of Devonian and Carboniferous platform carbonates.
5. Reef mounds developed on top of Middle Devonian carbonates and encased in Middle/Upper Devonian shale.

Basal Sandstone of the Albian Succession:

1. Lateral/up-dip pinchout of porous sandstone.
2. Anticlines in the Peel Plateau.

Upper Cretaceous Sandstones:

1. Anticlines in the Peel Plateau.

Reserve Estimates

A median value of $11.345 x 10^9 m^3$ of gas has been attributed to the three Colville Hills Cambrian discoveries (Morrell, 1995). A median value of $121.19 x 10^9 m^3$ of gas has been attributed to the scattered gas fields across the southern Great Slave Plain (Morrell, 1995) although production of gas at the Cameron Hills Field of over $170 x 10^6 m^3$ (Gal and Jones, 2003) has already exceeded previous published reserves estimates for this field (e.g. Morrell, 1995). It is very likely that the reserves estimates for most gas fields in this area will be revised drastically upwards in the future.

Hydrocarbon Potential

A qualitative assessment of the hydrocarbon potential of the Interior Platform indicates this area to be low to moderately prospective, varying throughout the area. The Colville Hills and southern Great Slave Plain remain the most prospective exploration areas with known oil, gas and condensate discoveries and the possibility of more discoveries. Large areas, such as the Peel Plain and Peel Plateau, remain relatively untested with only a few wells. In the western parts of the latter areas the possibility of shelf-edge reefs and/or biostromes or dolomitized and porous shelf-edge carbonates has yet to be tested in detail. The Franklin Mountains are considered to have a poor potential due to inferred high levels of thermal maturity and extensive surface exposure of potential reservoir rocks.

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BEAUFORT-MACKENZIE BASIN

Geology..........................	Proterozoic to Tertiary strata
Proven source rocks........	Upper Cretaceous Boundary Creek and Smoking Hills formations, coaly deltaic beds in the Tertiary
Reservoir rocks...............	Paleozoic carbonates, Jurassic-Cretaceous sandstones, Tertiary sandstones
Discoveries.....................	Numerous oil and gas discoveries ranging from oil in fractured Paleozoic carbonates to oil and gas in Cretaceous and Tertiary sandstones
Hydrocarbon potential......	High

Introduction

The Beaufort-Mackenzie Basin underlies Tuktoyaktuk Peninsula, Mackenzie Delta, outer Yukon Coastal Plain and the adjacent offshore area. In the offshore it extends from Amundsen Gulf westward to the US border, with deposits extending into the deep-water of Canada Basin.

Geological Setting

In a strict geological sense the Beaufort-Mackenzie Basin involves only latest Cretaceous to Recent sediments (Dixon et al., 1992), but is commonly used to include all sedimentary rocks underlying the geographic area referred to in the Introduction (Figs. 2 and 4). In the latter instance, rocks of Proterozoic to Recent age are involved.

Proterozoic strata are known from Campbell Uplift, near Inuvik, where low-grade metamorphosed sedimentary rocks are present. In the subsurface, some quartzite, pebbly quartzite and volcanic rocks of presumed Proterozoic age have been penetrated on Tuktoyaktuk Peninsula, in the vicinity of the Atkinson oil discovery (Dixon, 1979; Wielens, 1992). Seismic imaging indicates that a very thick Proterozoic succession underlies Tuktoyaktuk Peninsula (Cook et al., 1987a, b).

The lower Paleozoic succession is poorly known due to a lack of well penetrations and few outcrops. Based on regional comparisons and the limited available data the Paleozoic is a continuation of that seen on the Interior Platform. A thick carbonate succession of latest Cambrian to Middle Devonian age is present, grading laterally westward, and probably northwestward, into shale of the Road River Group. These are overlain by a clastic dominated late Middle Devonian to Late Devonian succession of the Canol and Imperial formations. Carboniferous and Permian carbonate and siliciclastic beds are preserved only under the southwest part of Mackenzie Delta and extend into outcrops of the northern Cordillera (Richards et al., 1997; Dixon et al., 1996; Dixon, 1998). Triassic sandstone, siltstone and carbonates are absent under the Mackenzie Delta and are relatively thin in the adjacent mountain areas (Dixon, 1998). Jurassic to Recent strata are dominated by shale and sandstone successions formed by a series of deltas and shoreline deposits with periods when deep-water sediment gravity-flow beds were prevalent (Dixon, 1982, 1986).

The Phanerozoic succession is interrupted by a number of major unconformities that mark the major tectonic phases; these include:

1. Base of Paleozoic succession (Early or Middle Cambrian),
2. Latest Devonian,
3. Earliest Jurassic (Hettangian-Sinemurian),
4. Early Cretaceous (Late Hauterivian),
5. Mid-Cretaceous (Late Albian),
6. L Late Cretaceous (Late Maastrichtian),
7. Early Tertiary (Late Eocene), and,
8. Late Tertiary (Late Miocene).

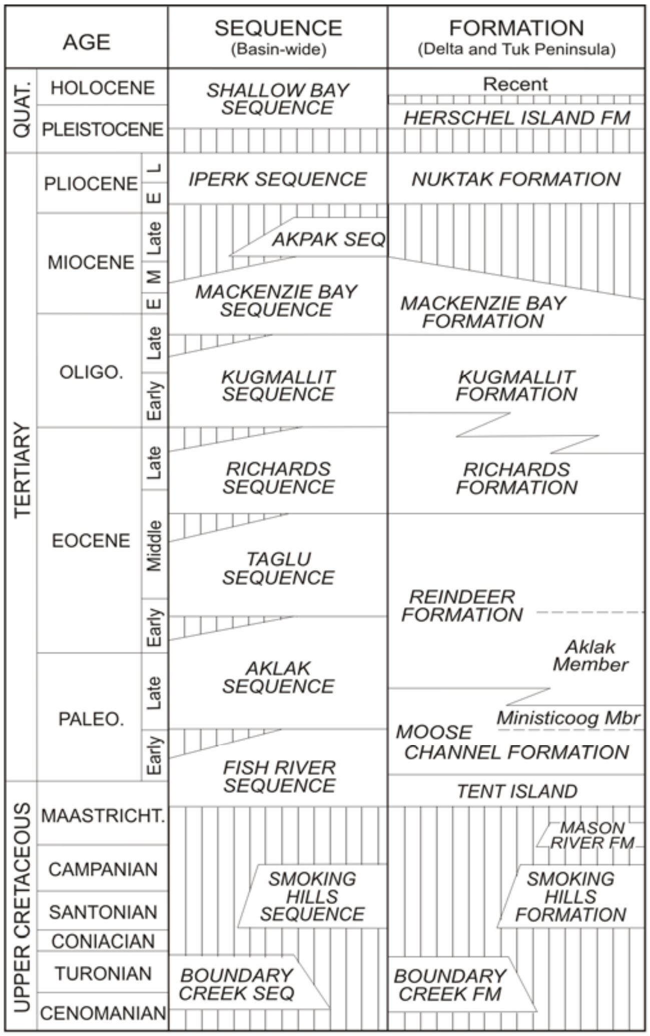

Figure 4. Comparison of lithostratigraphic and sequence stratigraphic nomenclature, Beaufort-Mackenzie Basin.

Other widespread unconformities are present but they are not as tectonically significant as those indicated above.

There are four broad structural domains in the Beaufort-Mackenzie area. Under Tuktoyaktuk Peninsula down-to-basement extensional faults are the prevalent structures (Fig. 5). Offshore from the northern Tuktoyaktuk Peninsula Tertiary strata are undeformed to mildly deformed.

Under Mackenzie Delta and the adjacent offshore the structural style is dominated by listric faults and associated folds (Fig. 5). Under the western Beaufort Sea thrust faulted anticlines are the prevalent structural features, forming an arcuate foldbelt that extends from the US to the western margin of Mackenzie Delta. In the latter area the folds are cut by listric faults.

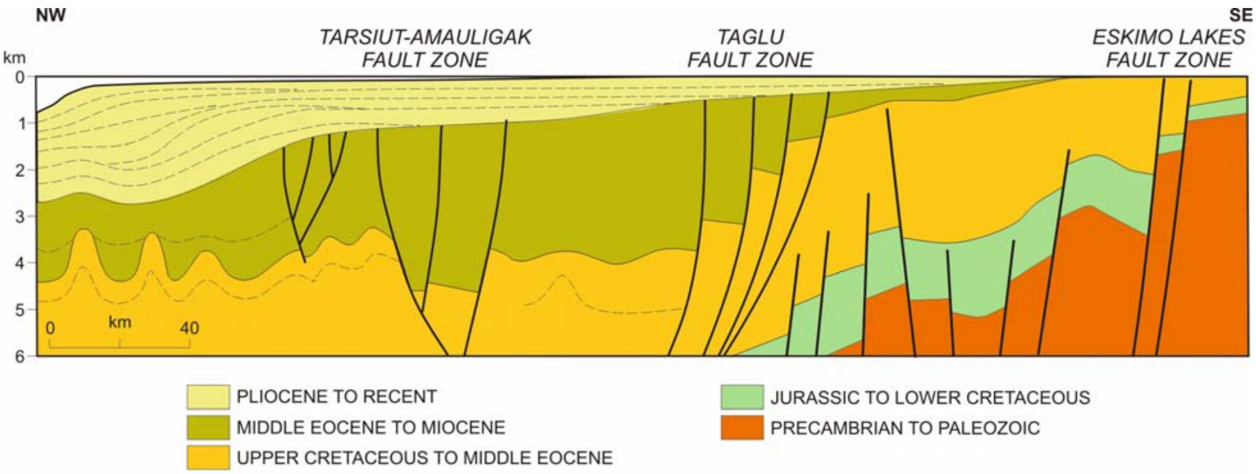

Figure 5. Schematic cross section through the central part of Beaufort-Mackenzie Basin.

Exploration History

The first well drilled in the area was the Atkinson H-25 well in 1969, which recovered oil, prompting an initial phase of exploration that resulted in a number of significant discoveries in Cretaceous and Tertiary sandstone reservoirs, such as Parsons Lake and Taglu. In the late 1970s exploration shifted to the offshore areas where a number of oil and gas wells were drilled (e.g., Kopanoar, Amauligak, Tarsiut). Exploration activity slowed during the late 1980s and virtually ceased in the 1990s. However, the increased demand for gas and increased prices in the North American market made the frontier areas look attractive and a new round of exploration began in 2001.

About 260 wells have been drilled in the area and several hundred thousand kilometers of seismic have been recorded, much of it now publicly available.

Although the presence of gas hydrates in the Mackenzie Delta has been known since the early days of drilling, they were considered a hazard rather than a potential resource. However, in the late 1990s and the early years of the 21st century a consortium from industry (including Japanese involvement) and the geological surveys of Canada and the United States began a series of scientific investigations in the Mallik area on Mackenzie Delta, drilling several test holes to understand the properties of gas hydrates and their potential for production (Dallimore et al., 1999; Dallimore and Collett, 2005).

Source Rocks

In early studies of the geochemical characterization of source rocks and oils three principle sources were identified, the Middle Jurassic to Lower Cretaceous Husky Formation, the Upper Cretaceous Boundary Creek and Smoking Hills formations and the Eocene Richards Sequence (Langhus, 1980; Creaney, 1980; Snowdon and Powell, 1979; Brooks, 1986a, b). The two Upper Cretaceous source rocks have organic carbon content of up to 12% by weight, whereas the Richards Sequence, primarily only the basal few tens of metres of shale, has only 1.2 to 1.5% of organic carbon. While the Upper Cretaceous source rocks contain oil-prone marine kerogen the Eocene strata contain predominantly terrigenous gas-prone kerogen. To explain the abundance of oil in Tertiary reservoirs, as well as gas, the presence of resinite in the Eocene shale was hypothesized to be the material from which oil could be generated (Snowdon, 1980).

Subsequent work in Tertiary strata has revealed that the geochemical biomarker signature that first identified the Richards Sequence as a source rock is present in the organic matter of other Tertiary coaly and shale successions (Snowdon, pers. comm., 2002). This increases the number of potential source intervals and includes some of the more organic rich coaly units in deltaic beds, such as the Fish River, Aklak, Taglu and Kugmallit sequences. Recent studies at the Geological Survey of Canada (Li, pers. comm.) has indicated that many of the oils indicate an initial origin from Upper Cretaceous source rocks, commonly modified by migrating through Tertiary strata.

Potential source rocks in older strata have not yet been identified although organic rich intervals in the Albian Arctic Red Formation under Tuktoyaktuk Peninsula have been noted (Dixon et al., 1989). Because gas is difficult to correlate with a source rock the origin of the gas in Lower Cretaceous reservoirs remains elusive, although Langhus (1980) considered the Husky Formation to be the main source for these gases. However, recent work (Snowdon, pers. comm. 2003) indicates that Lower Cretaceous McGuire strata also may be a source rock.

Reservoir Rocks

Reservoirs are present in the following units:

1. Fractured Paleozoic carbonates (Mayogiak),
2. Marine and deltaic sandstones of the Berriasian to Hauterivian Parson Group (e.g., Parsons Lake gas field; oil in Kugpik O-13),
3. Fan-delta sandstones and conglomerates of the Barremian to Aptian Atkinson Point Formation (Atkinson oil field),
4. Paleocene and Eocene deltaic sandstones (e.g., Adlartok oil discovery, Taglu gas field),
5. Eocene to Oligocene sediment gravity-flow deposits (e.g., Kopanaor oil field), and,
6. Oligocence deltaic sandstones (e.g., Amauligak).

Other potential reservoir units could include:

1. Upper Devonian turbidites in the Imperial Formation,
2. Carboniferous marine clastics and carbonates,
3. Permian marine sandstones,
4. Lower and Middle Jurassic sandstones,
5. Upper Barremian to Aptian sandstones of the Rat River Formation, and,
6. Paleocene deltaic sandstones.

Maturation and Generation

In general, Lower Paleozoic rocks tend to be highly mature to overmature (dry gas), Carboniferous to Albian strata mature to immature - a function of burial depth, and Upper Cretaceous to Tertiary strata range from mature to immature, also depending on burial depth. In general the Tertiary succession has a low maturity with respect to oil generation (0.25 to 0.65 %Ro), commonly even at depths of up to 4500 m in places (as low as 0.4 to 0.65 %Ro), although Issler and Snowdon (1990) suggest that thermal maturation gradients should increase dramatically about 1 km lower.

Migration and Accumulation

Most of the oil trapped in fractured Paleozoic carbonates and Lower Cretaceous sandstones was derived from Upper Cretaceous organic-rich shales (Creaney, 1980; Snowdon, 1980). To generate these hydrocarbons the Upper Cretaceous beds have been faulted to deeper levels than the traps, indicating significant vertical migration, probably along faults and fractures associated with the faults. In the Tertiary succession it seems probable that most of the hydrocarbons have been generated within the vicinity of the trap but off-structure, in adjacent synclines or adjacent down-faulted blocks. Some of the largest accumulations (e.g., Taglu and Amauligak) have large synclinal areas adjacent to the trapping anticline, from which most of the hydrocarbons could have originated. This implies some vertical and lateral migration, but not on a large scale. Alternatively, with the identification of many coaly beds as probable source rocks it is possible that in situ generation may have occurred within the Tertiary deltaic deposits, and probably continues to this day in the offshore.

Exploration Plays

Known Play Types:

1. Fractured Paleozoic carbonates associated with extensional faults (e.g., Mayogiak).
2. Jurassic and Lower Cretaceous sandstones in anticlines associated with basement-involved extensional faults (e.g., Parsons Lake).
3. Closure against basement-involved extensional faults (e.g., Atkinson Point).
4. Tertiary deltaic sandstones in anticlines associated with listric faults (e.g., Taglu, Amauligak).
5. Tertiary deltaic sandstones in faulted anticlines of the Tertiary fold belt (e.g., Adgo).
6. Tertiary turbidites in anticlines of the Tertiary fold belt (e.g., Kopanoar).

Potential and/or Untested Play Types:

1. Turbiditic sandstones in the Devonian Imperial Formation.
2. Pinchout against unconformities in Jurassic through Tertiary strata.
3. Anticlines associated with thrust faults in the western Beaufort.
4. Gas hydrate occurrences.

Reserve Estimates

Estimates of reserves in the discoveries, as published by Morrell (1995) are:
Gas - 360.2 x $10^9 m^3$,
Oil - 223.2 x $10^6 m^3$,
Condensate - 17.5 x $10^6 m^3$

The National Energy Board (1998) numbers for recoverable hydrocarbons (at the 90% confidence level) are:
Gas - between 186 x $10^9 m^3$ and 349 x $10^9 m^3$,
Oil - between 93 x $10^6 m^3$ and 229 x $10^6 m^3$.

Hydrocarbon Potential

The potential for additional resources is high and the area is likely to be a major source of gas in the near future. In 1994 the Geological Survey of Canada published estimates of potential resources (Dixon et al., 1994) and gave the following median values:
Gas - 1.49 x $10^{12} m^3$ (53.3 TCF), and
Oil - 862.4 x $10^6 m^3$ (5.39 billion barrels).

The gas hydrate resource in the Beaufort-Mackenzie area is highly speculative, with values ranging from $2.4 x 10^{12}$ to $87 x 10^{12}$ m^3 of raw natural gas (Majorowicz and Osadetz, 2001).

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NORTHERN YUKON FOLD COMPLEX

Geology............................	Paleozoic to Tertiary strata
Proven source rocks........	Carboniferous Blackie and Ford Lake formations; Upper Cretaceous Parkin Formation.
Reservoir rocks................	Paleozoic carbonates; Carboniferous carbonates and sandstones; Permian sandstones; Cretaceous sandstones
Discoveries.......................	Oil and gas from Carboniferous and Permian strata in Eagle Plain
Hydrocarbon potential......	Low in most areas but moderate to high in Eagle Plain

Introduction

The Northern Yukon Fold Complex extends from the Ogilvie Mountains north to the Yukon coastal plain. On the east are the Richardson Mountains and on the west the fold complex extends into Alaska. There are five terrains with hydrocarbon potential, these are (Fig. 1):

1. Bonnet Plume Basin.
2. Eagle Plain.
3. Kandik Basin.
4. Old Crow Basin.
5. Blow Trough.

The intervening mountainous areas may have some hydrocarbon potential. Their high levels of thermal maturation and high probability of groundwater invasion and breaching of reservoirs make them less prospective.

Geological Setting

Each of the areas listed above are large tectonic depressions surrounded by highly deformed Proterozoic through Cretaceous strata, commonly with Cretaceous clastic strata as the youngest fill, although in the case of the Bonnet Plume and Old Crow basins Lower Tertiary and Quaternary strata are present (Fig. 2). The depressions are located where major structural elements change trend, for example, Bonnet Plume Basin is located at the south end of north-south structures of the Richardson Mountains where they meet with the east-west structures of the Wernecke Mountains. Deformation within these depressions is generally less intense than the surrounding mountains. In Kandik Basin and Blow Trough the youngest sediments are Albian; under Eagle Plain the youngest strata are probably Campanian, but possibly as young as Santonian.

Exploration History

Eagle Plain has the most exploration wells with about 40, and has had several hydrocarbon discoveries in Carboniferous and Permian strata and some lower Paleozoic gas shows (Yukon Economic Development, 1994; Morrell, 1995). Of the areas, only Blow Trough has had any drilling, one well within the Depression and two wells on the perimeter. Kandik Basin has three wells in close proximity, along the eastern flank of the basin. There were no hydrocarbon shows in the Blow Trough and Kandik wells.

Seismic coverage is predominantly on Eagle Plain with some old, poor quality data along the Yukon coastal plain intersecting the Blow Trough. A few seismic lines are located on the eastern margin of Kandik Basin, associated with the three wells drilled in this area. The wells located on the eastern side of Kandik Basin were drilled on surface anticlines.

Source Rocks

Potential source rocks in Eagle Plain are the lower Paleozoic Road River Group and Prongs Creek shales, the Devonian Canol Formation, the Carboniferous Ford Lake, Hart River and Blackie shales, Albian shale of the Whitestone River Formation, and the basal beds of the Shale member, Upper Cretaceous Parkin Formation. Under Blow Trough and Kandik Basin there are thick shale successions in the Albian and throughout parts of the Lower Cretaceous and Jurassic. Old Crow and Bonnet Plume basins are the least known areas, but there may be potential source rocks in subcropping Paleozoic shale beds, and in the case of Old Crow Basin, some Jurassic and Lower Cretaceous shales.

Reservoir Rocks

Potential and known reservoir rocks for each of the areas are listed as follows:

Bonnet Plume Basin:

1. Albian conglomerates and sandstones.

Eagle Plain:

1. Lower Paleozoic platform carbonates of the Ogilvie and Bouvette formations (Fig. 2) - gas shows,
2. Upper Devonian turbidites (Imperial Formation).
3. Upper Devonian/Lower Carboniferous marine sandstones and conglomerates (Tuttle Formation, Fig. 2) - gas tested.
4. Canoe River Member (limestone), in the Carboniferous Hart River Formation - gas and oil recovered.
5. Chance Sandstone Member (marine), Hart River Formation - gas and oil recovered.
6. Lower member (marine sandstones) of the Permian Jungle Creek Formation - gas tested.
7. Marine and non-marine sandstones in the Upper Cretaceous Eagle Plain Group -gas tested from the Fishing Branch Formation.

Kandik Basin:

1. Albian marine sandstones and conglomerates.
2. Lower Cretaceous non-marine to marine sandstone (Kamik Formation).
3. Carboniferous and Permian carbonates.

Old Crow Basin:

1. Carboniferous carbonates.
2. Cretaceous marine sandstones.

Blow Trough:

1. Albian marine sandstones and conglomerates.
2. Lower Cretaceous marine sandstones (Kamik Formation).

Maturation and Generation

Most maturation data has been recovered from wells and outcrops in Eagle Plain, with lesser amounts of data from the wells and outcrop adjacent to Kandik Basin, Old Crow Basin and Blow Trough. There are no data from Bonnet Plume Basin but based on regional considerations it is anticipated that the Paleozoic strata surrounding the Albian to Tertiary fill are overmature. The Lower Tertiary strata contain coaly beds, described in the literature as lignite, suggesting low levels of thermal maturity.

Kandik Basin (Snowdon and Price, 1994) and Blow Trough are surrounded by and contain rocks that are highly mature to overmature. In Blow Trough, the Blow River E-47 well has overmature rocks at surface. Old Crow Basin contains a thin fill of Tertiary and Quaternary strata that are probably immature. Surrounding Old Crow Basin are highly mature to overmature Paleozoic and Mesozoic strata that are presumed to underlie the basin.

In Eagle Plain rocks range from immature in the youngest Cretaceous rocks to overmature in some of the lower Paleozoic strata (Snowdon, 1987; Link and Bustin, 1989a, b). Oil and gas generation has occurred, probably from Carboniferous source rocks, although other unidentified sources may have contributed.

Migration and Accumulation

Most of the known hydrocarbon occurrences are in the Carboniferous Chance Sandstone, a lenticular conglomeratic sandstone body within the Hart River Formation. Its stratigraphic proximity to source rocks in the Blackie and Ford Lake formations, its location in the mature zone of hydrocarbon generation, and its occurrence in anticlines makes this potentially an ideal setting for hydrocarbon migration and accumulation in reservoirs.

A lack of data and hydrocarbons in the other prospective areas in the Northern Yukon Fold Complex precludes any valid interpretations about migration and accumulation.

Exploration Plays

Exploration plays and concepts for this region are outlined in Yukon Economic Development (1994) and in Morrell (1995). These include:

1. Anticlinal traps formed during Early Tertiary during Laramide and pre-Laramide deformation.
2. Stratigraphic pinchout of upper Paleozoic sandstones and conglomerates in combination with structural closure.
3. Stratigraphic updip subcrop traps of upper Paleozoic sandstones and conglomerates beneath the “sub-Cretaceous” unconformity in the subsurface of Eagle Plain.
4. Porous Carboniferous and/or Permian carbonates in structural, stratigraphic and subcrop traps.
5. Lower Paleozoic shelf-edge carbonates - probably limited to the margins of Eagle Plain - in structural and stratigraphic traps.

Reserves Estimates

Morrell (1995) cites reserves estimates at the 50% confidence level in Eagle Plain as:
Gas - $2.524 x 10^9 m^3$ and
Oil - $1.86 x 10^6 m^3$.

Hydrocarbon Potential

Eagle Plain remains the most likely area in the Northern Yukon Fold Complex to have the best potential for more discoveries. Elsewhere, high levels of thermal maturity indicate that any hydrocarbons present would most likely be gas.

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MACKENZIE FOLD BELT

Geology.............................	Proterozoic sedimentary rocks, Cambrian to Triassic with minor Cretaceous
Proven source rocks..........	Devonian Horn River and Canol formations (calcareous shale) and Bluefish Member of the Hare Indian Formation, Devonian to Carboniferous Besa River Formation, Carboniferous Golata and Clausen formations, and the Cretaceous Slater River Garbutt formations
Reservoir rocks.................	Lower Paleozoic carbonates, Middle Devonian reefs (Kee Scarp Formation) and diagenetic coarsely crystalline white dolomite, Carboniferous and Cretaceous sandstones
Discoveries.........................	Gas in dolomitized Middle Devonian carbonates. Oil in a Middle Devonian reef at Norman Wells.
Hydrocarbon potential.........	Low

Introduction

The Mackenzie Fold Belt includes the Liard Plateau, Mackenzie Plain, and the Mackenzie Franklin, and Ogilvie-Wernecke mountains (Fig. 1). The flat to rolling upland that forms Liard Plateau passes northward to the more mountainous terrain of the Mackenzie Mountains north of the South Nahanni River. The Mackenzie Mountains form a broad arc that is convex northeastward facing the Interior Platform. Within this generally mountainous terrain there are the lowlands of the Mackenzie Plain, lying between the Mackenzie and Franklin mountains. Immediately west of the NWT-Yukon Territory border the Ogilvie-Wernecke Mountains trend nearly due west towards the Alaska border. The Mackenzie Fold Belt is a continental-scale, northeast-facing arc of mountain ranges bordering the broad Interior Platform and the physiographically more variable Northern Yukon Fold Complex.

Geological Setting

The Mackenzie Fold Belt is the northern continuation of the Rocky Mountain Foreland Belt of western Canada. It is bounded on the east by the relatively undisturbed strata of the Interior Platform and on the west by the more intensely deformed strata of the Selwyn-Cordillera Fold Belt (Fig. 1). The dominant structural style of the Mackenzie Fold Belt is one of easterly and westerly verging and regionally continuous concentric folds and high angle thrust faults. The amount of structural shortening associated with deformation in the Mackenzie Mountain Fold Belt has been estimated to be about 50 kilometres (Gordey, 1981; Cecile et al., 1982.

Moderately folded and faulted Proterozoic to Upper Devonian strata are exposed across most of the Mackenzie and Ogilvie-Wernecke mountains. Carboniferous to Cretaceous strata are exposed only at the north and south ends of the Mackenzie Fold Belt, in the Liard Plateau and in the Ogilvie-Wernecke Mountains (Fig. 6). Carboniferous to Cretaceous-aged strata are exposed across most of Liard Plateau, whereas Carboniferous strata are the youngest strata exposed in the Ogilvie-Wernecke Mountains (Fig. 6; Bamber et al., 1992; Stott et al., 1992). Post-Devonian strata are absent across the entire Mackenzie Mountains except for a local graben of preserved Lower Cretaceous strata (Fig. 6; Blusson, 1971).

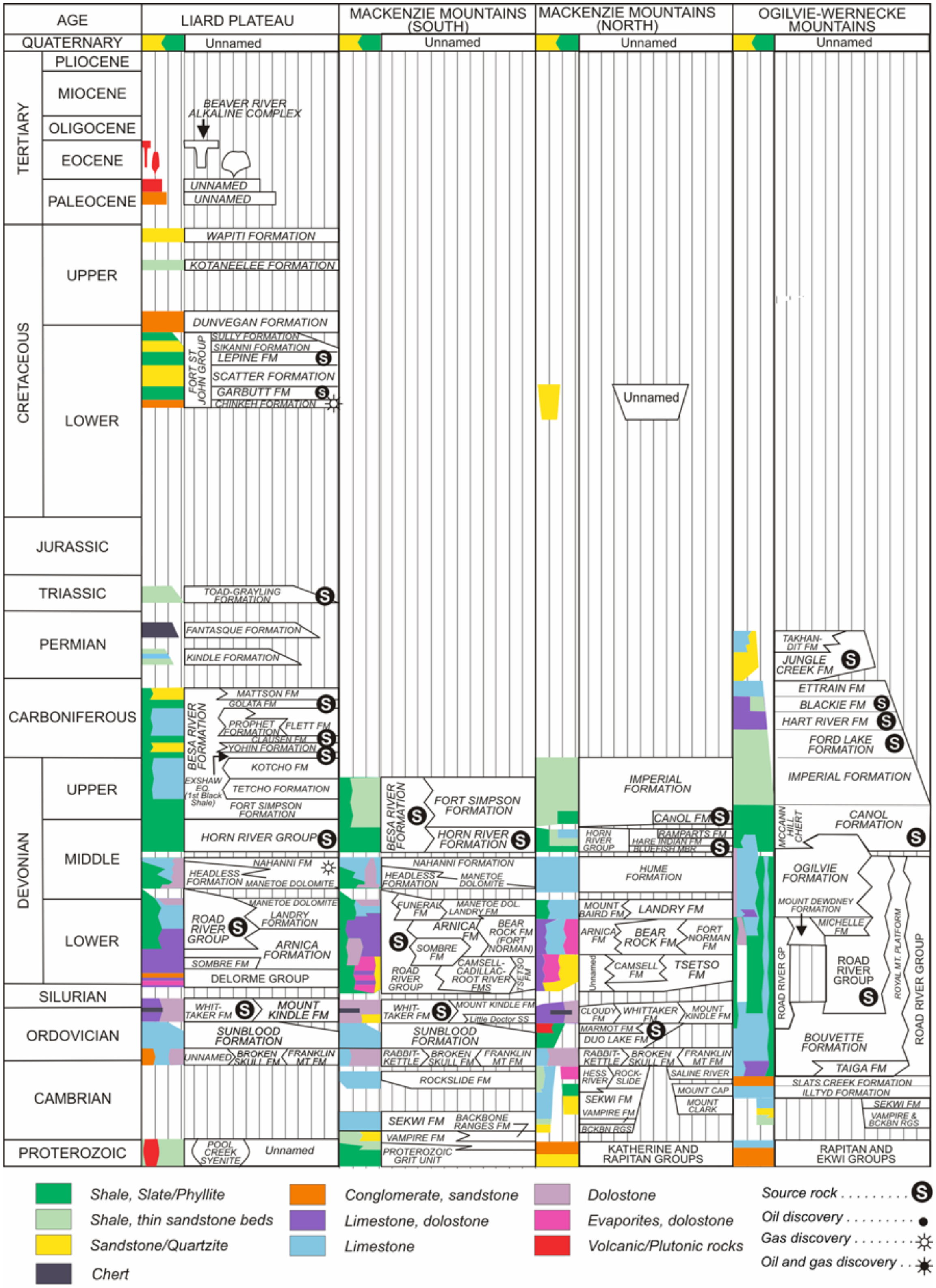

Figure 6. Correlation chart of Phanerozoic strata in the Mackenzie Fold Belt of the northern mainland

Neoproterozoic strata of the Mackenzie Mountain and Windermere supergroups exposed along the nearly 400 km long Plateau Thrust (Fig. 7) in the Mackenzie Fold Belt range up to 5.0 kilometres thick. This succession of pre-Phanerozoic shale, carbonate, sandstone volcanic rocks and diamictites is not significantly metamorphosed and is exposed across large areas in the northern Mackenzie Mountains (Fig. 7; Gabrielse and Campbell, 1992). The Proterozoic succession exposed across the Ogilvie-Wernecke Mountains has an aggregate thickness of up to 20 kilometres (Gabrielse and Campbell, 1992; Stott et al, 1993).

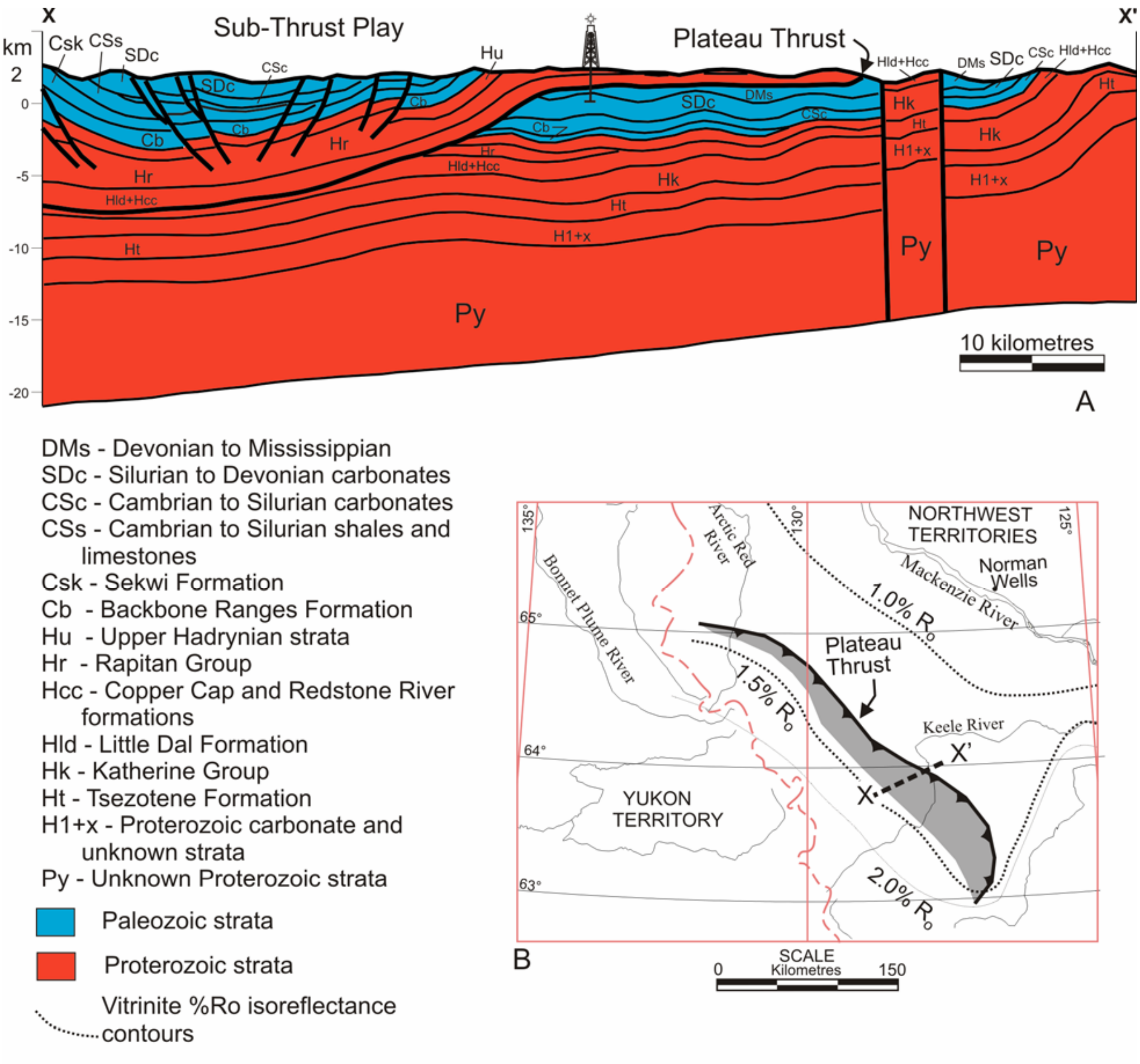

Figure 7. Plateau Thrust play in Mackenzie Mountains of the Mackenzie Fold Belt. Figure 7A is a southwest to northeast geologic cross section of the Plateau Thrust plate. Figure 7B is a map that shows where Proterozoic strata along the base of the Plateau Thrust overlie Paleozoic strata. Contours of vitrinite reflectance within Devonian strata are also shown in 7B.

Cambro-Ordovician sandstones and carbonates, with a variable thickness up to 20 kilometres, unconformably overlie Proterozoic strata across most of the Mackenzie Fold belt. Mackenzie Arch formed a linear landmass along the central axis of the Mackenzie Mountains in Cambrian time. This landmass separated a Cambrian depocentre in the eastern Mackenzie Plain containing siliciclastics and evaporites of the Mount Clark, Mount Cap and Saline River formations from the much thicker siliciclastic and carbonate succession of the Cambrian Backbone Ranges, Vampire, Sekwi and Rockslide formations in Selwyn Basin (Fig. 6; Dixon and Stasiuk, 1998) and the carbonates and sandstones of the Illtyd and Slats Creek formations of the Ogilvie-Wernecke Mountains.

The Franklin Mountain, Mount Kindle, and Bouvette formations, with a thickness of up to 2000 metres, which extend across almost the entire Mackenzie Fold Belt, were deposited in Late Cambrian to mid-Silurian time following the basal Cambrian transgression that inundated Mackenzie Arch (Aitken et al., 1973). South of Mackenzie Arch deeper water deposition of carbonates and shales of the Sunblood and Whittaker formations, and of the Road River Group, infilled Root Basin and in the Meilleur River Embayment within the southern Mackenzie Mountains and Liard Plateau (Cecile and Norford, 1992; Morrow and Cook, 1987).

Widespread exposure across the Mackenzie Fold Belt in late Silurian time caused development of the "sub-Devonian unconformity". Early Devonian transgression was accompanied by deposition of the up to 400 metre thick yellowish-orange siliciclastic, carbonate and evaporate succession of the Delorme Group (Tsetso, Camsell and Cadillac formations – Fig. 6; Morrow and Cook, 1987) across the Mackenzie Mountains and Liard Plateau (Morrow and Geldsetzer, 1992). During this time, Road River shale was deposited across most of the Ogilvie-Wernecke Mountains.

By late Early and Middle Devonian time, platform carbonate and evaporite deposition of the up to 2000 metre thick succession of the Arnica, Sombre, Bear Rock, Fort Norman, Landry, Nahanni and Hume formations blanketed the Mackenzie Mountains area and the eastern part of Liard Plateau. Gray and buff shale of the Road River Group and the Funeral and Mount Baird formations accumulated further west in the Selwyn-Cordillera Fold Belt region and across the western part of Liard Plateau. Platform carbonates of the Ogilvie Formation accumulated across the Ogilvie-Wernecke Mountains. The Manetoe Dolomite, an important coarsely crystalline and porous diagenetic dolomite petroleum reservoir facies has affected Landry and Nahanni limestones in the southern third of the Mackenzie Fold Belt (Fig. 6; Morrow and Geldsetzer, 1992).

Organic-rich black and gray shales of the Horn River Group and of the Canol Formation blanketed the Middle Devonian platform carbonates at the close of Middle Devonian time. Platform carbonate deposition, represented by Ramparts Formation limestone and the Kee Scarp Member reefal reservoir limestone, continued only in the extreme eastern part of the Mackenzie Mountains near Norman Wells and by limestone of the Tetcho and Kotcho formations in the eastern part of the Liard Plateau (Fig. 1; Fig. 6; Gordey et al., 1992). By Late Devonian time, the entire Mackenzie Fold Belt was blanketed by shale, siltstone and sandstone of the Imperial and Fort Simpson formations ending with deposition of the extensive organic-rich black shale source rock of the Exshaw Formation (the latter only preserved in the southern part of the fold belt.

Carboniferous and Permian strata are preserved only within Liard Plateau and in parts of the Ogilvie-Wernecke Mountains (Bamber et al., 1992). In Liard Plateau the Carbo-Permian succession is up to 3000 metres thick. In the Ogilvie-Wernecke Mountains this succession is up to 1000 metres thick. Carboniferous platform carbonates of the Flett and Prophet formations extend westward from the Interior Platform into the eastern part of Liard Plateau, as does the important reservoir sandstone of the Carboniferous Mattson Formation. These are overlain unconformably by siltstone and chert of the Permian Kindle and Fantasque formations. The Carboniferous shale and limestone succession of the Ford Lake, Hart River, Blackie and Ettrain formations and the unconformably overlying sandstones and cherts of the Permian Jungle Creek and Takhandit formations overlie Devonian strata in the western part of the

Ogilvie-Wernecke Mountains (Fig. 6; Richards et al., 1997). Triassic strata, represented by the siltstones of the Toad and Grayling formations, occur only in the southern part of the Liard Plateau.

Jurassic strata are absent across the entire Mackenzie Fold Belt. Cretaceous strata are almost entirely absent across both the Ogilvie-Wernecke Mountains and the Mackenzie Mountains (Fig. 6; Stott et al., 1992) but present in Mackenzie Plain. In Mackenzie Plain Albian strata of the Martin House and Arctic Red formations are present and Upper Cretaceous strata include the Slater River, Little Bear, East Fork and Summit Creek formations. The latter unit also includes some Lower Tertiary strata. Significant Cretaceous strata unconformably overlie Paleozoic strata and are preserved along the axes of north-trending synclines in Liard Plateau. The aggregate preserved Cretaceous succession here is up to 1500 metres thick. These strata include the alternating sandstones and shales of the Fort St. John Group, overlain by the resistant Dunvegan Formation sandstone and the more recessive Kotaneelee Formation shale and Wapiti Formation sandstone. The conglomeratic sandstone of the Chinkeh Formation is a transgressive shoreline at the base of the Cretaceous that forms the reservoir facies for the Maxhamish gas field in northeast British Columbia a short distance southeast of Liard Plateau.

Exploration History

A large number of exploration and production wells have been drilled Mackenzie Plain but only a very few in the mountain areas. Most of the latter, about 30 wells, are located within Liard Plateau and have led to a succession of large gas field discoveries in the southeast part of the Plateau in both the Yukon and Northwest territories. The most significant discovery is the Norman Wells oil-field in Mackenzie Plain, where oil from a Kee Scarp reef has been produced for the past 80 years. The Beaver River gas field (Fig. 8) was discovered in 1957 (A-1 Beaver River) in British Columbia just south of the British Columbia – Yukon Territory border and extended into the Yukon (Davidson and Snowdon, 1978). Subsequently, the Pointed Mountain (Pointed Mountain P-53 discovery well completed in 1966) and Kotaneelee (Kotaneelee YT P-50 discovery well completed in 1962) gas fields were discovered and had a sporadic production history in the period from the mid 1960s until the mid 1980s (National Energy Board, 2001&1966; Morrell, 1995). More recently, oil and gas has been discovered adjacent to the Mackenzie Mountains, southeast of Norman Wells, in the Summit Creek B-44 well, testing oil and gas from Lower to Middle Devonian carbonates (Unocal Corporation, 2006), and in Stewart D-57 which tested gas from Upper Cretaceous sandstone (Husky Energy, 2006).

The hydrothermally dolomitized limestone of the Lower to Middle Devonian Landry and Nahanni formations, the “Manetoe Dolomite” (Morrow et al., 1990) forms the porous reservoir rock in faulted anticlines at the Beaver River, Kotaneelee and Pointed Mountain gas fields. All of these pre-1990 gas fields have experienced severe production problems due to the influx of groundwater into the reservoir (National Energy Board, 2001 and1966; Morrell, 1995).

The Liard F-25A well drilled in 1985 was the discovery well for the Liard K-29 gas field northeast of the Pointed Mountain Field (Fig. 8) but production did not begin until 2000 shortly after the spectacular Liard K-29 well was drilled. The Ranger Fort Liard P-66A well, drilled in 1997, was the discovery well for the Liard P-66A Field, a short distance north of the Pointed Mountain and Liard K-29 fields (Fig. 8). This field was brought into production in 2000. The reservoir rock in all these fields is also the “Manetoe Dolomite” in faulted anticlinal culminations associated with regional Tertiary-aged (Laramide) compression.

A single well (La Biche F-08) gas pool straddling the Yukon and Northwest Territory border was discovered in 1971 (National Energy Board, 2001&1966; Morrell, 1995). This gas pool (Fig. 8) occurs in silicified detrital carbonates that have been interpreted to be paleocavern sediment fills within the Nahanni Formation (Morrow and Potter, 1998).

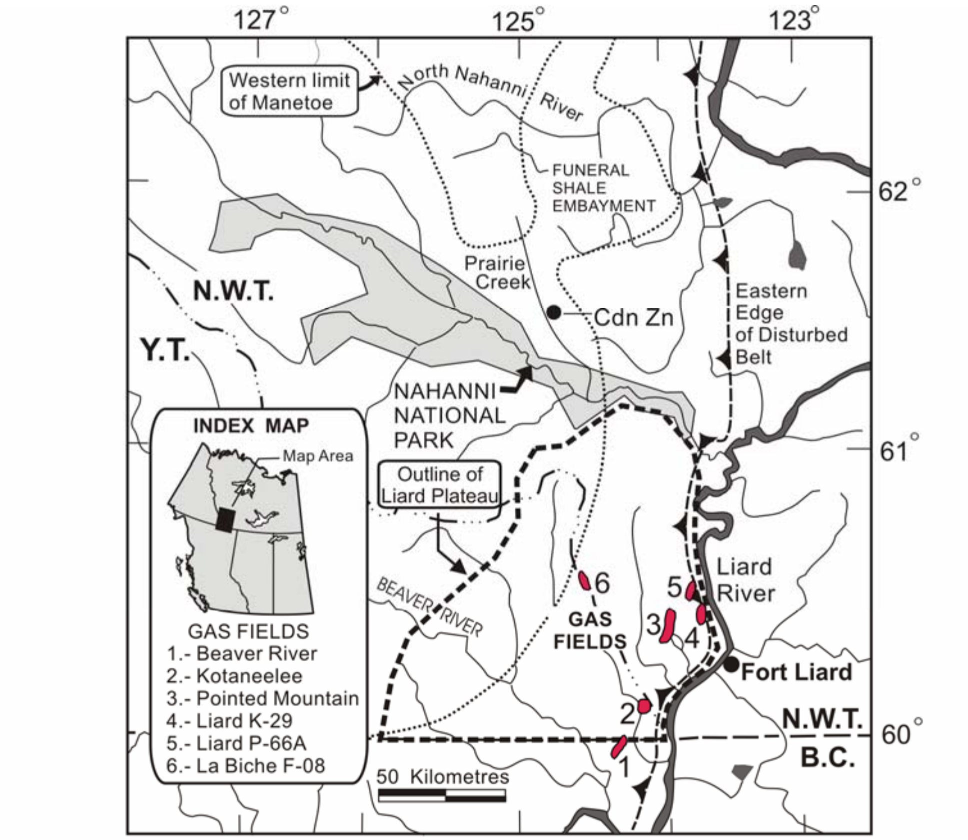

Figure 8. Map showing locations of gas fields in Liard Plateau of the Mackenzie Fold Belt. The western limit of the diagenetic Manetoe Dolomite reservoir facies is also shown.

In addition to the production from the Devonian "Manetoe Dolomite"-hosted gas fields, gas shows have been noted in the Fantasque, Prophet, and Besa River formations above these gas fields within Liard Plateau (National Energy Board, 1966). Also, the Fort Liard F-36 gas field has produced gas from two wells near Fort Liard since 2000 from the Mattson and Fantasque formations. The Fort Liard F-36 gas field is located slightly east of Liard Plateau on the western edge of the Great Slave Plain subdivision of the Interior Platform but is described here because the eastern limit of the main producing interval, the Mattson Formation, is restricted mainly to the Liard Plateau region.

Approximately a dozen scattered exploration wells have been drilled in the southeastern part of the Mackenzie Mountains but none have yielded commercially exploitable hydrocarbons. Most of these wells bottomed in Devonian strata such as the Arnica and bear Rock formations. No wells to date have been drilled in the Ogilvie-Wernecke Mountains. Only a limited amount of seismic is available through the National Energy Board for the extreme eastern slopes of the Mackenzie Mountains and in Liard Plateau in the area of the gas fields.

Source Rocks

There are at least 12 known, probable or potential source rocks in the Mackenzie Fold Belt (Fig. 6):

1. Scattered, thin beds of algal-rich shale in the Cambrian Mount Clark-Mount Cap succession (Dixon and Stasiuk, 1998) are probable source rocks in the Mackenzie Mountains.
2. Organic-rich cherty and shaly dolostone and organic-rich shale of the Upper Ordovician and Lower Silurian Whittaker and Duo Lake formations (Cecile and Norford, 1992) are probable source rocks in the Mackenzie Mountains.

3. Organic-rich gray to black shale intervals within the Road River Group (Cecile and Norford, 1992) are probable source rocks throughout the Mackenzie Mountains and Liard Plateau.
4. Organic-rich siliceous black shales within the Horn River Group including the Bluefish Member of the Hare Indian Formation (Feinstein et al., 1988; Morrow et al., 1993) are known and documented source rocks in the Mackenzie Mountains.
5. Organic-rich black shale equivalent to the Horn River Group in the lower part of the Besa River Formation (Morrow et al., 1993) are known and documented source rocks throughout the Mackenzie Mountains and Liard Plateau.
6. The Middle and Upper Devonian, Canol Formation black shale (Feinstein et al., 1988, 1991) are known and documented source rocks throughout the Mackenzie and Ogilvie-Wernecke mountains, and Mackenzie Plain.
7. The uppermost Devonian to lowermost Carboniferous Exshaw Formation (Fowler et al., 2000; Creany and Allen, 1990) or its lateral equivalent, the first black shale within the Besa River Formation are known and documented source rocks throughout the Mackenzie Mountains and Liard Plateau.
8. Carboniferous black shales of the Clausen Formation (Richards, 1989) are probable source rocks in Liard Plateau.
9. Carboniferous black shales of the Golata Formation and those within the overlying Mattson Formation (Richards, 1989, Morrow et al., 1993) are probable source rocks in Liard Plateau.
10. Carboniferous shaley siltstones and shales of the Ford Lake, Hart River and Blackie formations are all potential or probable source rocks (Hamblin, 1990, Snowdon, 1990) in the Ogilvie-Wernecke Mountains.
11. Permian shaly beds within the Jungle Creek Formation are potential source beds (Hamblin, 1990, Snowdon, 1990) in the Ogilvie-Wernecke Mountains.
12. Cretaceous shales in the Garbutt and Lepine formations are probable source rocks in Liard Plateau (Dixon, 1999, Snowdon, 1990).

Only the Canol shale has been documented to have been the source for oil, at the Norman Wells oil-field (Feinstein et al., 1988, 19991). The other documented source rocks described here (e.g. Bluefish Member) have not sourced any known hydrocarbon accumulations within the Mackenzie Fold Belt, but have been correlated with oil and gas pools in the Interior Platform. Probable source rocks are black shales that contain TOC (total organic carbon) values of more than 1.0% and/or may be associated with hydrocarbon pools or fields in the adjoining Interior Platform. Potential source rocks are black shale or basinal limestone (e.g. Hart River Formation) that may be rich in organic material.

There are many more possible source rocks in the Mackenzie Fold Belt than in the Interior Platform because the entire succession of Paleozoic platform carbonates passes westward to basinal, moderately to highly organic-rich shales (Fritz et al., 1992; Gordey et al., 1992).

Reservoir Rocks

Many stratigraphic units in the Mackenzie Fold Belt exhibit porosity and permeability sufficient to serve as potential hydrocarbon reservoir rock. Proterozoic and Paleozoic strata are exposed at surface across the Mackenzie, Ogilvie, and Wernecke mountains (Fig. 7) and most potential hydrocarbon reservoirs are either breached or have had their contained liquid hydrocarbons flushed by shallow groundwater. Groundwater flow in the Mackenzie Mountains has also been interpreted to have caused Tertiary-aged brecciation of the Devonian Bear Rock and Camsell formations in outcrop and in the shallow subsurface (e.g. in the Amoco Candex Shell A-1 Red Dog K-29 well; Morrow, 1991). Liard Plateau is the only part of the Mackenzie Fold Belt where lower and middle Paleozoic strata and any contained potential reservoirs are buried beneath a thick cover of upper Paleozoic and Mesozoic strata. In Mackenzie Plain a Kee Scarp reef, Lower to Middle Devonian carbonates, fractured dolostone in possible

Ordovician-Silurian carbonates, and sandstones in the Upper Cretaceous Little Bear Formation are known reservoirs.

Potential hydrocarbon reservoirs in the Ogilvie-Wernecke Mountains (Morrow, 1999; Bamber et al., 1992; Hamblin, 1990; Morrell, 1995) include:

1. Shoreface and nearshore sandstones of the Cambrian Slats Creek Formation,
2. Bioclastic, biostromal layers and oolitic sand bodies in carbonates of the Cambrian to Devonian Bouvette Formation,
3. Vuggy “karst” dolostones in the Cambrian to Devonian Bouvette Formation,
4. Biostromal and biohermal beds in limestone in the upper part of the Devonian Ogilvie Formation,
5. Crinoidal packstone limestone in the upper part of the Devonian Ogilvie Formation,
6. Fractured hydrothermal white coarsely crystalline dolomite masses within limestones of the Cambrian to Devonian Bouvette and Devonian Ogilvie formations,
7. Crinoidal limestones in the lower part of the Hart River Formation (Canoe River Member), and,
8. Conglomeratic sandstones of the Permian Jungle Creek Formation.

Potential hydrocarbon reservoirs in the Mackenzie Mountains (Morrow, 1999; Morrow, 1991; Morrow and Cook, 1987; Bamber et al., 1992; Morrell, 1995) and Mackenzie Plain include:

1. Shoreface and nearshore sandstones of the Cambrian Mount Clark Formation,
2. Bioclastic, biostromal layers and oolitic sand bodies in carbonates of the Cambro-Ordovician Franklin Mountain Formation,
3. Vuggy “karst” dolostones in the Cambro-Ordovician Franklin Mountain Formation,
4. Vuggy and fetid biostromal dolostones of the Ordovician-Silurian Mount Kindle Formation,
5. Biostromal dolostones of the Root River Formation in the Silurian-Devonian Delorme Group,
6. Limestone breccias of the Devonian Camsell and Bear Rock formations,
7. Vuggy, biostromal fetid dolostones of the Devonian Arnica Formation,
8. Biostromal and biohermal limestones in the upper parts of the Middle Devonian Hume and Nahanni formations,
9. Fractured hydrothermal white coarsely crystalline dolomite of the “Manetoe Dolomite” within limestones of the Devonian Landry, Headless and Nahanni formations,
10. Biostromal and biohermal limestones of the Devonian Ramparts Formation and the Kee Scarp Member
11. Sandstones in the upper part of the Devonian Imperial Formation, and,
12. Basal sandstone of the Albian succession (Martin House Formation).

Potential and proven reservoirs in the Liard Plateau (Morrell, 1995; National Energy Board, 1996; Morrow and Cook, 1987; Morrow et al., 1990) include:

1. Basal Cambrian unnamed sandstones.
2. Bioclastic, biostromal layers and oolitic sand bodies in carbonates of the Cambro-Ordovician Franklin Mountain Formation.
3. Vuggy and fetid biostromal dolostones of the Ordovician-Silurian Mount Kindle and Whittaker formations.
4. Vuggy and fetid biostromal dolostones of the Arnica Formation.
5. Fractured hydrothermal white coarsely crystalline dolomite of the “Manetoe Dolomite“ within limestones of the Devonian Landry, Headless and Nahanni formations.
6. Possible fractured reservoirs within Devono-Carboniferous Besa River shales.

7. Possible stacked fractured reservoirs within Devono-Carboniferous carbonates of the Tetcho, Kotcho, Prophet and Flett formations.
8. Porous deltaic sandstones of the Carboniferous Mattson Formation.
9. Possible fractured reservoirs within the Permian chert of the Fantasque Formation.
10. Porous sandstones of the Cretaceous Chinkeh and Scatter formations.

Maturation and Generation

Data concerning the level of organic thermal maturity are sparse and scattered both geographically and stratigraphically throughout the eastern part of the Mackenzie Fold Belt, primarily Liard Plateau and the Mackenzie Mountains. Recent summaries of vitrinite and vitrinite equivalent $\%R_o$ maturation data show a first order trend of uniformly increasing maturation for Devonian to Cretaceous strata westward from the Interior Platform into the Mackenzie Mountains and Liard Plateau (Stasiuk and Fowler, 2002; Stasiuk et al., 2002). This roughly parallels the general westward increase in thickness of the Paleozoic succession from the Interior Platform to the Mackenzie Fold Belt (Cecile and Norford, 1992; Morrow and Geldsetzer, 1992; Gordey et al, 1992; Bamber et al., 1992).

The Middle Devonian Hume and Nahanni formations in the Mackenzie Mountains and Liard Plateau range in levels of organic maturation from about 1.4 $\%R_o$ up to at least 2.6 $\%R_o$ and are thus well into the dry gas stage of hydrocarbon generation (Fig. 7; Tissot and Welte, 1984). In the Ogilvie-Wernecke Mountains, the level of organic maturation at the top of the Hume-equivalent Ogilvie Formation ranges from about 2.0 $\%R_o$ up to 4.0 $\%R_o$ (Link and Bustin, 1989; Morrow, 1999). Higher stratigraphic levels exhibit progressively lower levels of organic maturation. The overlying Upper Devonian Imperial Formation exhibits levels of organic maturation that range from about 1.6 $\%R_o$ up to at least 2.2 $\%R_o$ in the eastern part of the Mackenzie Fold Belt, or still in the zone of gas generation.

Only the Middle to Upper Devonian Canol Formation has been identified as a source rock for the Kee Scarp reef at Norman Wells (Feinstein et al., 1988, 1991). No known oil discoveries have been attributed to the Bluefish shale but oil staining in the underlying Hume Formation, just to the south of Norman Wells, has been linked to a local thermally mature Bluefish source rock (Feinstein et al., 1988). This indicates the Bluefish has charged subjacent reservoirs.

The absence of post-Devonian strata across most of the Mackenzie Fold Belt (Fig. 6) makes it difficult to determine the post-Devonian history of thermal organic maturation. Post-Devonian Carboniferous and Permian strata are present only in Liard Plateau and at the western end of the Ogilvie-Wernecke Mountains. In Liard Plateau, Carboniferous strata exhibit levels of organic maturation that range from about 0.8 $\%R_o$ (Mattson Formation) up to 1.5 $\%R_o$ (Prophet Formation; Potter et al., 1993). This range of maturation straddles the oil to wet gas generation zone. Cretaceous strata, unconformably overlying Paleozoic strata, are present locally in Liard Plateau, and are estimated to range in maturity between 0.6 $\%R_o$ and 0.8 $\%R_o$ or within the upper part of the oil window (Stasiuk et al., 2002).

The large gas fields (Beaver River, Pointed Mountain, Kotaneelee and Liard gas fields) in Middle Devonian strata of Liard Plateau (Fig. 8) is indicative of the tremendous volumes of gas generated in Paleozoic organic-rich shaly source rocks during progressively deeper burial (Morrow et al., 1990). The prevalence of solid bitumen in lower Paleozoic platform carbonates, such as in the Mount Kindle and Arnica formations (Morrow et al., 1990) is consistent with oil and gas generation.

Migration and Accumulation

Bitumen in the Cambrian Mount Clark sandstone documented farther east in the Interior Platform and as discussed with regard to the Interior Platform, indicates oil generation and probable eastward petroleum migration in post-Cambrian time. Oil or bitumen has not been recorded in reservoir quality

Cambrian strata (e.g., Slats Creek Formation) in the Ogilvie-Wernecke Mountains. Bitumen in vuggy carbonates of the lower Paleozoic Franklin Mountain and Mount Kindle formations of the Mackenzie Mountains and Liard Plateau may have been emplaced during lateral eastward migration of oils generated from Road River shale source rocks. Similarly, bitumens in vuggy and intercrystalline porosity of the Lower Devonian Arnica and Bear Rock formations (Morrow, 1991) may be indicators of the eastward passage of liquid hydrocarbons updip from basinal source rocks of the Road River Group (Cecile and Norford, 1992; Morrow and Geldsetzer, 1992).

Oil generation gave way to gas generation, during deeper burial, in the central and western parts of the Mackenzie Fold Belt and gas may be trapped where Paleozoic strata lie unconformably beneath impermeable Cretaceous shales overlying the sub-Cretaceous unconformity. This could only occur in areas with Cretaceous cover, such as across parts of Liard Plateau and the extreme eastern parts of the Mackenzie Mountains. Gas generated from lower Paleozoic source rocks may have accumulated also in gently deformed lower Paleozoic carbonates beneath the upper plate of the Plateau Thrust in the central Mackenzie Mountains (Fig. 7; Cecile et al., 1982).

Norman Wells soil is believed to have been generated within the adjacent, thermally mature, Canol shale, with minimal vertical or lateral migration required (Stasiuk and Fowler, 2002). The oil-bearing Kee Scarp reef is located on the north limb of a synclinal feature, with surrounding shale acting as lateral and up-dip seals. The fact that Norman Wells was discovered after drilling near an oil seep indicates that the seal-rock is leaky, suggesting that a considerable amount of oil has escaped.

Downward migration of oil and gas occurred during Carboniferous to Early Tertiary burial across Liard Plateau. Hydrocarbons generated from Middle and Upper Devonian shale source rocks of the Horn River and Besa River groups migrated downward into porous carbonate reservoir facies. Migration of this type charged the Devonian-aged reservoirs of the Pointed Mountain, Kotaneelee, and Liard fields where gas accumulated in porous “Manetoe Dolomite” across structural culminations during Cretaceous and Tertiary time (Morrow et al., 1990).

Oil and gas generated from upper Devonian and Carboniferous source rocks (Besa River, Exshaw, Clausen and Golata shales) probably migrated eastward into Upper Devonian and Carboniferous platform carbonates of the Tetcho, Kotcho, Prophet and Flett formations and notably into Carboniferous sandstones of the Mattson Formation, which is a significant gas producer at the Liard F-36 well in the Interior Platform near Fort Liard (Gal and Jones, 2003).

Oil generated from Lower Cretaceous shales such as the Garbutt Formation may have migrated into basal Cretaceous Chinkeh sandstones which has numerous oil shows (Leckie et al., 1991). Significant gas has been discovered in the Chinkeh Formation further east at the Arrowhead B-41 well, as discussed in the Interior Platform section.

Exploration Plays

Exploration plays in the Ogilvie-Wernecke Mountains would only be viable in areas where upper Paleozoic strata of sufficient thickness and lateral continuity cover potential Neoproterozoic and lower Paleozoic reservoir rock. Most potential reservoirs in these near-surface strata lie within the zone of modern day fresh groundwater recharge and any hydrocarbons may have been flushed from these rocks. Possible petroleum play situations in this region might include:

1. Fault traps with Cambrian Slats Creek sandstones structurally juxtaposed with Paleozoic shale source rocks,
2. Stratigraphic traps where porous lower Paleozoic Bouvette or Ogilvie carbonates pass laterally updip to Road River and/or Canol shale source rock,
3. Structural anticlinal traps where porous bioclastic strata in the upper part of the Devonian Ogilvie Formation are overlain and sealed by Canol shale source rocks,

4. Combined structural-stratigraphic traps where fractured hydrothermal white coarsely crystalline dolomite masses within the Bouvette and Ogilvie formations are overlain and sealed by Canol shale source rocks and involved in Laramide faults or folds, and,
5. Stratigraphic traps where porous crinoidal limestones are sealed within silty shale source rocks of the lower part of the Hart River Formation (Canoe River Member).

The elevated level of organic maturity within potential Canol and Road River source rocks indicates that any traps discovered in the Ogilvie-Wernecke Mountains will be gas filled.

Exploration plays in the Mackenzie Mountains, like those of the Ogilvie-Wernecke Mountains, are viable only in areas with a thick upper Paleozoic cover of siliciclastic sediments (Imperial and Besa River formations). The structural elevation of the Mackenzie Mountains with lower Paleozoic rocks exposed over broad regions indicates that most unbreached potential traps will have been flushed by fresh groundwater. Possible traps in this region include:

1. Fault traps with Cambrian Mount Clark sandstones structurally juxtaposed with Paleozoic shale source rocks,
2. Stratigraphic traps where porous lower Paleozoic Franklin Mountain, Mount Kindle, Arnica, Landry and Hume carbonates pass laterally updip to Road River and/or Canol shale source rock,
3. Structural anticlinal traps where porous bioclastic strata or reef build-ups in the upper part of the Devonian Hume and Nahanni formations are overlain and sealed by Horn River shale source rocks,
4. Combined structural-stratigraphic traps where fractured hydrothermal white coarsely crystalline dolomite masses within the Landry and Nahanni formations are overlain and sealed by Horn River-Besa River shale source rocks and involved in Laramide faults or folds, and,
5. A regional sub-thrust play where lower Paleozoic carbonates are overlapped and sealed by Proterozoic strata that form the hanging wall of the Plateau Thrust in the central part of the Mackenzie Mountains (Fig. 7).

The elevated level of organic maturity within lower Paleozoic strata indicates that any traps discovered in the Mackenzie Mountains will be gas filled.

Unlike the Ogilvie-Wernecke, and Mackenzie Mountains, the thick upper Paleozoic to Mesozoic stratigraphic cover across Liard Plateau provides more potential for the preservation of traps in lower Paleozoic strata. These include:

1. Proven structural traps of "Manetoe Dolomite" of the Nahanni and Landry formations involved in Laramide folds and faults – the large Beaver River, Kotaneelee, Pointed Mountain and Liard gas fields,
2. Stratigraphic, diagenetic traps of "Manetoe Dolomite" encased in Nahanni limestone and sealed by overlying Horn River shale,
3. Anticlinal traps with fractured reservoirs developed within Devono-Carboniferous Besa River shales,
4. Anticlinal traps with fractured reservoirs developed within Devono-Carboniferous carbonates of the Tetcho, Kotcho, Prophet and Flett formations,
5. Stratigraphic traps of deltaic sandstones of the Carboniferous Mattson Formation sealed by laterally equivalent Besa River shale, and
6. Structural traps involving fractured reservoirs within the Permian cherts of the Fantasque Formation.

Also, there may be some potential for stratigraphic traps involving sandstones of the Cretaceous Chinkeh and Scatter formations, although these units may not be sufficiently extensive across Liard Plateau to preserve hydrocarbons.

Reserve Estimates

A very approximate estimate of $50x10^9m^3$ of gas can be attributed collectively to the four main Manetoe gas fields in Liard Plateau, including the recently discovered Liard gas field (Morrell, 1995; Gal and Jones, 2003). In the Norman Wells oil-field about $37.5x10^6m^3$ of recoverable oil is present (Morrell, 1995).

Hydrocarbon Potential

In Mackenzie Plain there have been many exploration programs to try and find another Norman Wells-like oil-field but with no success. However, the recent oil and gas discoveries in folded strata adjacent to the Mackenzie Mountains has revitalized exploration in this area.

Gas in the "Manetoe Dolomite" in Liard Plateau remains, arguably, the most attractive target for exploration both in structural and stratigraphic traps. Paleozoic platform carbonates and chert higher in the succession are also prospective, but probably for much smaller gas fields. Consequently, the remaining hydrocarbon potential for Liard Plateau is moderate to high. Both the Ogilvie-Wernecke and Mackenzie Mountains have low potential for hydrocarbons with the possible exception of the "sub-Plateau Thrust" play in the Mackenzie Mountains.

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SELWYN-CORDILLERA FOLD BELT

Geology.............................	Proterozoic, Paleozoic, Mesozoic and Cenozoic sedimentary and metamorphic rocks, Paleozoic and Mesozoic igneous rocks
Proven source rocks..........	No proven source rocks but Mesozoic siltstone and shale of the Tantalus and Richtofen formations in Whitehorse Trough are possible source rocks
Reservoir rocks.................	Mesozoic conglomerates and sandstones of the Laberge Group in Whitehorse Trough
Discoveries..........................	Gas in dolomitized Middle Devonian carbonates
Hydrocarbon potential.........	Low

Introduction

The Selwyn-Cordilleran Fold Belt occupies the southwest corner of the Yukon Territory in northwestern Canada. It extends westward from the Ogilvie-Wernecke Mountains, the Mackenzie Mountains and the Liard Plateau of the Mackenzie Fold Belt to the international border with Alaska, U.S.A (Fig. 1). Subdivisions of the Selwyn-Cordilleran Fold Belt include the Selwyn Fold Belt, Tintina Trench, Whitehorse Trough, St. Elias Fold Belt and unnamed parts of the Cordilleran Fold Belt that lie between Tintina Trench and the St. Elias Fold Belt (Fig. 1). The entire region is mountainous, high relief terrain transected by the northwest trending, broad trench-like valleys of the Tintina Trench separating Selwyn Basin from the Cordillera west of Tintina and of the smaller Shakwak Trench separating the St. Elias Fold Belt from the Cordilleran mountains to the east.

Geological Setting

The Selwyn-Cordilleran Fold Belt is a much more diverse composite of geologically distinct regions than the Interior Platform and the Mackenzie Fold Belt of the Northern Mainland. The main reason for the geological diversity of the Selwyn-Cordilleran Fold Belt is the fact that it includes parts of both the in-place Ancestral North America and of the allochthonous Ancient Phanerozoic Terranes of western North America (Gabrielse and Yorath, 1992). Tintina Trench trending northwest across the middle of the Selwyn-Cordillera Fold Belt marks a fundamental tectonic suture separating Ancestral North America from the allochthonous Ancient Phanerozoic Terranes. The allochthonous Ancient Phanerozoic Terranes originated externally to North America and were successively accreted to western North America during Mesozoic and early Cenozoic plate collisions attendant on sea floor spreading (Gabrielse et al., 1992). These allochthonous Ancient Phanerozoic Terranes were subsequently disrupted, or smeared out northwestward by dextral transcurrent movements along the continental margin. Large volumes of igneous rock were emplaced in the Selwyn-Cordilleran Fold Belt during both continental accretion and during subsequent Late Cretaceous and Tertiary-aged dextrally dominated transtensional and transpressive deformation (Gabrielse et al., 1992).

Exploration History

No petroleum exploration wells have been drilled, and no seismic data has been acquired in the Selwyn-Cordilleran Fold Belt. Whitehorse Trough was recognized early as having possible petroleum potential and some hydrocarbon exploration began within Whitehorse Trough (Fig. 1) in about 1950 (National Energy Board, 2001). In the period of 1961 to 1981, a total of 50 exploration permits were granted and agents acting on behalf of permit holders conducted regional geological studies concerning petroleum prospectivity. In 1985 Petro-Canada carried out fieldwork in the Whitehorse area accompanied by a geochemical and reservoir analysis sampling program and several areas with oil and gas potential were identified (Morrell, 1995; National Energy Board, 2001).

Whitehorse Trough was also found, in the early 1900s, to contain significant coal resources of bituminous to anthracite grade, principally in the Upper Jurassic to Lower Cretaceous Tantalus Formation (National Energy Board, 2001).

Source Rocks

There are no proven source rocks in Whitehorse Trough. However, Templeman-Kluit (1978) noted that the back-reef facies of the Lewes River Group (Hancock Member of the Aksala Formation) are locally bituminous, with up to 1.0% TOC (National Energy Board, 2001), and could source hydrocarbons in coeval reefal and shoal belt carbonate facies of the Lewes Group (Fig. 9). Other possible source rocks include shales in the Jurassic Richtofen Formation and in the Jurassic/Cretaceous Tantalus Formation, both with more than 1.0% TOC. No source rock data have been acquired for the stratigraphically lower Cache Creek Group but some dark algal (dololaminites and dark argillaceous limestones are reported to emit a fetid odour when struck National Energy Board, 2001).

Reservoir Rocks

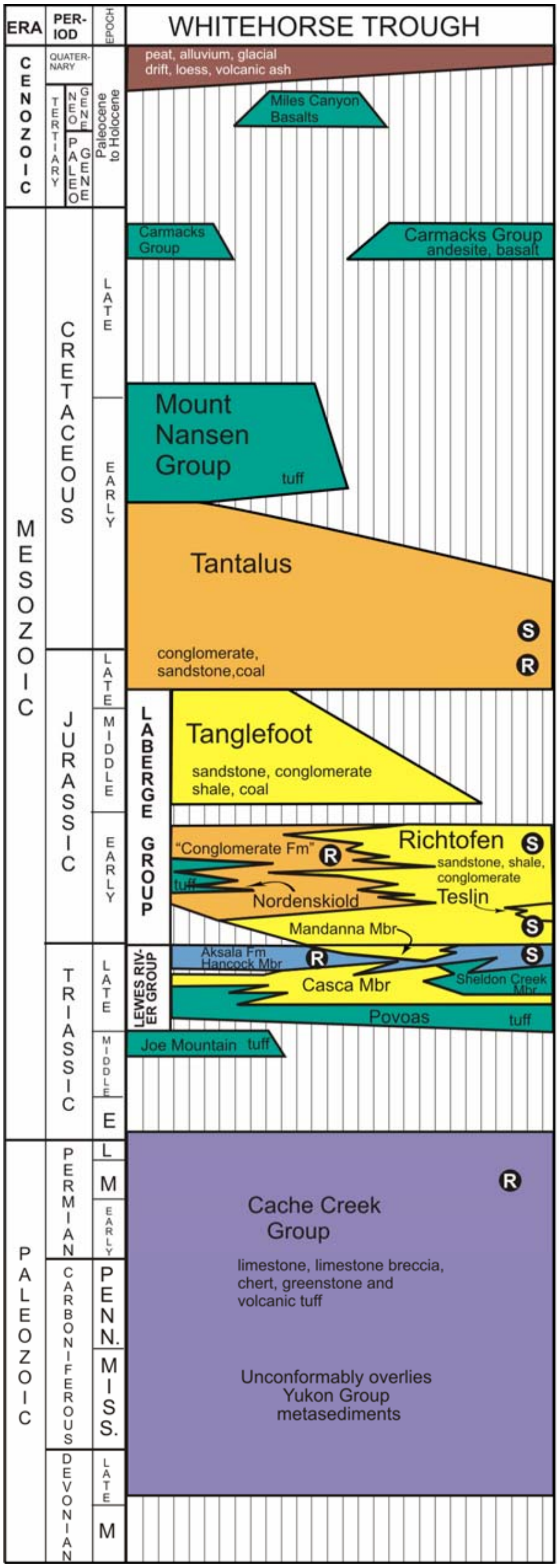
Potential petroleum reservoir strata (National Energy Board, 2001; Fig. 9) in Whitehorse Trough include:

1. Fractured cherty carbonates in the upper Paleozoic Cache Creek Group (Nakina Assemblage),
2. Primary and secondary leached porosity reefal and shoal carbonate mounds of the Triassic Hancock Member in the Aksala Formation (Lewes River Group),
3. Primary porosity in the Lower Jurassic conglomeratic sandstones of the "Conglomeratic Formation" in the Laberge Group, and,
4. Primary porosity in fluvial channel conglomeratic sandstones and fan delta sandstones of the Jurassic/Cretaceous Tantalus Formation.

Maturation and Generation

The geologic history of strata within the Selwyn-Cordilleran Fold Belt, apart from Whitehorse Trough, has generally precluded the preservation of commercial quantities of hydrocarbons. Potential source rocks have been deformed, metamorphosed and heated by high heat flow attendant on deep burial and on igneous intrusions beyond the limits of hydrocarbon preservation as sooty (elemental carbon) metasediments and graphitic schist across large parts of the Selwyn-Cordillera Fold Belt. Even the less deformed and metamorphosed Ancestral North American eastern part of this fold belt has undergone widespread high heat flow attendant on dominantly Mesozoic-aged igneous activity. Paleothermal indicators equivalent to a vitrinite reflectance of 4.5 %Ro indicate that sub-Mesozoic strata have been uniformly heated to at least 300^{O}C (Gordey and Anderson, 1993). Paleotemperatures this high precludes the preservation of significant quantities of even dry gas hydrocarbons (Tissot and Welte, 1984; Dougherty et al., 1991). The pervasive and long-lived brittle deformation of strata in the Selwyn-Cordillera Fold Belt during continental accretion and shearing is also unfavourable for the preservation of early-formed hydrocarbons in traps.

Strata in Whitehorse Trough exhibit a wide range of organic maturity. The background level of organic maturity for much of the Tantalus Formation is estimated to be about 1.7 % (National Energy Board, 2001; Hunt and Hart, 1993) or near the base of the oil generation window. Generally Tantalus strata along the eastern and western flanks of Whitehorse Trough are in the lower part of the oil window but are in the zone of gas generation along the axis of the trough (National Energy Board, 2001). Near igneous bodies, maturity values are dramatically higher.



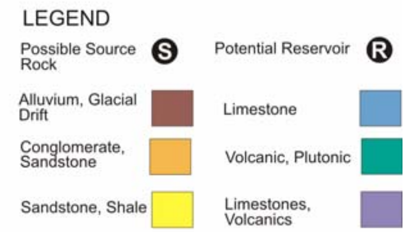


Figure 9. Stratigraphic relationships and nomenclature for the stratigraphic succession within Whitehorse Trough.

Migration and Accumulation

There is little information available concerning possible hydrocarbon migration pathways within strata that occupy Whitehorse Trough. Migration pathways are necessarily inferential and are based solely upon the validity of unproven conceptual hydrocarbon exploration plays (*see* Exploration Plays). In particular, no observations of pore-filling bitumen have been recorded for strata in Whitehorse Trough.

Exploration Plays

Exploration plays in the Selwyn-Cordillera Fold Belt would only be viable in areas where upper Paleozoic to Cenozoic strata of sufficient thickness and lateral continuity cover potential lower Paleozoic to Mesozoic reservoir rock. However, most potential reservoirs in this belt have too elevated a level of organic maturity for preservation of hydrocarbons and also commonly lie within the zone of modern day fresh groundwater recharge so that any hydrocarbons generated may have been flushed from these rocks or biodegraded.

As discussed previously, Whitehorse Trough is the only large region containing a thick succession of Phanerozoic strata at an appropriate level of organic maturity to generate hydrocarbons. Play situations in this region might include:

1. Unconformity pinch-outs beneath the post-Permian unconformity where leached porosity and interfragment breccia porosity in Cache Creek limestones are sealed by basal Lewes River Group strata unconformably overlying the Cache Creek Group (Fig. 9) as a gas play,
2. Stratigraphic primary porosity play of “reefal” carbonate mounds within the Triassic Hancock Member of the Aksala Formation. Mandanna Member siliciclastics provide the surrounding and overlying seal for these reef mounds (Fig. 9) as a gas play,
3. Stratigraphic updip pinchouts of primary and secondary leached porosity within conglomeratic sandstones of the Jurassic “Conglomerate Formation” enhanced by structural development of local anticlines and faults. Intertonguing shale of the coeval Richtofen Formation may act as reservoir seals for this possible oil and gas play,
4. Stratigraphic updip pinchouts of primary and secondary leached porosity within conglomeratic sandstones of the Jurassic “Conglomerate Formation” interfingering with less permeable volcanic rocks of the Nordenskiold Formation that could act as reservoir seals,
5. Structural closures of oil and gas in primary porosity in fluvial conglomeratic sandstone bodies within the Jurassic Tanglefoot Formation,
6. Stratigraphic updip and lateral facies pinchouts and structural closures of oil and gas in primary porosity in fluvial conglomeratic sandstone bodies within the Jurassic/Cretaceous Tantalus Formation against less permeable fine grained siliciclastics within this unit, and,
7. Stratigraphic updip and lateral facies pinchouts and structural closures of oil and gas in primary porosity in coarser sand bodies encased within less permeable, finer grained Cenozoic strata.

Reserves Estimates

No discovered hydrocarbon resources occur within the Selwyn-Cordillera Fold Belt.

Hydrocarbon Potential

A recent petroleum assessment indicates that unbiased estimates for mean amounts of recoverable oil is 1.3×10^6 m^3 (12 MMBbl) and mean amounts of marketable gas is 5.55×10^9 m^3 (196 Bcf) for Whitehorse Trough (National Energy Board, 2001).

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