GEOLOGICAL SURVEY OF CANADA

OPEN FILE 5343

Oil and gas potential of the northern mainland, Canada (Mackenzie Corridor and northern Yukon)

P.K. Hannigan[1], J. Dixon[1], and D.W. Morrow[1]

2006

[1] Geological Survey of Canada (Calgary), 3303-33rd Street, N.W., Calgary, Alberta, Canada T2L 2A7

Natural Resources Canada Ressources naturelles Canada

Canada

GEOLOGICAL SURVEY OF CANADA

OPEN FILE 5343

Oil and gas potential of the northern mainland, Canada (Mackenzie Corridor and northern Yukon)

P.K. Hannigan[1], J. Dixon[1], and D.W. Morrow[1]

2006

Available from
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

[1] Geological Survey of Canada (Calgary), 3303-33rd Street, N.W., Calgary, Alberta, Canada T2L 2A7

Hannigan, P.K., Dixon, J., and Morrow, D.W.
2006: Oil and gas potential of the northern mainland, Canada (Mackenzie Corridor and northern Yukon); Geological Survey of Canada, Open File 5343, 45 p.

Open files are products that have not gone through the GSC formal publication process.

TABLE OF CONTENTS

ABSTRACT

A description of petroleum resource potential for all sedimentary strata in the northern mainland of Canada is presented in this open file. The study area includes the Interior Platform of Northwest Territories, Beaufort-Mackenzie Basin, Northern Foreland Belt and Northern Yukon Fold Complex in Northwest Territories and Yukon. Very conservative estimates of total resource endowment in the Interior Platform are 1.22×10^9 m^3 and 1.56×10^{12} m^3 of in-place oil and gas, respectively. Very high petroleum potential is expected to occur in the subcrop extent of Cambrian sands in the Colville Hills area, the Kee Scarp reef fairway near Norman Wells, and on the barrier and in the back-barrier of Presqu'ile barrier complex in the south. The greatest number of discoveries and potential in the northern mainland occurs in the Beaufort-Mackenzie Basin, where total resource estimates are 1.13×10^9 m^3 of mean recoverable oil and 3.32×10^{12} m^3 of mean recoverable gas. Gas hydrate potential in the Beaufort-Mackenzie Basin is immense ($2.4 - 87 \times 10^{12}$ m^3). In Liard Plateau of the Mackenzie Fold Belt, in-place resource potential for natural gas is 2.77×10^{11} m^3. In Eagle Plain basin, total resource endowment is predicted to be 6.94×10^7 m^3 and 1.71×10^{11} m^3 (in-place volumes). With respect to nation-wide petroleum potential, Beaufort-Mackenzie Basin is rated high while the remainder of the northern mainland has a low to moderate rating.

INTRODUCTION

A most crucial frontier region in Canada with respect to oil and gas potential is located north of 60^o latitude encompassing most of Northwest Territories (N.W.T.) and northern Yukon, west of the Canadian Shield. This 'northern mainland' area of Canada comprises the northward extension of the prolific Western Canada Sedimentary Basin of Alberta and British Columbia into the N.W.T. and Yukon and the Beaufort Sea. The Phanerozoic sedimentary succession of the northern mainland basin is separable into two distinct geological terranes, the relatively undeformed platform underlying the plains area of N.W.T. and the deformed fold and thrust belt of the Cordillera in western N.W.T. and northern Yukon. The area encompassing Phanerozoic strata of western N.W.T. is often referred as the Mackenzie Corridor since it encompasses the drainage system of the Mackenzie River.

The northern mainland is subdivided into four geological provinces. These provinces include the Interior Platform and Beaufort-Mackenzie Basin in the relatively undeformed platform terrane, and the Northern Yukon Fold Complex and Northern Foreland Belt within the fold and thrust belt of the eastern Cordillera (Figure 1). The northern foreland belt here is distinguished from the southern or Rocky Mountain Foreland Belt representing folded and thrusted strata east of the Rocky Mountain front in British Columbia and Alberta. Although Selwyn Fold Belt directly west of the Foreland Belt partly includes autochthonous Ancestral North America, it is considered to have little or no petroleum potential. The allochthonous terranes southwest of Tintina Trench in Yukon Territory are considered part of the Intermontane terrane of the Cordillera and are not discussed here. Underlying the Phanerozoic rocks throughout most of the northern mainland region is a thick Proterozoic succession of unmetamorphosed siliciclastic and carbonate sediments (Figure 2). In the southern part of the interior plains area, basement consists of Precambrian crystalline igneous and metamorphic rocks comprising the westward extension of the craton beneath Phanerozoic cover (Figure 2). The four geological provinces are informally divided further according to physiographic character into exploration regions or 'basins' displaying common petroleum geology (Figure 1).

The most significant discoveries to date in the northern mainland are oil and gas fields in the Beaufort-Mackenzie Basin, large gas fields in the Liard Plateau of the northern Foreland Belt, an oil field in the Mackenzie Plain at Norman Wells, and lesser oil and gas discoveries in the Colville Hills of the Interior Platform and Eagle Plain in the Northern Yukon Fold Belt. New discoveries in the Corridor include a condensate and natural gas find made in 2004 at Summit Creek B-44 and natural gas in 2006 at Stewart D-57; both wells located near the eastern edge of the Mackenzie Mountains in central Mackenzie Valley.

INTERIOR PLATFORM

The Interior Platform of the northern mainland underlies the plains of the N.W.T. east of the Cordillera and west of the craton. A small portion of northeastern Yukon and west-central Nunavut occurs in the Interior Platform geological province as well (Figure 1). The province contains Great Slave Plain, Great Bear Plain, Colville Hills, Horton Plain, Anderson Plain, Peel Plain and Peel Plateau exploration regions.

Geological setting

During Late Precambrian time, multi-phase rifting isolated the North American proto-continent and created a continental margin on its western side. Extensional tectonics occurring at this time created horst and graben features upon which sediments of the evolving and subsiding Paleozoic passive margin were deposited.

North of Great Slave Plain, a very thick succession of deformed Proterozoic sedimentary rocks underlies the Phanerozoic succession. This 13-16 km thick dominantly siliciclastic succession is principally known by seismic stratigraphy and very few wells have penetrated these rocks. The stratigraphy of these Proterozoic sediments is discussed further in Aitken (1993) and Cook and MacLean (2004). Enormous structures are present in these old rocks and large hydrocarbon reservoirs could be present. Little information exists, however, on the occurrence of porous units or potential source rocks. Aitken (1981) and Cook and MacLean (2004) identified very large stromatolitic reefs, bioherms and biostromes within parts of the Proterozoic assemblage.

Cambrian to Upper Devonian strata underlie most of the Interior Platform, except under Great Slave Plain where Cambrian to middle Lower Devonian sediments were largely removed or not deposited. Beneath Great Slave Plain, sedimentation commenced in Early Devonian time and continued in western Great Slave Plain to Late Carboniferous time and then recommenced in Middle Permian with Fantasque Formation deposition (Figure 2). Initial Cambrian deposition under most of the Interior Platform consists of basal transgressive sandstone called the Mount Clark or its equivalent Old Fort Island Formation overlain gradationally by shale with thin sandstone and carbonate beds of the Mount Cap Formation. Dixon and Stasiuk (1998) indicate that Cambrian sandstones do not extend into Peel Plain and are missing under Great Slave Plain. The relatively thin Mount Clark-Mount Cap succession and the apparent lack of abrupt thickness changes over large areas of the basin along with numerous marine characteristics (bioturbation, uneven blanket distribution of sands, carbonate beds) suggest deposition under slow uniform subsidence conditions in a pericratonic basin. The Mount Cap Formation is unconformably overlain by the Saline River Formation characterized by interbedded shale, carbonate and evaporites such as halite and anhydrite (Dixon and Stasiuk, 1998).

Early clastic deposition was superseded by a thick succession of Upper Cambrian to Middle Devonian shelf and bank carbonates containing a number of regional unconformities. Saline River strata are gradationally overlain by numerous cyclical carbonate platform successions separated by episodes of regression and erosion, the Franklin Mountain, Mount Kindle, Delorme, Bear Rock/Arnica, and Landry formations (Figure 2). Most of these carbonates are comprised of dolostone. The carbonates pass laterally westward into basinal shales of the Road River Group in Peel Plain (Figure 2).

Phanerozoic sedimentation beneath Great Slave Plain commenced with deposition of basal red beds (Figure 2) on the flanks of the Tathlina Arch, an east-west subaerially exposed topographic high that persisted until Late Devonian time (Meijer-Drees, 1993). Interbedded evaporites, shales and minor carbonates of the Mirage Point and Ernestina Lake formations and Lower Chinchaga member overlie the basal clastics and onlap Tathlina Arch.

The next major depositional cycle or sequence occurring beneath the Interior Platform began with a major transgression marked by the transition from a shallow epicontinental sea to a more open-marine environment and ended with a regression (the “Ebbutt” break) where the central part of the region emerged (Moore, 1993). This late Middle Devonian succession consists of carbonate and shale. Continued subsidence and marine transgression led to the development of a great carbonate barrier complex beneath Great Slave Plain stretching from Great Slave Lake southwestward to the Cordillera in northeastern British Columbia. The Presqu'ile barrier complex proved effective at this time in separating normal marine conditions to the north, where Hume and Ramparts shelf carbonates and Horn River Group shales were deposited, from restricted shallow marine waters to the south where evaporitic Muskeg sediments were laid down (Meijer-Drees, 1993). The barrier complex consists of shallow-water Upper Keg River dolomite and Sulphur Point limestone units. In many parts of the barrier complex, a diagenetic dolomite phase called Presqu'ile dolomite replaced Upper Keg River/Sulphur Point carbonates.

The pronounced base-level drop marking the end of the preceding major depositional cycle resulting in the deposition of coastal-marine shales of the Watt Mountain Formation also signalled the beginning of the ensuing major depositional sequence (Meijer-Drees, 1993; Moore, 1993). Transgression prevailed during the early part of the sequence. Coastal evaporation occurred at the beginning of transgression south of the Presqu'ile barrier. The anhydritic Fort Vermilion Formation is overlain by open-marine platform carbonates of the Slave Point Formation (Meijer-Drees, 1993). North of Presqu'ile barrier, condensed sediments of Horn River Group were deposited in a starved basin (Moore, 1993). In eastern Peel Plain, cyclic changes in water depth promoted episodes of reef-building, specifically Kee Scarp growth on the Ramparts platform. Kee Scarp reef growth represents the final episode of carbonate deposition in the region (Figure 2). Canol dark siliceous shales surround these reefs and interfinger with their flanking beds (Moore, 1993). Succeeding the Canol shales north of Great Slave Lake are siliciclastic sediments of shallow to deep marine character of the Imperial Formation (Moore, 1993). In Great Slave Plain south of Presqu'ile barrier, the western margin of the east platform displays interbedded carbonate shelves and shale successions in a general shoaling-upward sequence. A progradational phase follows where carbonate ramps extend further west into open-marine shales of the Fort Simpson Formation (Meijer-Drees, 1993).

The final Devonian depositional cycle south of the Presqu'ile barrier is marked initially by a major regression characterized by basal silty sand (Trout River Formation; Figure 2). Renewed transgression began with deposition of prograding ramp carbonates and shales of the Tetcho Formation and Kotcho formations (Figure 2). The carbonates were deposited during uniform subsidence (Meijer-Drees, 1993; Moore, 1993).

Throughout most of the Interior Platform, Carboniferous to earliest Cretaceous strata are missing, except for upper Carboniferous strata preserved in western Peel Plateau (Richards et al., 1993) and lower Carboniferous as well as middle Permian rocks in western Great Slave Plain (Richards et al., 1993; Henderson et al., 1993; Gal and Jones, 2003). In western Great Slave Plain, black shales of the Exshaw Formation disconformably overlie the Fammenian Kotcho Formation. This organic-rich unit was deposited in moderately deep water in an anaerobic basin. Gradationally overlying Exshaw strata are deep water turbiditic shale deposits and slope to shelf silty limestones of the Banff Formation (Figure 2). A major regional transgressive episode ensued with deposition of deeper-water Pekisko and Clausen formations, followed by the shallowing-upward succession of the Prophet and Flett formations. Subsequently, a major regression is recorded by deposition of a basinward-prograding succession characterized by prodelta deposits of the Golata Formation overlain by sandstone-dominated delta plain deposits of the Mattson Formation (Richards et al., 1993; Figure 2). Unconformably overlying the Mattson Formation in southwestern Great Slave Plain is a thin succession of cherts, siltstones and sandstones of the Permian Fantasque Formation.

Upper Lower Cretaceous Albian strata rest unconformably on Paleozoic rocks throughout the Interior Platform. The Columbian Orogen in the Cordillera to the west transformed the Paleozoic oceanic margin into a continental seaway where westerly-derived Mesozoic detritus was shed into the tectonically-generated foreland basin. In southwestern Great Slave Plain, Mannville-equivalent Fort St. John Group sandstones and shales were deposited. This assemblage contains numerous transgressive-regressive cycles. In Colville Hills, earliest Albian transgression is represented by an extensive thin basal sandstone (Martin House Formation) succeeded by a shale-dominant unit called the Arctic Red Formation (Figure 2). Fine-grained sand and mud were deposited in Great Bear Basin and marine shales were laid down on a broad shelf across Anderson Plain. By late Middle Albian time, coarse marine clastic sediments of the Trevor Formation were accumulating in Peel Trough. Regression during Middle to Late Albian time ended the Albian flooding. A regional unconformity separates Albian sediments from Upper Cretaceous strata throughout most of the Interior Platform, except in western Great Slave Plain where a conglomeratic piedmont-alluvial plain facies of the earliest Late Cretaceous Dunvegan Formation was deposited.

Preserved Upper Cretaceous strata include shales of the Slater River Formation and interbedded sandstone and shale of the Little Bear Formation and Trevor Formation in Peel Plain and Great Bear Plain, dark bituminous shales of the Smoking Hills Formation in Anderson Plain, shale beds of Mason River Formation in Anderson Plain and equivalent East Fork shales in Great Bear and Peel plains. The Upper Cretaceous has been stripped from the axis of the Keele Arch beneath Colville Hills. In southwestern Great Slave Plain, Upper Cretaceous formations include shale with thin sandstone layers in the Kotaneelee Formation overlain by sandstones of the Wapiti Formation (Figure 2).

In the Interior Platform, Proterozoic strata are folded and thrust-faulted but the overlying Phanerozoic succession is generally mildly deformed into broad folds on west-dipping homoclinal wedges. Broad ancient uplifts such as Tathlina and Keele arches and Campbell Lake Uplift were periodically reactivated during sedimentation. Minor normal faults are also present. Phanerozoic rocks are more intensely affected in Colville Hills due to Early Tertiary deformation creating numerous tight and thrust-faulted anticlines (Cook and Aitken, 1971, 1973). These folds are underlain by large Proterozoic structures (MacLean and Cook, 1992). The thrust-faulted anticlinal structure configuration is also observed in Peel Plain and Plateau, where these structures extend into Cretaceous strata. Favourable cyclic sea-level changes during Middle Devonian time led to greater differentiation of marine strata into large reef complexes and shale basins. Such reef complexes include the Presqu'ile barrier complex beneath Great Slave Plain and isolated reef bodies in Horn Plateau.

Exploration history

Although the first petroleum discovery in the northern mainland was made at Norman Wells in the Foreland Belt directly west of the Interior Platform, the development of the oil field greatly affected exploration activity in the Interior region. As a result of increased Norman Wells production in the late 1980's, exploration activity also increased in the remainder of the Northwest Territories. At the time of writing, approximately 465 exploratory wells have been drilled in the Interior Platform. Most drilling has been concentrated in Great Slave Plain. The first natural gas discovery in Northwest Territories was made in 1955 at Rabbit Lake beneath Great Slave Plain. Gas is found in Sulphur Point limestones containing good intergranular porosity. The gas accumulation occurs on the crest of an anticline draped over a horst structure formed by block faulting in the basement. In 1960, a single-well gas field was discovered in Slave Point platform carbonates on the highest central portion of the Celibeta structure at the western edge of Tathlina Arch in southwestern Great Slave Plain. The structure is a closed dome on the northwest side of a northeast-trending Precambrian fault zone. In 1961, a gas pool trapped in porous siliceous chalky limestones within the Slave Point Formation on the barrier shelf edge was discovered at Netla. More gas discoveries were made in 1964 and 1965 in reefal shelf-edge dolomites and limestones of the Slave Point Formation at Island River and Trainor Lake, respectively. Another single-well gas field, discovered in 1969, in Slave Point carbonates occurs at Grumbler, where differential drape overlies a wet Keg River pinnacle reef. The Tathlina Slave Point gas pool trap, found in 1973, is formed by drape over an uplifted Precambrian fault block at the margin of the Elk Point evaporite basin.

The next major gas discovery (1974) was made northeast of Great Bear Lake in Colville Hills. Tedji Lake K-24 discovered gas in Cambrian Mount Clark sandstone in a block-faulted anticline. Further discoveries in Cambrian sands were made to the south at Tweed Lake and Bele in 1985 and 1986, respectively.

A significant exploration play in southern Great Slave Plain occurs in the Cameron Hills area. An important geological feature of this area is the frequent occurrence of Precambrian basement faulting producing horsts and grabens. Gas and oil accumulations are present in Keg River, Sulphur Point and Slave Point formations. Porosity development and enhancement affected Keg River and Sulphur Point strata. Differential drape over horst blocks formed trapping configurations for Slave Point strata. Oil and gas production commenced in 2002 in nine wells from the three reservoir intervals (Gal and Jones, 2003).

The Arrowhead region in southwestern Great Slave Plain immediately east of the Bovie Lake Fault Zone yielded two gas discoveries. A Keg River pool was discovered in 1985 in the Nahanni/Manetoe dolomite facies in a small marginal reef buildup on the Keg River platform. In 1989, a well at Arrowhead B-41 discovered gas trapped in Cretaceous channel sands incised into the Paleozoic surface.

Great Slave Plain has yielded the greatest number of major oil and gas shows in exploration wells, 8 oil and 25 gas. Among three wells reporting gas flows in Colville Hills, Anderson Plain and Peel Plain, the H-35 well in Peel Plain is most significant where substantial sweet gas flowed from the Canol Formation.

Source rocks

There are numerous potential source rocks in the Interior Platform.

1) Scattered thin beds of algal-rich shales are present in Cambrian Mount Cap Formation in the Colville Hills (Wielans et al., 1990; Dixon and Stasiuk, 1998). The beds vary in total organic matter (TOC) from 1.5 to 6%. These oil-prone source rocks exhibit maturity levels ranging from thermally immature in central Colville Hills to mature with Type I kerogens near Tweed Lake (Dixon and Stasiuk, 1998). Snowdon and Williams (1986) completed a number of geochemical analyses of Cambrian strata to the south of Colville Hills in Great Bear Plain, and indicated that these rocks are probably within the oil generation window, but no potential source rocks have been found.

2) The source for gas accumulations in Cambrian strata at Colville Hills is unknown. One possibility may occur in the underlying Proterozoic sedimentary succession. There have been limited thermal maturation and petroleum source potential analyses completed on these rocks. Most samples have low total organic carbon contents of less than 0.4% (Snowdon and Williams, 1986). The most positive result was obtained in the Colville Hills from a 75 m thick shale unit (in the Proterozoic Dismal Lakes Assemblage) containing up to 1.4% organic carbon at maturities above the oil window, but within the gas generation phase (Snowdon and Williams, 1986).

3) There are thousands of metres of Lower Paleozoic graptolitic black shale in Richardson Trough juxtaposed against shelf carbonates in Peel Plateau and Plain. These Road River Formation strata occasionally yield high TOC values up to 9.6% of Type I and II kerogens (Link et al., 1989). Maturation studies show these once-excellent oil-prone source rocks generated hydrocarbons as early as Carboniferous time and are now overmature (Link and Bustin, 1989). Residual bitumen is fairly common on surface and in the subsurface, suggesting that most gas generated from the originally-held oil in the reservoirs has largely escaped, leaving behind the bitumen and possibly minor amounts of gas.

4) An organic-rich shale occurs in the Middle Devonian Bluefish member of the Hare Indian Formation beneath Peel and Anderson Plains. This oil-prone source rock has been correlated to bitumen found in Hume carbonates. These rocks are mature and may have generated large volumes of both oil and gas over much of the area (Snowdon et al., 1987; Feinstein et al., 1988).

5) In Great Slave Plain, a most important potential source rock is the Middle to Upper Devonian Fort Simpson/Horn River/Muskwa shale succession. The basal Evie member of the Horn River Formation is mature to overmature over most of the area (Feinstein et al., 1991a; Fowler et al., 2001). Both oil and gas would be expected to be generated in the area. Significant gas finds have been made in southwestern Northwest Territories, but no oil discoveries have been made to date. The Muskwa member is bituminous

organic-rich shale with Type II organic matter. The member is mature and likely generated large quantities of oil and gas. However, no discoveries have been correlated to this unit (Fowler et al., 2001).

6) Beneath Peel, Anderson, and Great Bear Plains and southern Colville Hills, Middle to Upper Devonian organic-rich bituminous Canol shales occur. Residual kerogen measured as total organic carbon range between 0.76 to 8.6% TOC (Morrow, 1999; National Energy Board, 2000a). This excellent source rock has been geochemically correlated to the Norman Wells oil pool beneath Mackenzie Plain in the Foreland Belt to the west of the Interior Platform and this proven source has likely generated hydrocarbons in the platform area as well.

7) In eastern Peel Plateau, the Upper Devonian Imperial Formation contains mature organic-rich shale in the lower part of the section (Pugh, 1983; Link et al., 1989). Highest TOC values range from 1.4 to 1.7% in these shales and these strata have fair to good gas source potential. Outcrop samples of solid bitumen (albertite) occur in Peel Plateau suggesting excellent oil source potential (Link et al., 1989). It is believed that the solid bitumen was derived from the Canol Formation. The Imperial Formation contains gas-prone kerogens under Anderson Plain with maturity levels within the oil window (Indian and Northern Affairs Canada, 1995).

8) The latest Devonian-earliest Mississippian Exshaw Formation is a proven organic-rich source rock throughout the Western Canada Sedimentary Basin. It is a good potential source rock in southwestern Great Slave Plain where it is mature and should have generated large quantities of hydrocarbons (Stasiuk and Fowler, 2002).

9) Leckie et al. (1991) identified source rock potential in Triassic Toad-Grayling and Lower Cretaceous Garbutt formations in Liard Basin. In the Garbutt Formation, TOC contents range from 1.39 to 5.2%. Most of the Liard Basin is thermally mature. Migration of hydrocarbons to the east into the Interior Platform is possible.

10) There are excellent Upper Cretaceous oil-prone source rocks on Anderson and Horton Plains. These outcrops of burning Smoking Hills bituminous shales, however, are immature, falling well below the oil window (Mathews and Bustin, 1984).

There are widespread Lower Paleozoic and Devonian platform carbonates and evaporites throughout the Interior Platform. No potential source rocks, however, have been identified in these strata.

Reservoir rocks

Strata containing hydrocarbon accumulations are established reservoir rocks and there are numerous reservoirs of sufficient quality throughout the Interior Platform. In Great Slave Plain, established reservoirs include Devonian reefal and dolomitized carbonate bodies in the Keg River to Slave Point interval along the subsurface edge of the Presqu'ile Barrier. Keg River, Sulphur Point and Slave Point oil and gas accumulations are also found in back-barrier carbonate platforms and isolated reefs in shelf basins. Porous channel sands in basal Cretaceous beds also host gas in Great Slave Plain. Basal Cambrian sandstones host gas pools beneath Colville Hills. These sands are dominantly quartz arenites with lesser quantities of glauconitic or feldspathic sandstones. Numerous cements are present, although quartz, dolomite and clay predominate (Dixon and McDonald, 1978). Dissolution of these cements along with some of the original grains has created highly porous sandstones in some parts of the basin. The common occurrence of bitumen in these sands indicates oil was once present.

There are many additional potential reservoirs in the Interior Platform as well.

1) Beneath Great Slave Plain, potential reservoirs include transgressive pre-Devonian basal clastic rocks onlapping and mantling basement highs such as Tathlina Arch, isolated pinnacle limestone reefs growing on the Middle Devonian Lonely Bay/Keg River carbonate platform in Horn Plateau, and leached or dolomitized Devonian and Carboniferous carbonate platforms such as Lonely Bay/Nahanni, Jean Marie, Kakisa, and Flett formations (Gal and Jones, 2003). It is believed that Kotcho and Tetcho limestones are invariably tight and make poor reservoirs in Great Slave Plain.

2) Post-depositional leaching may also produce potential reservoirs in the Lower/Middle Devonian Arnica/Landry platform carbonate throughout most of western Interior Platform.

3) The Lower-Middle Devonian Bear Rock dolomite and evaporite unit commonly has cavernous porosity.

4) Intergranular or vuggy porosity can also be developed in other Devonian platform carbonates or pinnacle reefs growing on the Hume platform.

5) Middle Devonian Kee Scarp reefs growing on Ramparts platforms are potential reservoirs beneath eastern Peel Plain and Anderson Plain.

6) The Canol shale may also be a producer if highly fractured.

7) Cretaceous sandstones, specifically the Albian to Santonian Martin House basal sand and Little Bear Formation may have reservoir potential.

8) Beneath western Peel Plain, there are numerous stacked shelf edge carbonates adjacent to and interfingering with an extensive shale succession in Richardson Trough. The limestones fringing the trough are usually tight, but there is development of patchy dolomitic facies further east (Indian and Northern Affairs Canada, 1995).

9) Shelf and slope deposits of the turbiditic Imperial Formation become sandier westward and northward and these sandstone lenses may occasionally develop sufficient porosity.

10) Shallow shelf and shoreface Mesozoic sandstones are potential reservoirs in Peel Plain.

11) Potential reservoir intervals under Colville Hills include vuggy and fractured Franklin Mountain and vuggy Bear Rock carbonates.

12) In Great Bear Plain, reservoirs include Cambrian sandstones and basal Cretaceous sandstones.

13) In Anderson and Horton Plains, Cambrian sands, Lower Paleozoic carbonates, and sandstones in the Imperial Formation and Cretaceous strata may have reservoir potential.

Accumulation and preservation

Trapping configurations in Slave Point, Sulphur Point and Keg River carbonate reservoirs in Great Slave Plain are commonly associated with broad uplifts, normal faults and stratigraphic bioherms and biostromes. Basement topography affected overlying Phanerozoic strata, producing subtle folds and orthogonal patterns of normal faults with small throw and northeasterly-trending wrench faults of Precambrian age (Morrow et al, 2002; MacLean, *in press*). Top seal for Slave Point accumulations is the thick Muskwa/Hay River/Fort Simpson shale succession. Sulphur Point gas pools are top-sealed by Watt Mountain shales and laterally by Horn River shales to the north. Keg River dolomite traps are sealed by Muskeg anhydrites and Horn River shales. In western Great Slave Plain, folding and thrusting associated with the Cordilleran Orogen trap gas. The Presqu'ile barrier reef front is controlled partly by erosion and embayments, which provides opportunities for the development of stratigraphic traps. Several Horn Plateau pinnacle reefs north of the barrier have been tested with little success. Lack of dolomitization in many of the reefs may have produced insufficient porosity. Breaching of the reservoir or barriers to migration between source and reservoir may be significant (Indian and Northern Affairs Canada, 1995). At Cameron Hills, horst blocks formed by reactivated Precambrian faults produce three stacked Middle Devonian reservoirs. Porosity-enhancing formation fluids were introduced to the carbonate strata by basement faults extending through the Middle Devonian succession. The main trapping configuration at Cameron Hills consists of draping of carbonate strata, increasingly subtle at higher stratigraphic levels, over the Precambrian horst blocks.

No oil and gas discoveries have been made in Upper Devonian carbonate successions in Great Slave Plain (Jean Marie, Tetcho and Kotcho formations). Gas production does occur, however, at the carbonate platform edge from the Jean Marie Formation in northeastern British Columbia, and the edge continues to the north under Great Slave Plain. Porous zones may have developed in dolomitized shelf platforms, shelf edges and reefal mounds near the platform edge in Northwest Territories. Mississippian subcrop traps beneath Cretaceous cover may exist in southwestern Great Slave Plain.

The principal exploration play in Colville Hills is a family of natural gas prospects occurring in basal Cambrian sandstones of the Mount Clark Formation as well as thin sands in the overlying Mount Cap Formation. The Tweed Lake pools occur in a large low-relief anticline created by Laramide transpressional reactivation of a Proterozoic fault (Cook and MacLean, 2004). MacLean and Cook (1992) interpret flower structures in Cambrian strata, typically resulting from transpressional stress. Extensional grabens and half-grabens localized by reactivation of Proterozoic faults produced roll-over anticlines or other structural culminations that may trap hydrocarbons. Potential stratigraphic trap configurations are another important feature to examine in the Cambrian reservoirs. Until the Laramide orogeny, Cambrian rocks were part of a west-dipping homocline. Since this homoclinal structure prevailed over a long period of time, it is reasonable to expect that hydrocarbons could have migrated updip until they were trapped against updip seals, paleotopographic highs or lateral facies changes. Effective regional top seals to Cambrian gas are the Cambrian Mount Cap shale succession and the overlying Saline River salt. No significant oil accumulations have been found despite the occurrence of a known oil-prone source rock.

In Peel Plain and eastern Peel Plateau, previous work (Pugh, 1983; Indian and Northern Affairs Canada, 1995; National Energy Board, 2000a) suggested a major conceptual play involving multiple potential targets may be present where the localization and stacking of Cambrian to Devonian shelf edge carbonates are adjacent to and interfingering with potential source rocks and seals of the Road River Formation to the west in Richardson Trough. Pugh (1983) stated that gas found in the porous zones of the Mount Kindle and Landry formations in Mobil Gulf Peel YT H-71 well is stratigraphically closed on its updip or western side by Road River shale in Richardson Trough. Osadetz et al. (*in press* (b)) objected to this potential stratigraphic trapping configuration because Laramide tectonics induced a westward regional dip of potential Paleozoic carbonate reservoirs. Any hydrocarbons that may have been generated in the Road River Group likely migrated eastward and updip past the shelf-edge margin into the carbonate platform (Osadetz et al. (*in press* (b)). East of the shelf edge, there is patchy porosity development within the carbonate platform. Isolated carbonate buildups growing on drowned carbonate platforms specifically on the Hume platform in eastern Peel Plain may embody diagenetic/stratigraphic traps containing these westerly-derived hydrocarbons. Structural traps in the region are dominantly Late Cretaceous and younger, post-dating the passage of Paleozoic source rocks through the oil window before the end of Mesozoic time (Link and Bustin, 1989). This timing constraint suggests that the most effective hydrocarbon traps formed before Tertiary time during periods of active oil migration. This timing restriction has also been noted in Liard Plateau where maturation models suggest a Late Devonian heating event and the generation of liquid hydrocarbons during Late Paleozoic to Early Mesozoic time (Potter et al., 1993). However, an effective petroleum system does exist in Liard Plateau, regardless of our understanding of its function or history. Peel Plateau appears to have similar stratigraphic and possibly thermal histories to Liard Plateau (Osadetz et al., *in press* (b)).

There was also speculation in previous work (National Energy Board, 2000a) that a pre-Laramide stratigraphic play-type similar to the Manetoe dolomite play in Liard Basin may also occur in Peel Plain and eastern Peel Plateau. Morrow (1999) indicated that the only identifiable dolomitized and fractured dolomite north of 63^{o} Latitude occurs in western Eagle Plain and Osadetz et al. (*in press* (b)) suggests that there is no reasonable expectation of hydrothermal dolomitization activity in the Peel region. Potential stratigraphic traps, however, likely occur within Upper Devonian Imperial turbidites and Lower Cretaceous sandstone reservoirs in Peel Plain and eastern Peel Plateau.

Structural trapping components beneath Great Bear Plain are limited. Structure is confined to minor fault displacement along northeast-trending principal fractures and subsidiary orthogonal fractures. This fracture pattern in Cambrian strata is inherited from the underlying Proterozoic fabric. The potential Cambrian clastic play in the region consists of small fault-bounded structural traps with stratigraphic pinchouts (Indian and Northern Affairs Canada, 1995). Another important stratigraphic trap-type in the region is the sub-Cretaceous unconformity configuration. Cambrian through Middle Devonian strata subcrop beneath Cretaceous cover. Seal integrity, however, may be compromised in eastern Great Bear

Plain because the overlying basal Cretaceous unit is sandy. Structural-stratigraphic traps related to underlying paleotopography in basal Cretaceous sandstones varying greatly in thickness are plausible (Indian and Northern Affairs Canada, 1995).

Stratigraphic trapping configurations are likely dominant beneath Anderson and Horton plains (Indian and Northern Affairs Canada, 1995). Lower to Middle Devonian strata subcropping beneath the pre-Cretaceous unconformity on the western flanks of Keele and Coppermine arches may trap hydrocarbons. Associated risks are reservoir development and breaching. Cambrian sands contain possible traps such as updip pinchouts in eastern Anderson Plain. Overlying Mount Cap shales and Saline River evaporites provide an effective top seal but the lack of an effective source rock is problematic. In Anderson basin, Lower Cretaceous sandstones underlie Upper Cretaceous shales. Potential channel sandstone stratigraphic traps in an incised drainage system are effectively sealed by overlying shales (Indian and Northern Affairs Canada, 1995).

Exploration plays

A listing of exploration plays of the Interior Platform and their characteristics are given in Table 1. There are 23 oil and/or gas exploration plays in the Interior Platform; thirteen of these plays are established. Many of these plays extend into northern Alberta and British Columbia and Yukon Territory. Total booked reserves in 2000 for all established plays located wholly or partly in the Interior Platform are 602.3 x 10^6 m^3 of oil and 1072.5 x 10^9 m^3 of gas (in-place volumes). Established reserves within the study area (Figure 1; not including Alberta and British Columbia) are very much reduced chiefly due to relative limited exploration in the territories. These reserves are 1.2 x 10^6 m^3 of in-place oil and 9.03 x 10^9 m^3 of in-place gas. Major gas accumulations are found in Cambrian sands in the Colville Hills region.

Recent resource estimates

Most established plays and selected conceptual plays had been previously assessed for petroleum potential. Table 1 lists the most recent estimates of conventional oil and gas resources for these exploration plays in the Interior Platform (Reinson et al., 1993; Barclay et al., 1997; Warters et al., 1997; Lee, 1998; Canadian Gas Potential Committee, 2001; Drummond, 2004; Osadetz et al., *in press* (b)). The methodology and vintage of these assessments are given. In some cases, resource potential studies are restricted by political boundaries (see Comments on resource volumes column in Table 1) rather than with respect to the underlying geology defining the play. These political restrictions have left numerous gaps with respect to defined play areas resulting in incomplete resource potential predictions. New established plays have been discovered and defined from previous conceptual plays since these most recent assessment studies. Also, numerous defined conceptual plays in the area had not been quantitatively assessed at any time by modern assessment techniques. Many plays defined in Great Slave Plain are located in the mature Western Canada Sedimentary Basin, where much exploration has taken place since assessments were completed and numerous new discoveries have been made. Periodic updated assessments are required in plays possessing these active exploration programs. Numerous gaps with respect to hydrocarbon assessment results in many of the exploration plays are evident from Table 1, making estimates of total remaining resource in the Interior Platform suspect at best.

Qualitative oil and gas resource assessments have also been completed in the area (Indian and Northern Affairs Canada, 1995; Gal and Jones, 2003; Gal, 2005). These assessments assign comparative hydrocarbon qualitative rankings ranging from low to very high within the Interior Platform. Very high petroleum potential areas include the Cambrian sandstone play area in the Colville Hills exploration region and the southern Great Slave Plain exploration area corresponding to the Middle Devonian Presqu'ile barrier and back-barrier areas (Gal and Jones, 2003; Gal, 2005). These areas contain known oil, gas or condensate discoveries and are expected to contain many more discoveries. In southern Great Slave Plain there are less than 400 wells, but in neighbouring northern Alberta and British Columbia there are more than 50,000 wells with numerous discoveries in areas of similar geology. Large areas in Peel Plain and Plateau, Anderson Plain and Great Bear Plain remain relatively untested with few wells.

With respect to nation-wide oil and gas potential, however, the petroleum potential in the Interior Platform is likely low. According to National Energy Board's report on Canada's energy future (National Energy Board, 2003), only 1% of Canada's oil and 3% of gas is expected to be present in mainland Northwest Territories and Yukon (which would also include the Northern Foreland Belt and Northern Yukon Fold Complex regions discussed below).

BEAUFORT-MACKENZIE BASIN

The second and most significant geological province with respect to oil and gas potential in the Mackenzie Corridor is the Beaufort-Mackenzie Basin (Figure 1). This province underlies Mackenzie Delta, Tuktoyaktuk Peninsula, Richards Island, Yukon coastal plain and the adjacent offshore area in the Beaufort Sea.

Geological setting

Unnamed Proterozoic platformal sedimentary strata underlie Mackenzie Delta and Tuktoyaktuk Peninsula and are exposed at Campbell Lake Uplift south of Inuvik. Deep reflection seismic studies reveal very thick (12 to 15 kilometres) thrust-faulted low-grade metamorphic sediments (Cook et al., 1987; Wielens, 1992). In the British Mountains adjacent to the Yukon coastal plain, highly deformed argillites, sandstones and argillaceous limestones of presumed Proterozoic age are exposed. Proterozoic strata thin dramatically towards the Beaufort Sea (Cook et al., 1987).

A major regional unconformity separates Proterozoic strata from overlying Upper Cambrian to Devonian strata (Figure 2). Lower to Upper Cambrian clastics associated with evaporites prominent in Anderson Plain and Colville Hills pinch out towards the Eskimo Lakes area and do not appear to be present beneath the basin. A thick carbonate succession of latest Cambrian to Middle Devonian age was deposited on the early Paleozoic passive continental margin. These shallow water shelf sediments are dominantly dolostone (Franklin Mountain and Mount Kindle formations and unnamed carbonates equivalent to Arnica, Landry, and Peel formations). Westward off the continental margin, the carbonates are replaced by deep-water shales, cherts and turbidites of the Road River Group. Topping this major carbonate succession are platformal limestones of the Hume Formation (Figure 2). The carbonate succession is succeeded unconformably by a thick wedge of Upper Devonian clastic rocks. The distinct black organic-rich Canol shale directly overlies the carbonate. The Canol Formation is overlain by much thicker gravity-flow conglomerate, sandstone, siltstone, and shale of the Imperial Formation (Figure 2). These Upper Cambrian to Devonian strata appear to be folded or thrust-faulted under Tuktoyaktuk Peninsula (Wielens, 1987). Lower Paleozoic strata are isoclinally folded in the Barn Mountains.

Beneath southwestern Mackenzie Delta, Carboniferous and Permian rocks are preserved. The oldest Carboniferous succession is dominated by terrigenous clastics of the Kekiktuk and Kayak formations. These strata lie unconformably on Devonian rocks and are overlain by shelf carbonates of the Lisburne Group (Figure 2). Unnamed Permian marine sandstones and shales unconformably overlie the Lisburne Group. Triassic sediments seem to be absent under the Mackenzie Delta.

A fundamental change in depositional style and paleogeography is represented by the next tectono-stratigraphic assemblage; a series of northwestward-prograding wedges of clastic sediments ranging in age from Jurassic to Lower Cretaceous (Hauterivian). The coarser clastics are preserved beneath southern Mackenzie Delta and in a northeast-trending arenaceous belt along Tuktoyaktuk Peninsula in Kugmallit Trough. Alternating shale and sandstone-dominant formations occurring within the arenaceous belt grade laterally westward and northwestward into shale-dominant strata of the Kingak Formation. The formations in ascending order in the arenaceous belt are sandstone-dominant Bug Creek Group, shale-dominant Husky Formation and sandstone-dominant Parsons Group (Figure 2). These strata are mostly marine shoreline or shelf sediments except for the lower part of the Kamik Formation (part of the Parsons

Group) that contains a significant nonmarine alluvial component beneath the Mackenzie Delta. Source for this sedimentary package is from the craton to the east and southeast.

A major regional unconformity at the base of the Mount Goodenough Formation marks the beginning of the next tectono-stratigraphic assemblage. The shale-dominated offshore shelf deposits of the Mount Goodenough Formation are widespread occurring beneath Mackenzie Delta, northern Yukon and the Beaufort Sea. The interbedded sandstones and shales of the Rat River Formation gradationally overlie Mount Goodenough rocks. These are coarsening-upward cyclical marine strata. During Mount Goodenough-Rat River marine deposition, a sandstone-conglomeratic fan-delta complex was deposited on the northern flank of the Eskimo Lakes Arch. This complex, deposited under central Tuktoyaktuk Peninsula only, is called the Atkinson Point Formation (Figure 2).

Rifting and sea-floor spreading in the Canada Basin profoundly affected mid-Cretaceous Albian sedimentation. The thick 600 m flysch deposits (Arctic Red Formation) in Kugmallit Trough are slope and basinal strata deposited in a rapidly subsiding basin. Mid- to Upper Cretaceous Cenomanian-Turonian organic-rich, bentonitic and ferruginous Boundary Creek shales unconformably overlie the Arctic Red Formation in the Beaufort-Mackenzie Basin. Another organic-rich marine shale succession overlies Boundary Creek strata. These Upper Cretaceous Coniacian-Campanian rocks deposited on an outer shelf or slope environment are called the Smoking Hills Formation. Uppermost Cretaceous Campanian-Maastrichtian marine shelf muds of the Tent Island/Mason River formations rest unconformably on Smoking Hills/Boundary Creek shales.

A series of basinward prograding deltaic complexes constitute Tertiary to Holocene sedimentation in Beaufort-Mackenzie Basin. Under central Beaufort Sea, the sedimentary succession is 12 to 14 km thick. The rising Cordillera supplied vast supplies of sediment to form these major deltaic complexes. The final orogenic pulse came to an end by latest Miocene time producing a major regional unconformity. The succeeding Plio-Pleistocene strata represent another prograding clastic wedge beneath the Beaufort Shelf (Stott et al., 1993).

Underneath Mackenzie Delta, the Tertiary succession contains alternating sandstone and shale successions. The sandstone-dominant intervals are gradually replaced by shales basinward. In ascending order the formations are Paleocene-Eocene Moose Channel/Reindeer deltaic sandstones, 2000 m of Middle to Late Eocene Richards Formation mudstones (pro-delta shelf deposit), Oligocene Kugmallit Formation deltaic sands, and marine pro-deltaic shelf to slope shales of the Mackenzie Bay Formation (Figure 2). The Middle to Upper Miocene Akpak sequence is present throughout most of the offshore Beaufort-Mackenzie basin but is not present beneath Mackenzie Delta (Dietrich et al., 1985). It consists of mud and silt with a few sandstone beds. The Plio-Pleistocene Nuktak Formation contains a lower non-marine gravel member and an upper marine mud member (Stott et al., 1993). The youngest sequence identifiable by seismic in the offshore Beaufort region is the Holocene Shallow Bay succession consisting of mud, silt, sand and gravel of the modern delta.

Along the southeastern basin margin adjacent to the Eskimo Lakes Arch, a zone of sub-parallel large-scale normal faults exhibit major downthrow to the northwest. These faults showing major movement of Jurassic and Lower Cretaceous units, represent rifting and opening of the Canada Basin during the Mesozoic (Dixon et al., 1994). The Mackenzie Delta and central Beaufort Sea areas are deformed by an extensional structural regime of listric faults and tilted fault blocks. Under western Beaufort Sea, however, compressional and strike-slip structures such as elongate anticlines cut by high-angle thrust faults are prevalent (Lane, 1998). To the north and east, the folds become more symmetric and lack thrust faults. Repeated thinning of strata over structures indicates intermittent growth associated with episodic compression. Large-scale structural elements west of Mackenzie Delta include Blow River and Herschel highs which are positive features cored by closely spaced anticlines. Demarcation subbasin offshore northern Yukon is a syncline filled with Tertiary strata.

Exploration history

In 1965, the first exploratory well was drilled at Reindeer D-27 on southeastern Richards Island. The well was dry but established the presence of a thick Tertiary and Mesozoic sequence. After five more dry wells, the subsequent exploratory well completed in 1970 found a small oil accumulation in a small Lower Cretaceous fan delta (Atkinson Point Formation) adjacent to the Eskimo Lakes fault zone (Atkinson H-25). The first onshore and largest gas and condensate discovery was made in 1971 at Taglu G-33 in north-central Richards Island within Eocene deltaic sandstones. Also, in 1971, a second small oil discovery was made in fractured Paleozoic carbonates subcropping under Tuktoyaktuk Peninsula at Mayogiak J-17. The Parsons gas and condensate field was discovered in 1972 in Kamik sandstone in the Lower Cretaceous Parsons Group. Onshore drilling peaked in 1973.

Offshore drilling began in 1973 with the completion of the Immerk B-48 and Adgo F-28 tests. These wells were drilled on artificial islands. Adgo F-28 discovered oil and gas in Taglu deltaic sandstones. Drilling activity shifted to deeper waters in 1976 where oil and gas was discovered at Nektoralik K-59 in the outer shelf area. Major oil and gas discoveries were made at Kopanoar, Tarsiut, Issungnak and Amauligak in the 1980's. Exploration slowed in the 1980's and virtually ceased in the 1990's. Increased demand and price for gas has led to renewed exploration in Beaufort-Mackenzie since 2001.

About 260 wells have been drilled in the region and several thousand line-kilometres of seismic survey have been acquired. The exploration history discovered 14 oil fields, 21 gas fields, and 18 oil and gas fields. The first commercial production of natural gas from the region commenced in 1999 when a pipeline was constructed connecting the Ikhil gas field to the town of Inuvik for power generation and domestic consumption. A major gas pipeline has been proposed to connect onshore Beaufort-Mackenzie gas reserves to the continental pipeline network in northern Alberta. This project proposal is now proceeding through the regulatory process.

Gas hydrates have been known in the Mackenzie Delta area since early exploration. It was considered a drilling hazard rather than a potential resource. A consortium of industry and governments has recently completed a series of scientific investigations with respect to the properties of gas hydrates and potential production in the Mallik field (Dallimore et al., 2005).

Source rocks

Early studies of potential source rocks at Beaufort-Mackenzie identified three stratal units supplying substantial hydrocarbons to various reservoirs. These units are the Middle Jurassic to Lower Cretaceous Husky Formation (terrigenous gas-prone kerogens supplying gas to the Parsons Lake gas field in the overlying Parsons Group); the Upper Cretaceous Boundary Creek and Smoking Hills formations (oil-prone marine kerogens, 2-12% TOC); and the Eocene Richards Sequence (gas-prone terrigenous kerogens) (Bruce and Parker, 1975; Snowdon and Powell, 1979; Creaney, 1980; Langhus, 1980; Snowdon, 1980; Brooks, 1986a, 1986b). Although Boundary Creek/Smoking Hills strata are rich potential sources of oil, they appear to have contributed little oil to Tertiary reservoirs. Snowdon (1980) speculated that resinite in Eocene shale, which generates oil at low maturity, may be responsible for the abundant oil accumulations in Tertiary strata. Total organic content in Tertiary shales is generally quite low (1-2%) but potential source rock intervals are thick. These thick intervals reach maturity at depths below 4000 m and wide variations in depth occur across fault blocks in the area.

Later work determined that similar biomarker signatures to the Richards source rock also occur in other Tertiary coal and shale successions, such as Fish River, Aklak, Taglu and Kugmallit sequences, suggesting possible additional Tertiary source intervals (Snowdon, pers. comm., 2002). Source intervals in older strata have not been correlated to hydrocarbon accumulations, although Dixon et al. (1989) described potential organic-rich strata in the Albian Arctic Red Formation. Snowdon (pers. comm., 2003) indicated that Lower Cretaceous McGuire strata may also provide a gas source for Lower Cretaceous reservoirs.

Reservoir rocks

There are numerous known and potential reservoirs in the Beaufort-Mackenzie basin. Established reservoirs are as follows:

1. fractured Lower Paleozoic carbonates such as Mount Kindle dolomites and Hume limestones (Mayogiak and West Atkinson oil pools);
2. fractured Upper Carboniferous Lisburne limestones (Unak gas pool);
3. basal Lower Cretaceous Parsons Group, specifically the Kamik Formation consisting of lower fluvial and marginal marine sandstones and an upper unit containing a series of barrier bars (Parsons and Tuk gas pools, Kamik and Kugpik oil pools);
4. a clean sandstone unit in the Lower Cretaceous Mount Goodenough Formation (Imnak oil pool);
5. the Barremian to Aptian Atkinson Point Formation containing fan-delta sandstones and conglomerates (Atkinson oil discovery);
6. Aptian Rat River sandstones displaying nearshore inner shelf sedimentation (Unak gas pool);
7. Paleocene to Oligocene delta-front/delta plain sandstones in Moose Channel, Reindeer and Kugmallit formations (4 oil discoveries, 15 gas discoveries, 15 oil and gas discoveries); and,
8. Oligocene to Miocene deep-water submarine fan sandstones in Kugmallit and Mackenzie Bay formations (Kopanoar, Koakoak, and Nektoralik oil and gas fields, Kenalooak gas pool, and Havik and Nerlerk oil fields).

Numerous potential reservoir units are also present in the basin. They are:

1. turbidites in the Upper Devonian Imperial Formation;
2. interbedded fluvial sandstones and conglomerates of the Lower Carboniferous Kekiktuk Formation;
3. Permian marine sandstones correlatable with Sadlerochit Group;
4. Lower and Middle Jurassic sandstone units in the Bug Creek Group which were deposited as shelf sands prior to significant rifting and subsidence; and,
5. youngest Nuktak and Shallow Bay sands in the Beaufort Sea.

Gas hydrate-bearing zones include delta-front/delta plain sandstones in the Kugmallit Formation and deep-water submarine fan sandstones in the Kugmallit and Mackenzie Bay formations (Figure 2; Majorowicz and Hannigan, 2000a; 2000b). Shallow Nuktak sands also have been identified as a potential gas hydrate-bearing zone (Figure 2).

Accumulation and preservation

Trapping configurations for Paleozoic and Mesozoic hydrocarbon accumulations are dominantly structural. Tilted fault blocks and closures against normal faults of the Eskimo Lakes Fault Zone along the northwestern flank of Eskimo Lakes Arch are significant traps. In southern Mackenzie Delta, closure against normal faults is also noteworthy. Under Tuktoyaktuk Peninsula, two oil discoveries in Lower Paleozoic carbonates are located in traps on the northwest flank of Eskimo Lakes Arch. These traps are positioned favourably to capture migrating oil from source rocks deeply buried in the adjacent Kugmallit Trough. The oil was derived from Upper Cretaceous organic-rich shales faulted to deeper levels than the Paleozoic reservoirs, signifying large-scale vertical migration must have occurred, possibly along these faults. The Paleozoic carbonates are capped by organic-rich Canol shale, but this shale is thermally overmature in the area and could only have been a gas source. Thick overlying Jurassic-Cretaceous shale units provide a regional top seal.

The onshore Mesozoic pools and prospects are also dominantly trapped by closure against faults and tilted fault blocks. Thick overlying and interbedded shale units provide adequate seals. Source rocks are varied for these Mesozoic onshore plays ranging from gas-prone Middle Jurassic Husky and Lower Cretaceous Mount Goodenough shales to oil-prone Smoking Hills and Arctic Red organic-rich shale units.

Most oil and gas discoveries in the basin (partly onshore and mostly offshore) occur in Tertiary strata. Taglu and Kugmallit sequences account for most of the reserves. Generally, the Tertiary succession exhibits low maturity with respect to oil generation varying from 0.25 to 0.65% R_o (R_o represents reflectance of vitrinite macerals immersed in oil) even at depths up to 4500 m in central Beaufort Basin. Issler and Snowdon (1990) believe that thermal maturation gradients should increase dramatically near 5500 m depth. Identified organic matter in Tertiary rocks is predominantly Type III, implying terrestrial and gas-prone kerogens. Gas accumulations in Tertiary strata were likely derived from these kerogens. Crude oils show compositional traits similar to Richards and Paleocene shales. Therefore, it seems probable that most hydrocarbons in Tertiary strata are generated within the vicinity of the trap. Most of the hydrocarbons were generated off-structure with some vertical and lateral migration. In-situ gas generation is likely taking place in Tertiary deltaic deposits from interbedded coaly source rocks in the offshore.

Each Tertiary prograding sequence contains a variety of depositional environments, such as lower delta-plain, delta-front, nearshore, shelf and submarine fan settings. Complex facies relationships reflect shifting positions of the shelf break and deltaic distributary channels. During rapid subsidence and deposition, large-scale listric faults and associated tilted fault blocks were formed. Rapid rates of sedimentation led to large downward-north displacements along these faults. There is a long history of movement on these faults but most faulting appears to have ended in Late Miocene time. Effective seals are provided by interbedded mudstone successions. Stratigraphic unconformity-type traps are also likely present in the Tertiary basinal sediments.

In western Beaufort Sea, compressional folds and thrust faults occur, reflecting the continuation of the highly deformed Cordilleran Fold Belt into the Beaufort Sea. The trapping structures in this area are elongate anticlines cut by high-angle thrust faults. Symmetric folds are more dominant to the northeast and these folds lack thrust faults.

Exploration plays

A listing of exploration plays for Beaufort-Mackenzie Basin is presented in Table 2. There are 20 oil and/or gas exploration plays in the basin; thirteen of these plays are established. Total booked reserves in 1994 for all established plays located in Beaufort-Mackenzie Basin are 277.29 x 10^6 m^3 of oil and 332.44 x 10^9 m^3 of gas (mean recoverable volumes; Dixon et al., 1994). In 1998, the National Energy Board published much reduced reserve figures (183.44 x 10^6 m^3 of mean recoverable oil plus condensates; 254.7 x 10^9 m^3 of mean marketable gas; National Energy Board, 1998). Indian and Northern Affairs Canada (1995) gives oil plus condensate reserves of 240.7 x 10^6 m^3 and 360.2 x 10^9 m^3 of gas (recoverable volumes). These differences in reserve estimates result from variations in interpretation and definitions (Osadetz et al., 2005).

Major oil fields are restricted to offshore Mackenzie Delta (Amauligak), West Beaufort Sea (Adlartok), and Deep Water areas (Koakkoak, Kopanoar). Major gas accumulations are in Tertiary deltaic sands at Taglu and delta-front sandstones in the mid-shelf area of the Beaufort Sea (Amauligak).

Recent resource estimates

Most established plays and selected conceptual plays had been previously assessed for petroleum potential by the Geological Survey of Canada. Table 2 lists the most recent estimates of conventional oil and gas resources for these exploration plays in the Beaufort-Mackenzie Basin (Dixon et al., 1994; Hannigan, 2001a; Osadetz et al., 2005). The methodology and vintage of these assessments are given. Osadetz et al. (2005) discusses the reserve and resource estimates by various agencies and comments on the major differences encountered in the basin. The potential for additional resource potential is high and Dixon et al. (1994) gives estimates of total resource potential in the basin. They predict 1134.29 x 10^6 m^3 of mean recoverable oil and 1841.74 x 10^9 m^3 of mean recoverable gas occur in the basin.

Gas hydrate resource predictions in the basin are immense and highly speculative. Majorowicz and Osadetz (2001) predict 2.4 x 10^{12} to 87 x 10^{12} m^3 of in-place gas hydrate in the basin.

Qualitative oil and gas resource assessments have also been completed in the area (Indian and Northern Affairs Canada, 1995; Gal, 2005). These assessments assign comparative hydrocarbon qualitative rankings ranging from low to very high within the Beaufort-Mackenzie Basin. Very high petroleum potential areas of both oil and gas exist in Lower Cretaceous and older reservoir rocks along Tuktoyaktuk Peninsula (Atkinson Point play), along the trend of Eskimo Lakes Fault under southern Mackenzie Delta (South Delta Mesozoic and Paleozoic plays), within Kugmallit Trough (Parsons and Mayogiak plays) and in the outer delta, shallow offshore and offshore delta, particularly in the Taglu and Kugmallit sequences.

With respect to nation-wide oil and gas potential, the petroleum potential in the Beaufort-Mackenzie Basin is considered to be high. According to National Energy Board's report on Canada's energy future (2003), about 10% of Canada's oil and 11% of gas is expected to be present in the basin.

NORTHERN FORELAND BELT

The third geological province in the northern mainland is a northeast-facing arc of mountain ranges bordering the Interior Platform called the Northern Foreland Belt. It includes Liard Plateau (including eastern Liard Basin to Bovie Fault), Mackenzie Plain, Franklin Mountains, Mackenzie Mountains and Ogilvie-Wernecke Mountains (Figure 1). Liard Plateau is relatively flat to rolling and it passes northward into the mountainous terrain of the Mackenzie Mountains forming a convex arc facing eastward, northeastward and northward to the Interior Platform. West of the Mackenzie Mountains, the Ogilvie-Wernecke Mountains lie south of the Yukon Fold Complex (Figure 1). Thrust-faulted and folded Proterozoic and Paleozoic strata in the Franklin Mountains separate Mackenzie Plain from the Interior Platform.

Geological Setting

The Northern Foreland Belt represents the northern continuation of the Rocky Mountain Foreland Belt of western Canada. It is composed of a series of imbricated and folded miogeoclinal and clastic wedge assemblages deposited on and adjacent to the stable craton of North America (Gabrielse et al., 1992). The Northern Foreland Belt is bounded on the east by relatively flat-lying undisturbed strata in the northern Interior Plains and on the west by the eastern slope of the Selwyn Fold Belt (Figure 1). The structural style dominantly consists of easterly- and westerly-verging and regionally continuous concentric folds and high-angle thrust faults. Underlying strata consists of shallow-water carbonates and clastics of Proterozoic to mid-Paleozoic age forming the eastern portion of the miogeocline (Cook, 1992). Structural shortening associated with deformation in the northern belt is much less than estimated shortening in the southern Rocky Mountains; 50 km (Gordey, 1981; Cecile et al., 1982) compared to 200 km in the south (Price and Fermor, 1985).

Basement in the Northern Foreland Belt contains folded and faulted strata of the Middle Proterozoic Mackenzie Mountain Supergroup and Upper Proterozoic Windermere Supergroup. These strata near the 400 km long Plateau Thrust range up to 5 km thick. These pre-Phanerozoic rocks consisting of shales, carbonates, sandstones, volcanics, conglomerates and diamictites are not significantly metamorphosed and are exposed in large areas of central and northern Mackenzie Mountains (Gabrielse and Campbell, 1992). Southern Mackenzie Plain and Franklin Mountains are underlain by the Middle Proterozoic Hornby Bay-Dismal Lakes sedimentary succession containing sandstones, mudstones and lesser dolomites and siltstones (Figure 2).

Unconformably overlying Proterozoic sediments over most of the Northern Foreland Belt are Cambrian sandstones and carbonates of variable thicknesses ranging up to 20 km. A linear landmass called Mackenzie Arch was prevalent along the central axis of the Mackenzie Mountains during Cambrian time. The Arch separated the major Cambrian depocentre in the Interior Plains from a much thicker sedimentary succession containing Backbone Ranges, Vampire, Sekwi and Rockslide formations in the Selwyn Basin. The Arch also limited the deposition of the Illtyd and Slats Creek formations to the Ogilvie-Wernecke Mountains. Most of the Cambrian is missing beneath Liard Plateau.

Mackenzie Arch was submerged in early Late Cambrian time leading to widespread platform carbonate deposition, specifically Late Cambrian to mid-Silurian Franklin Mountain and equivalent Broken Skull formations, and Sunblood and Mount Kindle formations on the ancestral North American miogeocline. These strata have an aggregate thickness of 2000 m. Westward the carbonate platforms were bordered by a series of embayments, basins and troughs occupied by deeper water basinal facies (Whittaker, Duo Lake and Rabbitkettle formations and Road River Group) (Cecile and Norford, 1992).

Late Silurian regression across the Northern Foreland Belt caused development of the “sub-Devonian unconformity”. Early Devonian transgression resulted in deposition of an argillaceous and peritidal carbonate, siliciclastic and evaporite succession called the Delorme Group (Tsetso, Cadillac, Vera, Camsell and Sombre formations) in the eastern miogeocline and Road River Group basinal shales in the western miogeocline.

A maximum 2000 m thick succession of Arnica, Bear Rock, Landry, Nahanni, Hume and Ogilvie platform carbonates and evaporites blanketing all Mackenzie Plain, Franklin Mountains, Mackenzie Mountains and Ogilvie-Wernecke Mountains as well as the eastern portion of the Liard Plateau was deposited during Early and Middle Devonian time (Figure 2). At the same time, shales of the Road River Group and Funeral and Mount Baird formations accumulated further west in Selwyn Basin and western Liard Plateau. The Manetoe Dolomite is a generally stratiform diagenetic coarsely crystalline facies that replaced Landry and Nahanni limestones in the southern third of the Foreland Belt (Morrow and Geldsetzer, 1992). In some places, the dolomite masses are hundreds of metres thick in the Devonian stratigraphic succession (Morrow et al., 1990). The Manetoe Dolomite is the primary reservoir for gas in the Liard Plateau.

By the close of Middle Devonian time, organic-rich black and grey shales of the Muskwa Formation in the Horn River Group or Bluefish member of the Hare Indian Formation blanketed the Mackenzie Plain, Franklin Mountains, Mackenzie Mountains and Liard Plateau. Shallow-water carbonate deposits at this time were restricted to Mackenzie Plain and eastern Mackenzie Mountains and are represented by Ramparts platform limestones and Kee Scarp reefs, and beneath Liard Plateau by limestones of the Tetcho and Kotcho formations. Cyclical changes in water depth promoted episodes of reef-building, specifically Kee Scarp growth on the Ramparts platform at Norman Wells. Kee Scarp reef growth represents the final episode of carbonate deposition in Mackenzie Plain (Figure 2). Canol shales surround and interfinger with Kee Scarp reefs beneath Mackenzie Plain. In the Ogilvie-Wernecke Mountains, black Canol shales were also deposited. Late Devonian shales, siltstones and sandstones of the Imperial Formation and Fort Simpson shales blanket the Mackenzie Plain and Mackenzie and Ogilvie-Wernecke mountains.

Carboniferous and Permian strata are preserved only beneath Liard Plateau and parts of the Ogilvie-Wernecke Mountains. In Liard Plateau, the Permo-Carboniferous succession is up to 3000 m thick while in the Ogilvie-Wernecke Mountains, the succession is 1000 m thick. At Liard, Carboniferous sedimentation begins with deposition of Exshaw-equivalent organic-rich black shales. These shales are overlain by thick sandstones and sandy siltstones of the Yohin Formation succeeded conformably by black shale and siltstone interbeds of the Clausen Formation. Carboniferous carbonate platform deposits beneath Liard include Flett and Prophet limestones that extend westward from the Interior Platform. Carboniferous sedimentation ends at Liard with deposition of sandstones of the Mattson Formation. Siltstones and cherts of the Permian Kindle and Fantasque formations unconformably overlie Carboniferous strata at Liard.

In the Ogilvie-Wernecke Mountains, Carboniferous shales, siltstones, and limestones of the Ford Lake, Hart River, Blackie and Ettrain formations are unconformably overlain by sandstones and cherts of the Permian Jungle Creek and Takhandit formations (Richards et al., 1997).

Triassic strata are only present beneath southern Liard Plateau, where siltstones of the Toad-Grayling Formation were deposited. Jurassic and Neocomian strata are absent across the entire Northern Foreland Belt. Across most of the Foreland Belt, deformed Proterozoic and Paleozoic strata are either exposed at surface or lie unconformably beneath thin Quaternary strata.

Significant Cretaceous strata of Aptian-Albian age unconformably overlie Triassic or Paleozoic strata in Liard Plateau. Here the preserved thickness is near 1500 m. Alternating sandstones and shales of the Fort St. John Group overlain by resistant conglomerates and sandstones of the Dunvegan Formation are present. Kotaneelee shales and Wapiti sandstones are Upper Cretaceous strata overlying Dunvegan clastics. The oldest Cretaceous strata in the Fort St. John Group are transgressive shoreline conglomeratic sandstones of the Chinkeh Formation that form the reservoir for gas at Maxhamish gas field in northeast British Columbia.

In Mackenzie Plain, earliest Albian transgression is represented by an extensive thin basal sandstone (Martin House/Sans Sault Formation) succeeded by a shale-dominant unit called the Arctic Red Formation (Figure 2). Preserved Upper Cretaceous strata include shales of the Slater River Formation, interbedded sandstone and shale of the Little Bear Formation, East Fork shales, and interbedded sandstone, conglomerate and shale of the Summit Creek Formation (Figure 2).

In Liard Plateau and Plain, anticlines and thrust faults formed by Laramide Cordilleran deformation occur within strata forming an easterly-tapering sedimentary wedge in a Paleozoic miogeocline and platform on the ancestral North American passive margin overlain by deposits of the Cordilleran foreland basin. The remainder of the Northern Foreland Belt are characterized by large en-echelon arcuate upright folds and subordinate thrust faults within a broad synclinorium. Phanerozoic rocks are intensely affected in Mackenzie Plain and Franklin Mountains due to Early Tertiary deformation creating numerous tight and thrust-faulted anticlines (Cook and Aitken, 1971, 1973).

Exploration history

Oil seeps along the banks of the Mackenzie River were long known and utilized by the Dene people. The first recording of these seeps was made in 1789 by Alexander Mackenzie during his exploration of the area. These seepages attracted commercial interest and the first petroleum discovery in the Interior Platform was made at Norman Wells in 1920. The oil field is estimated to have contained an original in-place oil volume of 100 million cubic metres or 620 million barrels (Johnson and McMillan, 1993). The oil is pooled in the up-dip eastern portion of a Middle Devonian Kee Scarp reef under the Mackenzie River. Production began in 1920 for local consumption. Oil production was limited until the early 1940's when a northern oil source was deemed a strategic necessity during World War II. The Canol pipeline was built between Whitehorse and Norman Wells to support the war effort in the Pacific theatre. Flow through the pipeline ceased after the war and the pipeline was dismantled. A pipeline became economically feasible again as a result of the price shock in the 1970's, and a major expansion of the Norman Wells field and construction of a 900 km oil pipeline along the Mackenzie Valley was completed in 1986. Norman Wells is still one of the top producing oil fields in Canada.

There are about 120 exploratory wells in the Northern Foreland Belt, and the vast majority are concentrated in Mackenzie Plain and Liard Basin. Exploration at Liard has led to discoveries of a succession of large gas fields in Yukon and Northwest Territories (Figure 3). The first well drilled in 1957 tested the Beaver River anticline in northeastern British Columbia, a structure with a 51 kilometre hinge (Osadetz et al., 2003). This well, completed in 1961, discovered gas in Manetoe dolostone, a diagenetic facies derived from Nahanni limestones. Although the anticline was broad and simple on surface, thrust-faulted cores form numerous closures and reservoir compartments in the subsurface (Snowdon, 1977). This well also discovered gas in the Carboniferous Mattson Formation. Subsequent drilling confirmed the extension of the 'Manetoe' play into Yukon Territory and Northwest Territories with gas discoveries in hydrothermal dolomites at Kotaneelee in 1963 and Pointed Mountain in 1966 (Figure 3). At Pointed Mountain, the field is hosted in the Pointed Mountain Anticline, which is an asymmetric northeast-trending anticline located on the hangingwall of the Pointed Mountain thrust fault (Gal and Jones, 2003). The Manetoe facies reservoir is very thick at Pointed Mountain (up to 580 m with average pay of 205.4; Meding, 1994). This thickness anomaly results from the development of vertical plumes or sinks where Manetoe dolomitization affected Nahanni, Landry and locally Arnica formations (Morrow et al., 1990). The reservoir quality of the hydrothermally dolomitized strata has been enhanced by fracture porosity (average primary porosity is only about 2.5%). However, this pervasive fracturing resulted in formation damage during development of these early gas fields with mud invasion during drilling and influx of groundwater into the reservoir (National Energy Board, 2001).

At the eastern limit of Cordilleran deformation, the north-trending Bovie Anticline was tested in 1967 (Figure 3). The well discovered gas in dark grey vuggy dolostone with veins of coarse white dolomite in the Nahanni Formation (Bovie Lake J-72; Gal and Jones, 2003). MacLean and Morrow (2004) interpret the reservoir as occurring in the hangingwall of a west-directed high-angle thrust.

In 1971, the La Biche gas field was discovered within a large northwest-trending structure called the La Biche Anticline (Figure 3; Douglas, 1976; Meding, 1994). It is located about 25 km northwest of Pointed Mountain. The La Biche well located near the apex of the surface expression of the elongate, discontinuous faulted anticline discovered gas in Nahanni limestone and siltstone. Below the siltstone interval, the Nahanni has been altered to Manetoe dolomite (Morrow et al., 1986). The reservoir and gas pool lie predominantly in the siltstone zone which is highly porous and fractured (Meding, 1994). The siltstone may be paleokarst infill (Gal and Jones, 2003).

The next discovery occurred in British Columbia in 1973 when gas was found in Carboniferous Mattson sandstones at Windflower (not shown on Figure 3). The Mattson Formation contains a middle quartzose sandstone unit often characterized by good quality reservoir. In 1974, the Beaver River pool in the Banff Formation was also discovered in northern British Columbia.

The Liard gas field, discovered in 1986, was drilled on the southern end of the Liard anticline and gas was found in the Nahanni Formation. The discovery well flowed gas on production test, but production was suspended shortly after testing due to economics. The field remained dormant for the next 14 years until 1999 when Chevron and partners drilled the successful gas well at Liard K-29 (Figure 3). The well encountered gas-charged vuggy and fractured Manetoe dolomite. In 1998, Ranger discovered the Liard P-66A gas pool in the Nahanni Formation (Figure 3).

The Liard F-36 and Southeast Fort Liard gas fields discovered in 1998 and 2001, respectively, are Mattson and Fantasque accumulations in upright subsurface folds related to the Bovie thrust fault (Figure 3). Deltaic and shoreface sandstones in Mattson Formation and porous cherts in Fantasque Formation provide reservoir. Fractures along the axial hinge provide effective permeability (Gal and Jones, 2003).

Another gas field discovered in British Columbia is the Maxhamish Chinkeh Formation gas accumulation. This 1991 discovery occurs in Lower Cretaceous fluvial and shallow marine clastics of the Fort St. John Group (Leckie et al., 1991; Osadetz et al., 2003).

Prior to 2004, twelve wells were drilled in the southeastern portion of the Mackenzie Mountains, but none have yielded significant hydrocarbon results. No wells to date have been drilled in northern Mackenzie Mountains or Ogilvie/Wernecke Mountains. Most seismic coverage was acquired in Liard Basin and Mackenzie Plain, but there are also small areas of seismic survey coverage on the extreme eastern slopes of Mackenzie Mountains.

In 2004, the Summit Creek B-44 well at the eastern edge of the Mackenzie Mountains southwest of Tulita discovered gas and condensate in the Bear Rock carbonate reservoir. Production tests were completed in 2005 on two separate zones over a gross pay of 153 m. Approximately 0.5 million cubic metres of gas and 999 cubic metres of light oil and condensate per day were produced (Husky Energy news release, Oct. 11, 2005).

In 2006, a gas discovery was made in the Summit Creek area in Mackenzie Plain. The gas was found in the Cretaceous Little Bear Formation in the Stewart D-57 well. This well is located about 26 kilometres east of Summit Creek B-44. The Stewart D-57 well yielded a combined flow rate of 140,000 cubic metres/day of sweet gas in two drill stem tests. Initial estimates of 26 m of gas pay within a closed structure of 9.5 square km were reported (Husky Energy news release, May 17, 2006).

There are an additional 6 oil shows and 2 gas flows from drill-stem tests in Mackenzie Plain. The most significant occurrence is represented by heavy oil recovered in the Franklin Mountain Formation in the East MacKay B-45 well.

Source rocks

There are numerous potential or probable source rocks in the Northern Foreland Belt.

1. Scattered thin beds of algal-rich shale in the Cambrian Mount Cap Formation in the Mackenzie Depocentre (Dixon and Stasiuk, 1998) are probable source rocks east of Mackenzie Arch in eastern Mackenzie Mountains and Mackenzie Plain (Figure 2). In Mackenzie Plain, the thermal maturity of Cambrian strata is unknown. However, Feinstein et al. (1991b) measured younger Paleozoic rocks in the area and demonstrated that these rocks are overmature in the Root Basin area and Devonian strata are within the oil window near Norman Wells. The appreciable thickness of pre-Devonian strata in the area suggests that Cambrian strata are likely within the gas generation zone, past the peak of oil generation (Dixon and Stasiuk, 1998).

2. Cecile and Norford (1992) describe organic-rich cherty and shaly dolostones in the Upper Ordovician and Lower Silurian Whittaker Formation and dark organic-rich shales in the mid-Ordovician Duo Lake Formation. These are possible source rocks in the Mackenzie Mountains.

3. Thick graptolitic shale intervals in basinal Upper Ordovician to Middle Devonian Road River Group represent probable source rocks throughout the Mackenzie Mountains and Liard Plateau (Cecile and Norford, 1992; Osadetz et al., 2003).

4. Organic-rich black siliceous shales and interbedded limestones within the Middle Devonian Horn River Group, specifically the Bluefish member of the Hare Indian Formation and Besa River Formation, are known source rocks in the Mackenzie Mountains and Liard Plateau, respectively. These source rocks are generally overmature in the Foreland Belt and consist mainly of Type II and possibly some Type I marine organic matter (Feinstein et al., 1991b). Despite the overmaturity of these source rocks, they have retained moderate TOC and bitumen, suggesting that these rocks remain a good potential source for gas. Potential source rocks in Liard Plateau contain TOCs between 1 to 4% and are composed of Type II marine kerogen (Potter et al., 1993). Thermal maturity values represented by vitrinite reflectance values between 1.6 to 4.6% R_o indicate that the rocks are currently in the overmature zone (Potter et al., 1993). Uppermost Besa River shales probably generated condensate and wet gas, but Besa River shales below 3 km depth may have been a prolific source of catagenic gas, since it entered the gas window about 280 million years ago and may have contributed significant gas to the reserves in Manetoe-hosted gas fields.

The Middle Devonian Bluefish organic-rich shale member of the Hare Indian Formation beneath Mackenzie Plain is an oil-prone source rock. It has been correlated to bitumen found in Hume carbonates and is not thought to have been a major source of Norman Wells oil due to its geochemical characteristics (Snowdon et al., 1987; Feinstein et al., 1988). The Bluefish shale is the oldest member of the Hare Indian Formation and the sealing effect of the overlying Hare Indian shale likely prevented most of the generated oil from reaching the overlying Kee Scarp reservoir. Maturity data suggest that the source rock is within the oil window at current depths in the Norman Wells area, but is overmature with respect to oil generation to the south beneath Root Basin (Feinstein et al., 1991b). In Root Basin, the maturity level is still suitable for gas generation and preservation. Maturity levels also increase in deeper parts of the basin toward the Mackenzie Mountains.

5. Organic-rich black shales of the Middle to Upper Devonian Canol Formation represent probable source material in the Mackenzie and Ogilvie-Wernecke Mountains. Canol shales are mature in Mackenzie Plain and along eastern Mackenzie Mountains and overmature further south and west (Feinstein et al., 1991a.). At Summit Creek B-44 well, the site of the recent gas and condensate discovery, excellent to very good thermally mature potential source rocks occur in the Canol as well as

the Bluefish and Hare Indian formations (TOC 3-5% over 140 m; %R_o 1.1-1.2; T_{max} ~ 455-465^{o}C) (Stasiuk et al., 2006). Hydrocarbon fluid inclusions in microfractures in these source rocks have estimated gravities of 45 to 55^o API (Stasiuk et al., 2006). The Upper Devonian bituminous Canol shale draping the Kee Scarp reef at Norman Wells has been geochemically correlated to the oil accumulation (Snowdon et al., 1987; Feinstein et al., 1988). This widespread organic-rich shale is also responsible for most of the oil seeps along the Mackenzie River. Similar to the Bluefish member, Canol strata are within the oil window at present depths beneath Norman Wells.

6. Basinal laminated black shales of the uppermost Devonian to lowermost Carboniferous Exshaw Formation are only present in the Liard Plateau region. The potential source rocks contain 0.6 to 4 % TOC. Vitrinite reflectances of Exshaw shales range from 1.2 to 1.5% R_o indicating thermal maturities ranging from the end of oil window into the wet gas zone (Potter et al., 1993).

7. Black fissile shales in the basal section of Carboniferous Mattson Formation and common thin sapropelic coals in the middle to upper portions of the Mattson Formation are potential source rocks beneath Liard Basin. The shales contain mixed Type II and III kerogens with TOCs greater than 10% in algal laminites associated with coals while non-laminite shales contain 2 to 5% TOC (Potter et al., 1993). Kerogens in surface and subsurface Upper Mattson Formation are thermally mature suggesting hydrocarbons may have been generated recently. Lower and Middle Mattson kerogens could potentially be a source of wet gas and condensate.

8. Basinal and bituminous black shales of Carboniferous Ford Lake, Hart River and Blackie formations in the Ogilvie-Wernecke Mountains are generally overmature and subject to erosional breaching at the surface destroying most of the generated hydrocarbons (Link and Bustin, 1989, Link et al., 1989). Moderate to significant amounts of organic carbon are present (0.9 to 4.9% TOC) suggesting good source rock potential. Most organic matter consists of Type II and III mixtures (Link and Bustin, 1989, Link et al., 1989).

9. Siltstones and silty shales of the Triassic Toad and Grayling formations are possible source material beneath Liard Basin (Leckie et al., 1991). These strata were assessed by analyzing wireline logs but could not be geochemically corroborated due to lack of subsurface samples.

10) Lower Cretaceous Garbutt and Lepine marine shales are probable source rocks in Liard Basin. Total organic content ranges from 1.4 to 5.2% indicating good to very good source rock potential. Hydrogen index values are generally low but there are some values between 150 and 300, indicating potential gas and liquid hydrocarbon generation (Leckie et al., 1991). Maturation levels obtained from T_{max}, R_o and thermal alteration index measurements indicate that most of Liard Basin is thermally mature and within the oil window, having R_o-equivalent values between 0.5 to 1.0% (Leckie et al., 1991). There is an immature area in northeastern Liard Basin.

11) In Mackenzie Plain, the East MacKay B-45 well recovered heavy oil from the Upper Cambrian-Ordovician Franklin Mountain Formation. Feinstein et al. (1988) determined that this oil was sourced from the Upper Cretaceous Slater River Formation. The well occurs on the core of Keele Arch, which was uplifted and deeply eroded during Early Devonian to pre-Cretaceous time. The eroded core remained as a topographic high resulting in onlap of Slater River organic shales directly on top of Franklin Mountain carbonates (MacLean and Cook, 1999). TOC content of Slater River shales vary from 3.1 to 7.1% and the rocks are low to moderately mature with respect to the oil generation window (Feinstein et al., 1991a). Due to moderate maturation and limited deformation, there is a high probability for preservation of hydrocarbons from Slater River source rocks. Slater River strata may extend eastward into Great Bear Plain but these rocks may be insufficiently buried in this area to generate oil.

Possible source rock for petroleum at the Summit Creek B-44 discovery may be the Cenomanian to Albian Slater River Formation. Good to very good Type I/II kerogen potential source rocks with 4-8% TOC and Hydrogen Indices of 300 to 500 over approximately 180 m were measured (Stasiuk et al., 2006).

Reservoir rocks

There are many stratigraphic units in the Northern Foreland Belt exhibiting sufficient primary or secondary porosity to represent potential reservoir rock. Much of the Paleozoic strata, however, are exposed at surface across the Mackenzie and Ogilvie-Wernecke mountains providing greater opportunity for breaching of reservoirs or flushing of contained hydrocarbons by meteoric or shallow ground water flow. Liard Basin and Mackenzie Plain provide the greatest potential for petroleum preservation because potential reservoir units are buried beneath a thick cover of upper Paleozoic and Mesozoic strata.

The sole producing reservoir, however, in Mackenzie Plain is the Middle Devonian Kee Scarp Formation. Kee Scarp oil production occurs from the margin and crest of an atoll-type reef developed on top of the Ramparts limestone platform. Under Mackenzie Plain, vuggy or fractured dolostones in Upper Cambrian-Lower Ordovician Franklin Mountain Formation sometimes contain oil. Porous sandstones in Cretaceous Little Bear Formation host a new sweet gas discovery at Stewart D-57. Potential reservoirs beneath Mackenzie Plain include carbonate and sandstone units in Proterozoic Dismal Bay/Hornby Lake and Mackenzie Mountains supergroups, Cambrian Mount Clark sands, Ordovician to Middle Devonian carbonate platforms (Mount Kindle, Arnica, Landry, Bear Rock, and Hume formations), Upper Devonian Imperial clastics and carbonates, and Cretaceous Sans Sault sandstones.

Potential and proven reservoirs beneath Liard Basin include (Leckie et al., 1991; National Energy Board, 2001; Gal and Jones 2003; Osadetz et al., 2003):

1. fractured hydrothermal white coarse-crystalline Manetoe dolomite replacing pre-existing carbonates of the Arnica, Landry and Nahanni formations;
2. highly fractured Middle Devonian Besa River shales;
3. stacked and fractured Upper Devonian to Carboniferous Tetcho, Prophet and Flett carbonates,
4. fluvio-deltaic sandstones of Upper Carboniferous Mattson Formation;
5. fractured Permian Fantasque Formation cherts; and
6. valley-fill, channel and shelf sandstones and conglomerates of the Lower Cretaceous Chinkeh Formation. These sands have porosity values ranging from 8 to 18%.

Potential and proven reservoirs in the Mackenzie and Ogilvie-Wernecke mountains include (Cecile et al., 1982; Morrow and Cook, 1987; Hamblin 1990; Morrow, 1999):

1. shoreface sandstones of the Cambrian Mount Clark Formation east of Mackenzie Arch in eastern Mackenzie Mountains;
2. bioclastic, biostromal and oolitic sand bodies and karstic to vuggy dolostones in the Cambro-Ordovician Franklin Mountain and Broken Skull carbonates in the Mackenzie Mountains;
3. bioclastic, biostromal and oolitic sand bodies and karstic to vuggy dolostones in the Cambro-Devonian Bouvette carbonates in the Ogilvie-Wernecke Mountains;
4. vuggy reefoid and coralline biostromal dolostones of Ordovician-Silurian Mount Kindle Formation in the Mackenzie Mountains;
5. Lower Devonian Camsell and Bear Rock dolostone-evaporite breccia successions in the Mackenzie Mountains;
6. Lower Devonian Arnica Formation subtidal biostromal slightly vuggy thick-bedded dolostones in the Mackenzie Mountains;
7. biostromal to biohermal stromatoporoidal limestone beds, crinoidal limestone and fractured hydrothermal dolomites in Middle Devonian Ogilvie Formation in the Ogilvie-Wernecke Mountains;
8. Middle Devonian biostromal and coralline biohermal limestones of the Hume and Nahanni formations in the Mackenzie Mountains;
9. biostromal to biohermal limestones of the Middle to Upper Devonian Ramparts and Kee Scarp formations beneath northeastern Mackenzie Mountains; and
10. sandstone and conglomerate beds in Upper Devonian Earn Group in the Ogilvie-Wernecke Mountains.

Accumulation and preservation

The oil-bearing Kee Scarp reef beneath Mackenzie Plain grew on a limestone platform in response to rising sea level. The overlying Canol shale acts both as source and lateral and up-dip seal for the Norman Wells oil field. Numerous oil seeps near Norman Wells suggest that the seal rock is leaky in parts and a considerable amount of oil has likely escaped. There are large reefal developments similar to the oil field north of Norman Wells. These reefs are proximal to outcrop exposures at Franklin Mountains, so there is increased risk associated with reservoir breaching, biodegradation and uneven porosity development (Williams, 1986).

Potential traps beneath Mackenzie Plain include sub-unconformity traps where basal Cambrian sands deposited on the flanks of the ancient Keele Arch are overlapped by Cretaceous shales, pre-Laramide folds and fault blocks, Laramide thrust folds, and imbricate thrusting closer to the Mackenzie Mountain front. Basal Cambrian strata are periodically cut by small faults that root in the Proterozoic and there may be structural culminations related to this faulting (MacLean and Cook, 1999). Salt beds in the Mount Cap or Saline River formations could provide seal. At the East MacKay B-45 well, oil is trapped in the porous Franklin Mountain Formation against the pre-Cretaceous angular unconformity on the crest of the Keele Arch (Feinstein et al., 1988). This heavy oil accumulation correlates to source rocks in the Slater River Formation. Other oil reservoirs could occur where the Slater River acting as both source and seal is in direct unconformable contact with potential reservoir rocks. MacLean and Cook (1999) interpret Slater River in direct unconformable contact with Paleozoic carbonates along the west flank of the Gambill Diapir, located just west of Tulita (formerly Fort Norman). Similarly, pre-Cretaceous structures juxtaposing reservoir rocks against Canol source rocks are potential traps. Traps may also occur in the underlying 6 to 14 km thick unmetamorphosed Proterozoic sedimentary succession where enormous structures are present (Cook and MacLean, 2004). Giant stromatolitic reefs up to 300 m high have been mapped in the adjacent Mackenzie Mountains (Aitken, 1981). Carbonate banks are also present in Proterozoic sediments. Cretaceous sandstones interfingering with oil-prone source rocks may provide small stratigraphic traps.

Organic thermal maturity data are sparse and scattered in the remainder of the Northern Foreland Belt. Regional summaries of maturity data throughout the Western Canada Sedimentary Basin delineate a general and uniform westward increase of thermal maturities in Devonian to Cretaceous strata (Stasiuk and Fowler, 2002; Stasiuk et al., 2002). This trend roughly coincides with the general westward increase in thickness and burial depths of potential source rocks in the Phanerozoic succession from the Interior Platform to the Cordillera.

Middle Devonian strata in the Mackenzie Mountains and Liard Basin range in levels of organic maturation from about 1.2% to at least 2.6% R_o and are, thus, well into the dry gas stage of hydrocarbon generation (Stasiuk and Fowler, 2002). In Ogilvie-Wernecke Mountains, the level of organic maturity at the contact of Middle Devonian Ogilvie and Canol formations varies from 1.5 to 4.0% R_o indicating present-day overmaturity (Link and Bustin, 1989; Morrow, 1999). Higher stratigraphic levels exhibit progressively lower levels of organic maturation (Link and Bustin, 1989; Stasiuk and Fowler, 2002). Upper Devonian Imperial-equivalent strata exhibit westward- and southward- increasing maturity levels from 1.0 to 2.2% R_o, straddling the oil to dry gas zone (Stasiuk and Fowler, 2002).

Carboniferous-Permian strata are missing in the Mackenzie Mountains, but are present beneath Liard Basin and Ogilvie-Wernecke Mountains. In Liard Basin, thermal organic maturation varies from 0.85% R_o in the Mattson Formation to 1.5% R_o for the Prophet Formation, straddling the oil-wet gas generation zone (Potter et al., 1993). No maturation values have been measured in the Ogilvie-Wernecke Mountains. Cretaceous strata in Liard Basin have maturities ranging from 0.6 to 0.8% R_o, within the oil window (Stasiuk et al., 2002).

Bitumens present in vuggy and porous Lower Devonian Arnica and Bear Rock formations may indicate the eastward passage of liquid hydrocarbons updip from basinal source rocks of the Road River

Group (Morrow, 1991). Gas generation brought about by deeper burial of Paleozoic source rocks occurred in the Northern Foreland Belt. The gas may be trapped in updip stratigraphic traps in Paleozoic strata lying unconformably beneath impermeable Cretaceous shales under Liard Basin and on the eastern edge of the Mackenzie Mountains. Natural gas generated from Lower Paleozoic source rocks may also have accumulated in Paleozoic carbonates occurring beneath the Plateau Thrust plate in central Mackenzie Mountains (Cecile et al., 1982). Although suitable source and reservoir rocks are present throughout the Mackenzie Mountains, the hydrocarbon potential of the region is low due to breaching of major structures.

In Liard Basin, maturation models suggest a Late Devonian heating event with subsequent generation of liquid hydrocarbons during Late Paleozoic to Early Mesozoic time (Morrow et al., 1993; Potter et al., 1993). The gas-bearing Devonian Manetoe reservoirs often contain pore-coating bitumens attributable to this early hydrocarbon generation interval. Downward migration of oil from overlying Besa River shales into Manetoe reservoirs may have occurred. Catagenesis of oil to gas took place when the reservoir entered the gas window about 280 million years ago (Morrow et al., 1993; Potter et al., 1993). This migration episode charged the reservoirs in the Pointed Mountain, Kotaneelee and Liard structural culminations during Cretaceous and Tertiary time (Morrow et al., 1990). Top seal for Manetoe dolomites is the overlying Besa River shale.

Basic structural trapping mechanisms in Liard Basin are Laramide antiforms developed during fold and thrust tectonism. Cretaceous reservoirs are stratigraphic in nature where channel fill and nearshore sands laterally pinchout into marine shales or onlap the sub-Cretaceous unconformity. Garbutt shales provide probable top seal and source rocks for Cretaceous reservoirs.

Exploration plays

Proposed and established exploration plays in the Northern Foreland Belt are listed in Table 3. The plays in Mackenzie Plain and Franklin Mountains have defined equivalents in the Interior Platform province (compare with Table 1). There are 12 established or conceptual oil/gas exploration plays in the Belt. Three established immature plays within Liard Basin extend south into British Columbia. Total 2002 booked gas reserves in Liard Basin is 85.903 x 10^9 m^3 (in-place volumes). In Mackenzie Plain, the Norman Wells oil field has in-place reserves of 1.0 x 10^8 m^3 oil and 6.23 x 10^9 m^3 of solution gas. Established reserves in the study area (Figure 1; not including British Columbia) are 1.0 x 10^8 m^3 oil and 61.565 x 10^9 m^3. The major discovered gas fields, all in Manetoe dolomite, are Beaver River, Kotaneelee, Pointed Mountain and Liard K-29, and the lone oil field, in a Kee Scarp reef, is Norman Wells.

There are numerous speculative plays in Mackenzie and Ogilvie-Wernecke mountains, but the major regional play-level risk associated with the plays in these areas is the surface or near-surface distribution of potential reservoirs. Almost all major structures are breached in the area. Potential reservoirs lying in near-surface strata are subject to meteoric groundwater recharge, severely degrading preserved hydrocarbons or flushing hydrocarbons out of the rocks. Possible petroleum plays in this region include:

1. fault traps where Cambrian Mount Clark or Slats Creek formations are juxtaposed against Paleozoic shales acting both as seal and source;
2. stratigraphic lateral updip traps where porous Paleozoic strata abut against Road River or Canol shales acting both as seal and source;
3. anticlinal traps where porous bioclastic or biohermal Devonian strata are overlain and sealed by Horn River or Canol shales (Summit Creek B-44 discovery);
4. fractured hydrothermal white coarsely dolomite masses within Devonian strata are overlain and sealed by shales and involved in Laramide faults or folds;
5. stratigraphic traps where porous crinoidal limestones are sealed within silty shale source rocks of the lower Hart River Formation (Ogilvie-Wernecke Mountains only); and
6. unconformity-related structural traps where lower Paleozoic carbonate reservoirs unconformably underlie Cretaceous shale source rocks (eastern Mackenzie Mountains).

The general elevated level of organic maturity within Paleozoic potential source rock strata indicates that most strata in the Mackenzie and Ogilvie-Wernecke mountains are gas-filled. Light oil and condensate, however, has been found at Summit Creek B-44 on the eastern edge of the Mackenzie Mountains presumably sourced from Paleozoic shale units.

Recent resource estimates

The established plays have been previously assessed for total natural gas resource by various authors. Except for the Laramide-Manetoe exploration play, these resource assessments do not take into account total play area or all potential reservoirs. Resource potential volumes are given in Table 3. The methodology and vintage of these assessments are given (Osadetz et al., 2000, 2003; Drummond, 2004). In some cases, resource potential studies are restricted by political boundaries rather than to the underlying geology defining the play. These political restrictions have left numerous gaps with respect to defined play areas indicating complete resource potential is not presented for certain plays. New established plays have been defined from previous conceptual plays since the last assessment study. Some defined conceptual plays in the area have not been quantitatively assessed with modern assessment techniques. Numerous gaps with respect to hydrocarbon assessment results in many exploration plays are evident from Table 3 making estimates of total remaining resource in the Northern Foreland Belt suspect at best.

Qualitative oil and gas resource assessments have also been completed in the area (Indian and Northern Affairs Canada, 1995; Gal and Jones, 2003; Gal, 2005). These assessments assign comparative hydrocarbon qualitative rankings ranging from low to very high within the Northern Foreland Belt. The very high petroleum potential areas are represented by the Kee Scarp reef fairway near Norman Wells and the Manetoe dolomite play in the Liard Basin (Gal and Jones, 2003; Gal 2005). These areas contain known oil, gas or condensate discoveries and are expected to contain more accumulations. In the same areas, Paleozoic platform carbonates and clastics are also prospective, but probably for smaller gas fields. Remaining potential in Liard Plateau is moderate to high. The Ogilvie-Wernecke and western Mackenzie Mountains have low potential for hydrocarbons with the possible exception of the "sub-Plateau Thrust" play in the Mackenzie Mountains. In Mackenzie Plain, there have been numerous exploration programs looking for another Norman Wells-type accumulation, but these activities have been mostly unsuccessful. However, gas and condensate have most recently been discovered in a structural trap at Summit Creek B-44 at the eastern edge of the Mackenzie Mountains, constituting the first significant discovery in the region since Norman Wells. Another drill-test at Stewart D-57 in the same area discovered sweet Cretaceous gas in an anticlinal trap. The eastern Mackenzie Mountains have at least moderate potential for more petroleum discoveries of structural play types similar to the Summit Creek discoveries.

NORTHERN YUKON FOLD COMPLEX

The Northern Yukon Fold Complex extends from the Ogilvie-Wernecke Mountains northward to the Yukon coastal plain (Figure 1). It is bounded to the east by Peel Plateau in the Interior Platform and it extends west into Alaska. Within this mountainous region are six basins or sedimentary depocentres with hydrocarbon potential. They are Eagle Plain, Bonnet Plume, Kandik, and Old Crow basins, Blow Trough and western Peel Plateau (Figure 1). The intervening mountains and ranges may have limited hydrocarbon potential, but high levels of thermal maturation and exposure of reservoirs make them less prospective. Thus, any discussion of these mountain ranges (British-Barn Mountains, Keele Range, northern Ogilvie Mountains, and Richardson Mountains) with respect to petroleum accumulations is not included.

Geological setting

During Early Paleozoic time, northern Yukon was a relatively stable cratonic area characterized by shallow water carbonate deposition. The Yukon Stable Block was an early Paleozoic cratonic fragment that was rifted from the margin of the Ancestral North American continent, most likely associated with Precambrian structural elements and trends. The Richardson Trough which persisted from Cambrian to Middle Devonian time separated the Yukon Stable Block from the North American craton (Cecile, 1982, 1986). Two major positive tectonic elements within the Yukon Stable Block are the Ogilvie Arch and Dave Lord High (Morrow, 1999). Ogilvie Arch is a late Precambrian or Proterozoic positive feature bordering the southern margin of the Yukon Stable Block. There is some evidence that the Arch influenced Early to Middle Cambrian sedimentation. The Dave Lord High defined by the absence of Ordovician to earliest Devonian strata beneath the Ogilvie Formation occurs beneath western Eagle Plain (Morrow, 1999). To the east, the Richardson Anticlinorium roughly follows the Richardson Trough. The Anticlinorium is now a structurally inverted and east-verging thrust sheet (Hall, 1996). Western Peel Plateau occupies the eastern portion of the structurally-inverted Richardson Anticlinorium.

Upper Paleozoic (Late Devonian to Permian) facies belts originally trended northwest-southeast along the western margin of the craton, but were re-oriented east-west to northeast-southwest as the Ancestral Aklavik Arch became active (Bamber and Waterhouse, 1971). A series of tectonic pulses produced several clastic wedges. Shallow water clastic and carbonate successions pass southward into basinal shales now exposed in the Ogilvie Mountains (Hamblin, 1990).

Each of the prospective areas are large tectonic depressions surrounded by highly deformed Proterozoic through Cretaceous strata. The depressions occur in areas where major structural element trends change direction. Deformation within these depressions is generally less intense than in the surrounding mountainous areas. In Eagle Plain Basin, a major northeast-southwest feature called the Eagle Arch, a pre-Mesozoic upwarp of Paleozoic strata, marks the northern erosional edges of various Upper Paleozoic successions. The Arch was active during Late Carboniferous to Early Permian time when the Carboniferous succession was eroded north of its hinge (Richards et al., 1997). It does not directly influence the Laramide-related anticlines in Eagle Plain.

The stratigraphy and their relationships vary dramatically between tectonic depressions. Details of stratigraphy have been previously documented both regionally (Mountjoy, 1967a; 1967b; Bamber and Waterhouse, 1971; Pugh, 1983; Norris, 1984, 1985, 1997; Dixon, 1986; 1992; Morrow, 1999) and by individual basin (Eagle Plain, Martin, 1972, 1973; Graham, 1973; Hamblin, 1990; National Energy Board, 2000b; Osadetz et al., *in press* (a); Bonnet Plume Basin, Norris and Hopkins, 1977; Williams, 1988; Hannigan, 2000; Kandik Basin, Indian and Northern Affairs Canada, 1995; Howell, 1996; Hannigan et al., 1999; Old Crow Basin, Lawrence, 1973; Morrell and Dietrich, 1993; Hannigan, 2001b). A brief discussion follows. (The stratigraphy in western Peel Plateau was previously discussed in the Peel Plateau and Plain section since their stratigraphies are similar).

In the Eagle Plain basin, thick Cambrian Illtyd limestones unconformably overlie Middle Proterozoic metamorphosed siltstones and shales of the Quartet Group (Figure 2). Upper Proterozoic Windermere Supergroup sediments represent effective 'basement' beneath Kandik and Bonnet Plume basins. Old Crow Basin is underlain by Upper Proterozoic Neruokpuk metasediments along the northern margin of Ancestral North America. Illtyd silty limestones and massive dolomites unconformably overlie Precambrian units beneath Bonnet Plume Basin. On the southwestern margin of the Yukon Stable Block beneath Kandik Basin, strata equivalent to Illtyd Formation are found within the Lower Jones Ridge Formation of Early Cambrian to Early Ordovician age (Brabb, 1967). This thick-bedded carbonate succession is underlain by the same unconformity that underlies the Illtyd Formation to the east (Fritz, 1992).

Middle Cambrian sandstones of the Slats Creek Formation directly overlie Illtyd Formation in Eagle Plain. Slats Creek deposition beneath Bonnet Plume Basin consists of about 1400 m of sandstones, siltstones and conglomerates. Disconformably overlying Slats Creek clastics in Bonnet Plume Basin is the locally preserved Upper Cambrian Taiga Formation consisting of limestones, argillaceous limestones and dolostones (Hannigan, 2000).

The development of the Lower Paleozoic Richardson Trough in northwestern Yukon between the Yukon Stable Block to the west and the Mackenzie Peel Shelf to the east greatly influenced deposition of Lower Paleozoic sediments beneath Eagle Plain and Bonnet Plume basins (Morrow, 1999). The north- to northwest-trending Trough (Gabrielse, 1967; Pugh, 1983; Norris, 1985) defined a region of deep-water slope and basin sedimentation between two broad regions of shallow-water shelf carbonate deposition (Morrow, 1999). The Richardson Trough remained a negative physiographic feature from Early Cambrian to Devonian time.

Subsequent to deposition of Upper Cambrian Taiga sediments, the typical basinal strata of shales and argillaceous limestones of the Road River Group were deposited in the Trough and along its margins. Road River Group deposition also occurred upon eastern Yukon Stable Block interfingering and overlying the Upper Cambrian to Middle Devonian Bouvette Formation carbonate platform (Morrow, 1999) (formerly, 'unnamed carbonate sequence', Norford, 1997).

Under Eagle Plain, the Cambrian clastic succession is unconformably overlain by the Bouvette Formation, a persistent carbonate platform about 1500 m thick passing eastward into the Road River clastics in Richardson Trough (Figure 2). At Bonnet Plume, the Taiga carbonate is unconformably overlain by the Bouvette Formation consisting of 1000 m of pelletal and coralline limestones and lesser dolostones. Jones Ridge limestones and dolostones found beneath Kandik Basin are approximately age-equivalent to dominantly Cambrian-Silurian Bouvette Formation. The presence of Lower Paleozoic carbonate rocks under Old Crow Basin is unlikely since the Silurian to Early Devonian transition from shelf carbonate to deep water shale occurs just south of the basin beneath Keele Range. It is believed that a thick succession of marine shale and argillaceous limestone of the Road River Group occurs beneath Old Crow Basin (Pugh, 1983; Morrow, 1989). Transgression during Early Ordovician to Devonian time was represented by deposition of the Road River Group of clastic sediments over most of the Yukon Stable Block including Eagle Plain, Bonnet Plume, Kandik and Old Crow basin areas. In earliest Emsian time, Road River basinal shale deposition was succeeded by basin- and slope-deposited calcareous shales and argillaceous limestones of the Michelle Formation beneath southern Eagle Plain (Figure 2). This formation was overlain by the Emsian to latest Eifelian Ogilvie carbonate platform extending across much of the Yukon Stable Block underlying Eagle Plain and eastern Kandik Basin. The Ogilvie Formation is predominantly a thick-bedded fossiliferous limestone sequence, although lower parts of the formation are primarily dolostone.

During the Late Devonian, sedimentation patterns changed dramatically as turbiditic, chert-rich clastics derived from the north and west flooded the northern Cordillera (Gordey, 1992). An abrupt change from shallow water to much deeper water sedimentation is marked by deposition of the euxinic siliceous Upper Devonian Canol shale (Morrow and Geldsetzer, 1992) beneath Eagle Plain and Bonnet Plume basins and McCann Hill chert beneath Kandik Basin. The Canol Formation conformably underlies the Upper Devonian Imperial Formation consisting of shales, siltstones and minor sandstones. Imperial rocks are turbiditic, with a southerly paleoflow. They underlie Eagle Plain (Figure 2) and western Bonnet Plume basins. Beneath Kandik Basin, interbedded chert conglomerates, arenites, siltstones, mudstones, and shales of the Nation River Formation are equivalent in age to the Imperial Formation but their provenance is from the west (Gordey, 1992).

The Imperial Formation conformably passes upward into prograding coarse clastics of the Tuttle Formation beneath eastern Eagle Plain (Figure 2). In northern Yukon beneath Old Crow Basin, the nonmarine Lower Mississippian Kekiktuk conglomerate rests with angular unconformity on deformed argillite and quartzite of the Precambrian Neruokpuk Formation or pre-Mississippian Road River shales. During Late Tournaisian to Visean time, a major transgression deposited Ford Lake Formation shales, up to 975 m thick beneath Eagle Plain and also Kandik Basin. Similarly, the Kayak succession of shales and minor sandstones and limestones record a transgressive deepening-upward depositional episode beneath Old Crow Basin. Coal-bearing siliciclastics deposited in shoreline and coastal plain settings in the basal

Kayak are succeeded by shales and carbonates deposited in shallow neritic and intertidal environments (Richards et al., 1997).

The oldest Carboniferous carbonate accumulations in the Northern Yukon Fold Complex conformably overlie the Kayak Formation in Old Crow Basin. These shelf carbonates forming the Lisburne Group are up to 1200 m thick and were deposited in protected to restricted shelf and shelf margin depositional environments (Bamber et al., 1992). Beneath Eagle Plain and Kandik basins, slope carbonate deposits of the Hart River Formation include the Canoe River and Alder limestone members. Beneath Eagle Plain, a 310 m thick unit called the Chance sandstone member also occurs within the Hart River Formation between these two limestone members. The units are conformably overlain by Blackie Formation basinal spicular shale sequences succeeded in turn by a shallowing-upward succession of slope carbonates (Bamber et al., 1992). Final Carboniferous carbonate accumulation is represented by the deposition of thick (330-550 m) upper slope to open-shelf limestones of the Ettrain Formation that prograde westward and southward over slope carbonates and shales of the Blackie Formation (Bamber et al., 1992) beneath Eagle Plain and Kandik basins.

A regional unconformity everywhere marks the base of the Permian separating these strata from underlying older Paleozoic units. During Late Carboniferous to Early Permian time, an upwarp through central Eagle Plain called the Eagle Arch is in part a rejuvenation of the persistent Lower Paleozoic Dave Lord High. The Eagle Arch provided opportunity for erosion of the Carboniferous and uppermost Devonian strata over its crest such that Imperial Formation subcrops below younger strata. To the south of the Arch, Upper Paleozoic potential reservoirs subcrop beneath Mesozoic cover and are isolated from those to the north. Permian strata are absent north of the Arch.

The Lower Permian Jungle Creek Formation disconformably overlies older Paleozoic units beneath southern Eagle Plain (Hamblin, 1990) and Kandik basins (Hannigan et al., 1999). Beneath Kandik Basin, a varied assemblage of siliciclastics and carbonates constituting the Jungle Creek Formation is disconformably overlain by Upper Permian siliciclastics, carbonates and cherts of the Takhandit Formation (Bamber et al., 1992; Hannigan et al., 1999) deposited on the south flank of the Ancestral Aklavik Arch. The Takhandit Formation grades westward into limey clastics and conglomerates of the Step Formation. In southern Eagle Plain, the Jungle Creek Formation is preserved below the sub-Cretaceous unconformity. It consists of fine-grained sandstone, siltstone and shale (Figure 2). Beneath Old Crow Basin, a relatively thin (~200 m) poorly known Lower Permian succession called the Sadlerochit Formation was deposited north of the Ancestral Aklavik Arch (Bamber et al., 1992; Richards et al., 1997). Shales, sandstones and minor carbonates of this formation unconformably overlie the Carboniferous Lisburne Group.

Triassic strata in the northern Foreland Belt are widely and sparsely preserved. Triassic rocks are thought to be preserved beneath Kandik Basin. At Kandik, Lower to Upper Triassic Shublik limestones and coeval Glenn Formation 'oil shales' in Alaska unconformably overlie Takhandit strata.

Lower and Middle Jurassic strata in the Yukon Fold Belt are platform deposits derived from the craton. Shelf sandstone in the east (including Porcupine River Formation) grade to basinal shales and siltstones to the west. Beneath Old Crow Basin and northern Eagle Plain, Lower and Middle Jurassic Bug Creek Group shelf sandstones and shales on the eastern extremities of the basin pass laterally into outer shelf Kingak shales and siltstones to the west (Poulton, 1992). A thick succession of Kingak shales overlies the Triassic Glenn/Shublik package at Kandik Basin. Sporadic occurrences of Jurassic shales have been reported in wells in Eagle Plain. These strata are a southerly extension of the Jurassic succession of northern Yukon.

In the northern part of the Foreland Belt, sedimentation was not influenced by Cordilleran uplift until Late Aptian to Early Albian time. Extensional tectonics related to rifting was dominant prior to Late Aptian. Therefore, pre-Aptian sediments were craton- or rift margin-derived, not sourced from a compressional orogen (Stott et al., 1992). Upper Jurassic marine sandstones of the Porcupine River

Formation pass laterally westward and northward into Upper Kingak and Husky open-marine shales beneath Old Crow and northern Eagle Plain basins (Figure 2) and Blow Trough.

Recurrent Neocomian clastic wedges overlie Kingak shales beneath northern Eagle Plain, Kandik, Old Crow and Blow Trough basins. These clastic wedges include mid- to outer shelf Martin Creek sandstones, McGuire bioturbated shales and siltstones, and marine Kamik sandstones. The primary source region for McGuire and Kamik clastics lay to the south and southeast from the craton (Stott et al., 1992). Uplift in Middle Hauterivian time led to the development of a regionally extensive unconformity at the base of the Mount Goodenough Formation. This formation is comprised of about 530 m of marine siltstones, shales and very fine-grained sandstones. Late Barremian to Aptian Rat River sandstones overlie Mount Goodenough strata in northern Eagle Plain.

As a consequence of Aptian to Albian tectonic activity, southerly and westerly source areas developed in the northern Cordillera. Sediments were shed into foreland troughs and basins that developed in front of the rising orogen (Stott et al., 1992). Albian sedimentation in northern Yukon basins include up to 1500 m of Whitestone River shales in Eagle Plain, 500 m of Kathul sandstones, shales and conglomerates beneath Kandik Basin, and unnamed flyschoid sediments in Old Crow Basin and Blow Trough. Extensive flooding occurring during Albian time was terminated by orogenic activity in the Cordillera resulting in a regionally extensive unconformity separating Albian strata from Upper Cretaceous sediments.

Upper Cretaceous sedimentation is represented through much of the Yukon Fold Belt by the Eagle Plain Group. These interbedded sandstones and shales are arranged in transgressive-regressive cycles recording the episodic progradation of coarse clastic wedges from the Cordillera (Dixon, 1992). In Kandik Basin, the northward to northeastward progradation of a coastal fan-delta complex is characterized by marine to non-marine conglomeratic sandstones and grit of the Monster Formation (Ricketts, 1988). In Bonnet Plume Basin, a major unconformity separates Upper Cretaceous to Eocene Bonnet Plume nonmarine sediments from underlying Devonian clastic sediments. Two members of the Bonnet Plume Formation have been recognized: a lower member of Late Cretaceous age containing conglomerate, sandstone and coal, and an uppermost Late Cretaceous-Eocene finer-grained member consisting of sandstone, shale and coal (Mountjoy, 1967a; Norris and Hopkins, 1977; Long, 1978, 1987; Dixon, 1986, 1992, 1997). This non-marine alluvial to fluvial succession was deposited during a Late Cretaceous to Early Tertiary compressional tectonic event when considerable quantities of clastics were deposited in the well-defined foreland basin north of the Cordilleran Orogen (Dixon, 1997). In Blow Trough, organic-rich shelf muds of the Cenomanian-Turonian Boundary Creek Formation lie unconformably on Albian shales. About 2400 m of Maastrichtian to Eocene terrigenous molasse deposits of the Fish River Group overlain by Reindeer delta plain sediments unconformably overlie Boundary Creek strata in Blow Trough. An unnamed sequence of Oligocene to Miocene coal-bearing and nonmarine sediments unconformably overlies Cretaceous shales and sandstones beneath Old Crow Basin.

There are several generations of structures in the northern Yukon Fold Belt, some of which are reactivated or modified during subsequent periods of deformation. The observable bedrock structures are Laramide contractional features that involved reactivation or modification of earlier structural elements (Norris, 1984; Morrow, 1999; Osadetz et al., *in press* (a)). Lane (1998) demonstrated that contractional Laramide structures in the Eagle Fold Belt post-dated the deposition of the youngest preserved Campanian strata. Lane (1998) also showed that the Eagle Fold Belt, Taiga-Nahoni Belt and Richardson Anticlinorium are linked Laramide structures influenced by the structural fabric of the underlying basement. Faults in the basement controlled distribution of Paleozoic successions on the Porcupine Platform. Laramide bedrock structures where Cretaceous strata are preserved are very well described by mapping (Norris, 1984; Dixon, 1992). Structures derived from earlier events, however, are difficult to identify and separate from Laramide deformation. There are also multiple detachment surfaces in the Phanerozoic strata beneath Eagle Plain complicating the structural picture even further (Lane, 1996).

Within Richardson Mountains west of Trevor Fault, Phanerozoic rocks were deposited in Richardson Trough, a north-northwest to south-southeast Paleozoic extensional basin separating Mackenzie-Peel shelf from the Yukon Stable Block (Morrow, 1999). Structural inversion of the Trough during the Laramide Orogeny transformed the Trough into the Richardson Anticlinorium, a gently north-plunging structure. It has been noted that strata in the area of western Peel Plateau are deformed by compressional thick-skinned thrust and fold structures (Osadetz et al., *in press* (b); his Figure 12).

Exploration history

Most petroleum exploration activity in the Northern Yukon Fold Belt has occurred in Eagle Plain Basin. In the basin area, 36 wells have been drilled, five of which discovered oil and/or gas. One well was drilled within Kandik Basin in Alaska, and three other wells were completed in the outcrop belt east of the basin in Yukon. Blow Trough has one well within the depression and two on the perimeter. Two wells were drilled west of Trevor Fault in western Peel Plateau. Old Crow and Bonnet Plume basins have no drilling.

Seismic coverage is quite extensive in Eagle Plain with 9952 line kilometres of reflection seismic surveys covering most of the prospective region at a regional scale. There is a concentration of seismic coverage in the vicinity of the three discovered fields. Approximately 200 line kilometres of reflection seismic were acquired for exploration drilling on the eastern flank of the basin. About 200 line kilometres of reconnaissance seismic were also shot in the Old Crow Basin area and a few seismic lines were also acquired in Yukon coastal plain which also intersected Blow Trough. Many seismic lines shot in eastern Peel Plateau were extended westward across Trevor Fault into the structurally-inverted eastern portion of the Richardson Anticlinorium of western Peel Plateau. There is no seismic coverage in Bonnet Plume Basin.

In Eagle Plain, petroleum exploratory drilling began in 1957 with the spudding of the Eagle Plain No. 1 N–49 well in the north-central part of the basin. This well drilled a surface anticline into Cambro-Ordovician shales and carbonates and encountered a trace of gas in Ogilvie carbonates. The second well drilled in 1960 was successful. The Western Minerals Chance No. 1 L-08 well discovered oil and/or gas in six separate zones. In these zones, a gas pool occurs in a 3.6 m brecciated cherty pebbly sandstone in the Upper Devonian-Lower Carboniferous Tuttle Formation, oil and gas pools are found in the lower limestone member (Canoe River) of the Hart River Formation, oil and gas pools occur in three units in the Chance sandstone member of the Hart River Formation, and significant gas flow was recorded from a DST (drill-stem test) in the Lower Cretaceous Fishing Branch sandstone in the Eagle Plain Group. Since this first discovery well, 34 additional exploratory and delineation wells were drilled leading to two additional significant hydrocarbon discoveries, Blackie in 1964 and Birch in 1965. Blackie discovered gas in the Lower Permian Jungle Creek Formation, a poorly sorted conglomeratic sandstone unit. At Birch, gas pools were found in the Tuttle and Chance sandstone units. Five oil and ten gas pools have been discovered in these three fields (Osadetz et al, *in press* (a)). Outside these fields, there are also two additional oil/condensate and nine gas recoveries from DSTs in 8 wells. In addition to petroleum-bearing stratigraphic units discussed above, gas shows were observed in the Alder limestone member of the Hart River Formation, Ettrain, and Ogilvie formations.

There are two surface oil seepages in Eagle Plain located about 35 kilometres northeast of Chance Field (Norris and Hughes, 1997). Upper Devonian shale saturated with natural aromatic hydrocarbons was mapped by Norris (1974). This seepage is located about 6 km northeast of an oil-saturated ridge-forming sandstone in the Upper Cretaceous Eagle Plain Group (Norris and Hughes, 1997).

Hydrocarbon shows are few and widespread in the other basins. Oil staining was discovered in local porous zones in outcrop in Takhandit limestones, Jungle Creek calcareous sandstones, Ogilvie carbonates and Jones Ridge limestones in the Alaskan portion of Kandik Basin. Subsurface oil staining and several gas kicks were encountered during drilling of the single well in Alaska. Stelck (1944) discovered two bitumen occurrences to the north of Bonnet Plume Basin in Mississippian Ford Lake shales. Petroliferous

Upper Devonian shale was also observed around the mapped anticline on the riverbanks adjacent to the occurrences (Stelck, 1944). Gas-cut mud was returned from a DST in the Caribou N–25 well in western Peel Plateau. No significant shows have been reported in Old Crow Basin and Blow Trough.

Source rocks

Identified and potential source rocks under Eagle Plain include:

1. the identified Lower Paleozoic Road River Group basinal shale succession containing up to 2% TOC, dominantly Type III kerogens with minor amounts of Type I or II, is gas-prone and occurs generally in the gas generation window (Snowdon, 1988). Link et al., (1989) indicated that the overall source rock potential of the Road River Formation throughout northern Yukon is poor, although high TOC values of up to 9.6% occurs in Richardson Anticlinorium;
2. a potential source rock may occur in the Lower Paleozoic Bouvette Formation (Osadetz et al, *in press* (a)). Although no specific oil-prone source has been identified as yet in the Bouvette Formation, there is potential due to the global presence of bituminous oil-prone source facies in Upper Cambrian to Ordovician carbonate platforms (Osadetz and Snowdon, 1995);
3. bituminous mudstone intercalations in Ogilvie carbonates represent another potential source with measurements of TOC up to 9.5% in the gas-prone organic-rich layers;
4. Link et al. (1989) and Link and Bustin (1989) identified the foremost Lower Paleozoic organic-rich source rock throughout northern Yukon as the black bituminous shale of the Canol Formation with TOCs between 2.4 and 8.6%, mixed Type II and III kerogens and currently overmature for oil;
5. the Imperial Formation has moderate quantities of Type III organic matter and could generate some gas (Link et al., 1989; Link and Bustin, 1989);
6. an important identified source rock in the area is the Upper Paleozoic Ford Lake shales containing up to 4% TOC , and thermally mature for oil and gas generation from both oil- and gas-prone kerogens (Type II and III; Link et al., 1989; Link and Bustin, 1989). This interval is the most likely source of oil accumulations in Chance sandstone in the Chance field;
7. shales and organic-rich carbonates in the Carboniferous Blackie Formation is another known source rock. It contains Type II and III organic matter up to 5% TOC, and is marginally to fully mature for oil generation; and,
8. Albian shales of the Whitestone River Formation which are marginally mature and contain Type III kerogens. Minor gas potential may be present in Mount Goodenough and Porcupine River formations.

Many of the known and potential source rocks identified in Eagle Plain likely are present beneath the other basins in northern Yukon. The quality of organic matter in these other areas, however, is not known. Some potential for gas exists in Cretaceous sediments in Bonnet Plume Basin and there could be potential for both oil and gas from older source bed intervals. Similarly in Old Crow Basin, Road River, equivalent-Ford Lake, Jurassic shales and Eagle Plain Group organic-rich successions may be present. An excellent hydrocarbon source rock was identified at Kandik Basin within oil shales of the Triassic Glenn Formation containing locally up to 10% TOC (Howell, 1996). Numerous other mid-Devonian to Lower Cretaceous source rocks have been identified as having potential; the organic-rich shales of the Canol, upper Road River and Mount Goodenough formations, carbonates of the Tindir Group and Jones Ridge Formation and cherty shale of the McCann Hill Formation. A Rock-Eval/TOC analysis of three wells penetrating the Paleozoic succession on the eastern margins of Kandik Basin reveal low TOC contents in most Paleozoic strata except for Ford Lake shales (Snowdon and Price, 1994). Thermal maturity is high and Type III kerogens predominate. Hite (1997) indicated that a restricted area in Kandik Basin may have oil potential due to the presence of bitumen and oil staining in porous Paleozoic outcrop. The potential thermogenic source for both oil and gas in Cretaceous to Tertiary rocks is likely the Glenn Formation.

Reservoir rocks

Potential and known reservoir units for each of the basins are listed below:

1. biostromal or bioclastic layers, oolitic carbonate sandstones and karsted and vuggy limestones and dolostones in the Lower Paleozoic Bouvette Formation are potential reservoir units beneath Eagle Plain and Bonnet Plume basins, and variably dolomitic thick bedded to massive carbonates of the Cambro-Ordovician Jones Ridge Formation beneath Kandik Basin;
2. biostromal to biohermal layers, crinoidal wackestones and packstones, and hydrothermally dolomitized Devonian Ogilvie carbonates are potential reservoir rocks beneath Eagle Plain and Kandik basins;
3. Upper Devonian-Carboniferous brecciated and porous chert turbiditic sandstones of the Tuttle Formation underlie Eagle Plains and western Peel Plateau;
4. Lower Carboniferous Kekiktuk basal conglomerates beneath Old Crow Basin contain quartz, chert, quartzite and granitic clasts in a generally tight siliceous matrix. However, leaching has produced significant reservoirs in Alaska, specifically in the Endicott Field (Craig et al., 1985);
5. lower limestone member (Canoe River) of the Carboniferous Hart River Formation hosts oil and gas in the Chance Field. It consists of thinly bedded micritic crinoidal limestone with porosities up to 13%;
6. middle Chance sandstone member of the Hart River Formation also hosts oil and gas in the Chance Field as well as gas at Birch in Eagle Plain. Thick units of very fine- to very coarse-grained sandstone are moderately to well-sorted and are generally porous and permeable with porosities ranging between 5 and 22% (average 14%) and permeabilities from 100 to 2000 millidarcies;
7. upper Alder limestone member of the Hart River Formation in Eagle Plains recovered minor amounts of gas. It is a micritic crinoidal unit with poor to fair porosity;
8. skeletal and cherty limestone in shelf margins may contain porous intervals in the Upper Carboniferous Ettrain Formation beneath Eagle Plain and Kandik basins. Coeval Alapah and Wahoo carbonates that have been dolomitized and leached occur in Old Crow Basin;
9. the Lower Permian Jungle Creek Formation hosts gas in the Blackie Field in Eagle Plain Basin. The unit is a medium- to coarse-grained, poorly sorted conglomeratic sandstone with porosities ranging from 5 to 20% and permeabilities from 100 to 22000 millidarcies (Hamblin, 1990). Jungle Creek strata also occur beneath Kandik Basin where fracture porosity and minor intercrystalline porosity were observed in well cuttings. Lower Permian Echooka sandstones of the Sadlerochit Group may have reservoir potential beneath Old Crow Basin;
10. Upper Permian Takhandit coarse-grained bioclastic limestones occur beneath Kandik Basin. Takhandit strata grade westward into shallow marine cherty conglomerates and sandstones of the Step Formation. Both of these formations may develop reservoir properties in the area;
11. Lower Cretaceous Martin Creek massive ridge-forming sandstones may have reservoir potential due to its shoreface/nearshore depositional environment beneath eastern Kandik Basin (Dixon, 1997) and Lower Cretaceous marine sandstones are also found beneath Blow Trough;
12. Albian Kathul conglomerates and sandstones have potential reservoirs in submarine fans in the Kandik area (Dixon, 1997). Sharp Mountain interbedded sandstones and pebble conglomerates (Dixon, 1986) may have significant reservoir potential beneath Old Crow Basin. Albian marine sandstones and conglomerates are also present beneath Blow Trough;
13. Upper Cretaceous Fishing Branch Formation hosts a gas pool at Chance Field in Eagle Plains. This unit is a fine-grained, moderately well-sorted cherty marine sandstone with porosities ranging from 15 to 25% (average 22%). The Upper Cretaceous Monster Formation in Kandik Basin is reported to be porous in Alaska (Howell, 1996). It is a heterogeneous mixture of conglomerate, sandstone, mudstone and thin coals deposited in a coastal fan to braided fluvial system (Ricketts, 1988; Dover, 1992; Dixon, 1997). In Bonnet Plume Basin, the Upper Cretaceous to Eocene Bonnet Plume Formation is a thick

succession of poorly-consolidated sediments with coarse-grained sandstones and conglomerate horizons that often show fair to good porosity (Mountjoy, 1967a; Norris and Hopkins, 1977); and

14. there may be porous horizons in poorly consolidated Eocene and younger sediments in Old Crow Basin. There may be small accumulations of biogenic gas in these fluviatile and lacustrine sediments.

Accumulation and preservation

Snowdon (1988) investigated petroleum source rock potential and thermal maturation in Eagle Plain. Thermal history modeling by Snowdon (1988) in Eagle Plain Basin suggests that Devonian source rocks reached peak oil generation during Late Carboniferous to Permian time. These same rocks entered the gas generation window during Carboniferous to Early Tertiary time. Carboniferous and Permian source rocks entered the oil window in Late Carboniferous to Early Tertiary time throughout most of Eagle Plain. Due to Upper Cretaceous burial, most of the Carboniferous source rocks in western Eagle Plain entered the gas generation window during the Late Cretaceous. In northwestern, eastern and southeastern Eagle Plain, potential Carboniferous source rocks remain in the oil window. In central Eagle Plain, Carboniferous and Permian source rocks remain thermally immature due to shallow burial and low paleogeothermal gradients. Lower Cretaceous source rocks in northwestern Eagle Plain entered the oil window during Late Cretaceous to Early Tertiary. Throughout the rest of Eagle Plain, Cretaceous potential source rocks were not buried deep enough to enter the oil window.

Laramide-related parallel northward-striking anticlines and synclines form the principal surface structures in Eagle Plain (Norris, 1985). These anticlines affect the entire stratigraphic section where many interbedded reservoir and seal units provide numerous potential stacked traps. Thrust faults paralleling the surface structures occur in the subsurface. Stratigraphic and combined traps are also important in Eagle Plain. Updip basinward facies changes, subcrop of Upper Paleozoic reservoirs beneath the sub-Cretaceous unconformity and carbonate-to-shale facies changes in Lower Paleozoic reservoirs are important stratigraphic trap configurations.

Kandik and Bonnet Plume basins have similar stratigraphy and trap-style to Eagle Plain Basin, and good potential occurs in stratigraphic and sub-unconformity traps, in anticlines and traps associated with faults. An additional possibility in both basins is overthrust traps. Significant play-level risks at Kandik are reservoir facies development, porosity preservation, source rock maturity and timing of migration.

Exploration plays

Table 4 lists established and conceptual exploration plays in all basins in the Northern Yukon Fold Belt. There are 10 exploration oil and/or gas plays in Eagle Plains Basin; five of which are established. In Kandik Basin, there are three conceptual oil and gas plays. Old Crow and Bonnet Plume basins contain three conceptual gas plays each. Three speculative plays having insufficient information for assessment purposes were also proposed in Bonnet Plume Basin. One conceptual and one speculative play have been defined in western Peel Plateau.

Eagle Plain Basin contains all the discoveries in the Northern Yukon Fold Belt. Total booked reserves in Eagle Plain in 2005 include 1.76 x 10^6 m^3 of oil in 5 pools in the Chance Field. Gas reserves are found in 10 pools in three fields (Chance, Birch and Blackie) and their total in-place volume is 2376 x 10^6 m^3 (Table 4; National Energy Board, 2000b; Osadetz et al., *in press* (a)). Oil accumulations occur in the Chance sandstone and Canoe River limestones members of the Hart River Formation. Natural gas accumulations also have been discovered in these two units of the Hart River Formation, but gas accumulations are also noted in Tuttle, Jungle Creek and Fishing Branch coarse clastic sediments.

Recent resource estimates

Most established plays and selected conceptual plays have been previously assessed for petroleum potential by the Geological Survey of Canada. Table 4 lists the most recent estimates of conventional oil and gas resources for these exploration plays in Eagle Plain, Kandik, Bonnet Plume and Old Crow basins

(Hannigan et al, 1999; Hannigan, 2000, 2001b; Osadetz et al., *in press* a, b). The methodology and vintage of these assessments are given. No hydrocarbon assessment work has been completed for the Blow Trough. The National Energy Board completed a petroleum assessment evaluation of Eagle Plain in 2000, and their results are displayed in Table 4 for comparison purposes. The resource potential, particularly in Eagle Plain basin, is high. High levels of thermal maturity elsewhere (except for Kandik Basin) indicate that any hydrocarbons present would most likely be gas. Estimates of total resource for all assessed basins in the Northern Yukon Fold Belt is 128.4 x 10^6 m^3 of in-place oil and 273.7 x 10^9 m^3 of in-place gas.

With respect to nation-wide oil and gas potential, however, the petroleum potential in the Northern Yukon Fold Belt is likely low. According to National Energy Board's report on Canada's energy future (2003), only 1% of Canada's oil and 3% of gas is expected to be present in the mainland Northwest Territories and Yukon.

CONCLUSIONS

Highlights from the discoveries and resource potential of the region are discussed below.

1. The Interior Platform, which is a northern extension of the prolific world-class Western Canada Sedimentary Basin, shares several established and conceptual plays in northern Alberta and northeastern British Columbia. Drilling density is much reduced in the Northwest Territories due to access and costs. Of the 682 oil pools and 1880 gas pools defined in these plays, only 1 oil pool (Cameron Hills) and 34 gas accumulations have been discovered within the Mackenzie Corridor study area (Figure 1; Table 1). The largest gas accumulation in Northwest Territories is the Tweed Lake M-47 gas field in Colville Hills.

2. The total resource endowment (discovered reserves and resource potential) in the Interior Platform is 1223.24 x 10^6 m^3 of oil and 1564.3 x 10^9 m^3 of in-place gas. Much of the subcrop extent of the various reservoirs in the Interior Platform have not been evaluated and assessed (see Table 1) so these endowment volumes are likely very conservative.

3. Qualitative hydrocarbon assessments completed in the Interior Platform assign comparative hydrocarbon qualitative rankings ranging from low to very high. Very high petroleum potential areas include the Cambrian sandstone play area in the Colville Hills exploration region and the southern Great Slave Plain exploration area corresponding to the Middle Devonian Presqu'ile barrier and back-barrier (Gal and Jones, 2003; Gal, 2005). These areas contain known oil, gas or condensate discoveries and are expected to contain more discoveries. However, compared to nation-wide oil and gas potential, the region should be considered to have a low to moderate rating.

4. A total of 53 hydrocarbon discoveries, 13 oil, 20 gas and 20 oil and gas, have been made in the Beaufort-Mackenzie delta basin, making this basin similar to other prolific delta basins around the world. Total oil and gas reserves among these discoveries are 277.29 x 10^6 m^3 of oil and 332.44 x 10^9 m^3 of gas (Table 2; mean recoverable volumes; Dixon et al., 1994; Osadetz et al., 2005). These discoveries were made among 247 exploratory wells, representing a discovery success rate of 21%. The potential in this basin for further discoveries is high.

5. Total resource estimates for Beaufort-Mackenzie Basin are 1134.29 x 10^6 m^3 of mean recoverable oil and 1841.74 x 10^9 m^3 of mean recoverable gas (Table 2; Dixon et al., 1994; Osadetz et al., 2005). Approximately 24% of the oil and 18% of the gas resource have been discovered to date. The largest oil fields are Amauligak J-44, Adlartok P-09 and Koakoak O-22 located in both the shallow and deep offshore of the Beaufort Sea basin. Largest gas fields (Taglu G-33, Amauligak J-44, and Parsons F-09) occur in the onshore and shallow offshore portions of the Beaufort-Mackenzie Basin.

6. Gas hydrate potential in the Beaufort-Mackenzie Basin is immense. The potential is predicted to be 2.4 x 10^{12} to 87 x 10^{12} m^3 of in-place gas hydrate (Majorowicz and Osadetz, 2001).

7. In the Northern Foreland Belt, the greatest exploratory success was achieved in the Liard Plateau area, representing the northern continuation of the prolific Rocky Mountain Foreland Belt. In the area, 16 gas fields, 9 of which are in the study area, have been discovered (Table 3). The largest fields are Liard

K-29 and Pointed Mountain. Gas production in 2005 occurred at Liard F-36 and K-29 fields. Previous production took place in the Beaver River, Kotaneelee, Pointed Mountain, and Liard P-66A and SE Ft. Liard N -01 fields.

8. Natural gas resource potential in Liard Plateau is 276.85 x 10^9 m^3 (in-place volume; Table 3; Osadetz et al., 2000, 2003; Drummond, 2004). Approximately 31% of this volume has already been discovered (Table 3). A very high petroleum potential is expected for the Liard Plateau area (Gal and Jones, 2003). 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.

9. Another exploration play of limited exploratory success in the Northern Foreland Belt is the Kee Scarp reef play hosting the Norman Wells oil field beneath Mackenzie Plain. Since its discovery in 1920, numerous exploration attempts were made in finding similar Kee Scarp hydrocarbon reservoirs. All these attempts have failed. However, a recent discovery at Summit Creek southwest of Tulita in a structural play will likely add significantly to gas and light oil potential in Mackenzie Plain and eastern Mackenzie Mountains.

10. Significant oil and gas has been discovered in Eagle Plain Basin in the Northern Yukon Fold Complex. In the basin, 1.76 x 10^6 m^3 of oil in 5 pools and 2376 x 10^6 m^3 of gas in 10 pools were discovered (Table 4; National Energy Board, 2000; Osadetz et al., *in press* (a)). No oil and gas have been found in the other basins of the Fold Complex.

10. Total resource endowment in Eagle Plain Basin is predicted to be 69.4 x 10^6 m^3 of oil and 171.47 x 10^9 m^3 of in-place gas (Table 4). About 2.5 % of the oil and 1.4% of the gas have been discovered so far in the basin. If these predictions are correct, very high potential for further oil and gas discoveries exists in the basin.

11. The total resource potential for all basins in the Northern Yukon Fold Complex is 128.4 x 10^6 m^3 of in-place oil and 273.6 x 10^9 m^3 of in-place gas (Table 4). However, with respect to nation-wide hydrocarbon potential, this geological province is considered to encompass an area of low potential.

REFERENCES

Aitken, J.D.

1981: Stratigraphy and sedimentology of the Upper Proterozoic Little Dal Group, Mackenzie Mountains, Northwest Territories; *in*, Proterozoic Basins of Canada, F.H.A. Campbell (ed.); Geological Survey of Canada, Paper 81-10, p. 47-72.

1993: Proterozoic sedimentary rocks, Subchapter 4A; *in*, Sedimentary Cover of the Craton in Canada, D.F. Stott and J.D. Aitken (eds.); Geological Survey of Canada, Geology of Canada, no. 5, p. 81-95.

Bamber, E.W., Henderson, C.M., Richards, B.C., and McGugan, A.

1992: Carboniferous and Permian stratigraphy of the Foreland Belt; *in*, Part A. Ancestral North America; Upper Devonian to Middle Jurassic assemblages, Chapter 8; *in*, Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (eds.); Geological Survey of Canada, Geology of Canada, no. 4, p. 242-265.

Bamber, E.W. and Waterhouse, J.B.

1971: Carboniferous and Permian stratigraphy and paleontology, northern Yukon Territory, Canada; Bulletin of Canadian Petroleum Geology, v. 19, no. 1, p. 29-250.

Barclay, J.E., Holmstrom, G.D., Lee, P.J., Campbell, R.I., and Reinson, G.E.

1997: Carboniferous and Permian gas resources of the Western Canada Sedimentary Basin, Interior Plains, Part I: Geological play analysis and resource assessment; Geological Survey of Canada, Bulletin 515, 88 p.

Brabb, E.E.

1967: Stratigraphy of the Cambrian and Ordovician rocks of east-central Alaska; United States Geological Survey, Professional Paper 559-A, 30 p.

Brooks, P.W.

1986a: Biological marker geochemistry of oils from the Beaufort-Mackenzie region, Arctic Canada; Bulletin of Canadian Petroleum Geology, v. 34, no. 4, p. 490-505.

1986b: Unusual biological marker geochemistry of oils and possible source rocks, offshore Beaufort-Mackenzie Delta, Canada; Organic Geochemistry, v. 10, nos. 1-3, p. 401-406.

Bruce, C.J. and Parker, E.R.

1975: Structural features and hydrocarbon deposits in the Mackenzie Delta; Proceedings of the Ninth World Petroleum Congress, Tokyo, v. 2, p. 251-261.

Canadian Gas Potential Committee

2001: Natural gas potential in Canada, 2001.

Cecile, M.P.

1982: The Lower Paleozoic Misty Creek Embayment, Selwyn Basin, Yukon and Northwest Territories; Geological Survey of Canada, Bulletin 335, 78 p.

1986: Lower Paleozoic embayments, troughs, and arches, northern Canadian Cordillera (abstract); Geological Survey of Canada, Abstracts for Forum on Oil and Gas Activities in Canada, p. 5-6.

Cecile, M.P., Cook, D.G., and Snowdon, L.R.

1982: Plateau overthrust and its hydrocarbon potential, Mackenzie Mountains, Northwest Territories; *in,* Current Research, Part A, Geological Survey of Canada, Paper 82-1A, p. 89-94.

Cecile, M.P. and Norford, B.S.

1992: Ordovician and Silurian assemblages; *in,* Cambrian to Middle Devonian assemblages, Chapter 7; *in,* Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (eds.); Geological Survey of Canada, Geology of Canada, no. 4, p. 184-196.

Cook, D.G.
1992: Mackenzie Mountains, Franklin Mountains and Colville Hills; *in*, Part E. Foreland Belt, Structural Styles, Chapter 17; *in*, Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (eds.); Geological Survey of Canada, Geology of Canada, no. 4, p. 642-646.

Cook, D.G. and Aitken, J.D.
1971: Geology, Colville Lake map-area and part of Coppermine map-area (96 NW and NE, part of 86 NW), Northwest Territories; Geological Survey of Canada, Paper 70-12, 42 p.
1973: Tectonics of northern Franklin Mountains and Colville Hills, District of Mackenzie, Canada; *in*, Arctic Geology, M.G. Pitcher (ed.); American Association of Petroleum Geologists, Memoir 19, p. 13-32.

Cook, D.G. and MacLean, B.C.
2004: Subsurface Proterozoic stratigraphy and tectonics of the western plains of the Northwest Territories; Geological Survey of Canada, Bulletin 575, 91 p.

Cook, F.A., Coflin, K.C., Lane, L.S., Dietrich, J.R., and Dixon, J.
1987: Preliminary interpretations of the Mackenzie-Beaufort Basin deep crustal reflection survey; Geological Survey of Canada, Open File 1549, 37 p.

Craig, J.D., Sherwood, K.W., and Johnson, P.P.
1985: Geologic report for the Beaufort Sea planning region, Alaska; U. S. Mineral Management Service, Report MMS 85-0111, 192 p.

Creaney, S.
1980: The organic petrology of the Upper Cretaceous Boundary Creek Formation, Beaufort-Mackenzie Basin; Bulletin of Canadian Petroleum Geology, v. 28, no. 1, p. 112-129.

Dallimore, S.R. and Collett, T.S. (editors)
2005: Scientific results from the Mallik 2002 gas hydrate production research well program, Mackenzie Delta, Northwest Territories, Canada; Geological Survey of Canada, Bulletin 585, 140 p.

Dietrich, J.R., Dixon, J., and McNeil, D.H.
1985: Sequence analysis and nomenclature of Upper Cretaceous to Holocene strata in the Beaufort-Mackenzie Basin; *in*, Current Research, Part A; Geological Survey of Canada, Paper 85-1A, p. 613-628.

Dixon, J.
1986: Cretaceous to Pleistocene stratigraphy and paleogeography, northern Yukon and northwest District of Mackenzie; Bulletin of Canadian Petroleum Geology, v. 34, no. 1, p. 49-70.
1992: Stratigraphy of Mesozoic strata, Eagle Plain area, northern Yukon; Geological Survey of Canada, Bulletin 408, 58 p.
1997: Cretaceous and Tertiary, Chapter 11; *in*, Geology and mineral and hydrocarbon potential of northern Yukon Territory and northwestern District of Mackenzie, D.K. Norris (ed.); Geological Survey of Canada, Bulletin 422, p. 301-317.

Dixon, J. and McDonald, D.A.
1978: Sedimentology and petrology of the Cambrian Old Fort Island and Mount Cap formations, northern Interior Plains, N.W.T.; *in*, Display Summaries, Canadian Society of Petroleum Geologists Core and Field Sample Conference, A.F. Embry (ed.); Canadian Society of Petroleum Geologists, p. 4-7.

Dixon, J., Morrell, G.R., Dietrich, J.R., Taylor, G.C., and Procter, R.M.
1994: Petroleum resources of the Mackenzie Delta and Beaufort Sea; Part I: Basin analysis, Part II: Resource assessment; Geological Survey of Canada, Bulletin 424; 44 p.

Dixon, J. and Stasiuk, L.D.
1998: Stratigraphy and hydrocarbon potential of Cambrian strata, Northern Interior Plains, Northwest Territories; Bulletin of Canadian Petroleum Geology, v. 46, no. 3, p. 445-470.

Douglas, R.J.W.
1976: Geology, La Biche River, District of Mackenzie; Geological Survey of Canada, Map 1380A, scale 1:250,000.

Dover, J.H.
1992: Geologic map and fold- and thrust-belt interpretation of the southeastern part of the Charley River quadrangle, east-central Alaska; United States Geological Survey, Miscellaneous Investigations Series, Map I-1942, scale 1:1,000,000.

Drummond, K.J.
2004: Oil and gas resources and field size distribution of the Deh Cho Territory; http://www.dehcholands.org/reports_oil_gas_potential.htm.

Feinstein, S., Brooks, P.W., Fowler, M.G., Snowdon, L.R., and Williams, G.K.
1988: Families of oils and source rocks in the central Mackenzie Corridor: A geochemical oil-oil and oil-source rock correlation; *in*, Sequences, Stratigraphy, Sedimentology: Surface and Subsurface, D.P. James and D.A. Leckie (eds.); Canadian Society of Petroleum Geologists, Memoir 15, p. 543-552.

Feinstein, S., Williams, G.K., Snowdon, L.R., Brooks, P.W., Fowler, M.G., Goodarzi, F., and Gentzis, T.
1991a: Organic geochemical characterization and hydrocarbon generation potential of mid-Late Devonian Horn River bituminous shales, southern Northwest Territories; Bulletin of Canadian Petroleum Geology, v. 39, no. 2, p. 192-202.

Feinstein, S., Williams, G.K., Snowdon, L.R., Goodarzi, F., and Gentzis, T.
1991b: Thermal maturation of organic matter in the Middle Devonian to Tertiary section, Fort Norman area (central Mackenzie Plain); Canadian Journal of Earth Sciences, v. 28, p. 1009-1018.

Fowler, M.G., Stasiuk, L.D., Hearn, M., and Obermajer, M.
2001: Devonian hydrocarbon source rocks and their derived oils in the Western Canada Sedimentary Basin; Bulletin of Canadian Petroleum Geology, v. 49, no. 1, p. 117-148.

Fritz, W.H.
1992: Cambrian assemblages; *in*, Cambrian to Middle Devonian assemblages, Chapter 7; *in*, Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (eds.); Geological Survey of Canada, Geology of Canada, no. 4, p. 155-184.

Gabrielse, H.
1967: Tectonic evolution of the northern Canadian Cordillera; Canadian Journal of Earth Sciences, v. 4, p. 271-298.

Gabrielse, H. and Campbell, R.B.
1992: Upper Proterozoic assemblages, Chapter 6; *in*, Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (eds.); Geological Survey of Canada, Geology of Canada, no. 4, p. 127-150.

Gabrielse, H., Monger, J.W.H., Wheeler, J.O., and Yorath, C.J.
1992: Part A. Morphogeological belts, tectonic assemblages and terranes; *in*, Tectonic framework, Chapter 2; *in*, Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (eds.); Geological Survey of Canada, Geology of Canada, no. 4, p. 15-28.

Gal, L.P.
2005: Hydrocarbon potential ranking and play maps of the Sahtu and Gwich'in Settlement areas; Northwest Territories Geoscience Office, N.W.T. Open File 2005-04, 2 maps, scale 1:1,000,000.

Gal, L.P. and Jones, A.L.
2003: Evaluation of oil and gas potential in the Deh Cho Territory; Northwest Territories Geoscience Office, N.W.T. Open File 2003-03, 89 p.

Gordey, S.P.
1981: Structure section across south central Mackenzie Mountains, District of Mackenzie, Geological Survey of Canada, Open File 809, Scale 1:250,000.
1992: Devonian-Mississippian clastics of the Foreland and Omineca Belts; *in*, Part A. Ancestral North America; Upper Devonian to Middle Jurassic assemblages, Chapter 8; *in,* Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (eds.); Geological Survey of Canada, Geology of Canada, no. 4, p. 230-242.

Graham, A.D.
1973: Carboniferous and Permian stratigraphy, southern Eagle Plain, Yukon Territory, Canada; *in*, Symposium on the Geology of the Canadian Arctic, Proceedings, J.D. Aitken and D. Glass (eds.); Geological Association of Canada-Canadian Society of Petroleum Geologists, p. 159-180.

Hall, K.W.
1996: Geophysical transect of the Eagle Plains foldbelt and Richardson Mountains Anticlinorium, northern Yukon and western Northwest Territories, Canada; Master's thesis, University of Calgary, 67 p.

Hamblin, A.P.
1990: Upper Paleozoic petroleum geology and potential, southern Eagle Plain, Yukon Territory; Geological Survey of Canada, Open File 2286, 49 p.

Hannigan, P.K.
2000: Petroleum resource assessment of Bonnet Plume Basin, Yukon Territory, Canada; Oil and Gas Resources Branch, Department of Economic Development, Government of the Yukon, 59 p.
2001a: Petroleum resource assessment of the Yukon north coast, Yukon Territory, Canada; Oil and Gas Resources Branch, Department of Economic Development, Government of the Yukon, 87 p.
2001b: Petroleum resource assessment of the Old Crow Basin, Yukon Territory, Canada; Oil and Gas Resources Branch, Department of Economic Development, Government of the Yukon, 64 p.

Hannigan, P.K., Osadetz, K.G., Dixon, J., and Bird, T.
1999: Petroleum resource assessment of the Kandik Basin, Yukon Territory, Canada; Oil and Gas Resources Branch, Department of Economic Development, Government of the Yukon, 74 p.

Henderson, C.M., Bamber, E.W., Richards, B.C., Higgins, A.C., and McGugan, A.
1993: Permian, Subchapter 4F; *in,* Sedimentary Cover of the Craton in Canada, D.F. Stott and J.D. Aitken (eds.); Geological Survey of Canada, Geology of Canada, no. 5, p. 272-293.

Hite, D.M.
1997: A native corporation evaluates potential of Alaska's Kandik area; Oil and Gas Journal, Nov. 17, 1997, p. 89-93.

Howell, D.G.
1996: Kandik Basin; *in,* 1995 National Assessment of United States Oil and Gas Resources-Results, Methodology, and Supporting Data, D.L. Gautier, G.L. Dolton, K.I. Takahashi, and K.L. Varnes (eds.); United States Geological Survey Digital Data Series-30, Release 2, CD-ROM.

Indian and Northern Affairs Canada
1995: Petroleum exploration in northern Canada: A guide to oil and gas exploration and potential, G.R. Morrell (ed.); Northern Oil and Gas Directorate, Indian and Northern Affairs Canada, 110 p.

Issler, D.R. and Snowdon, L.R.
1990: Hydrocarbon generation kinetics and thermal modelling, Beaufort-Mackenzie Basin; Bulletin of Canadian Petroleum Geology, v. 38, no. 1, p. 1-16.

Johnson, R.D. and McMillan, N.J.
1993: Petroleum, Subchapter 6A; *in,* Sedimentary Cover of the Craton in Canada, D.F. Stott and J.D. Aitken (eds.); Geological Survey of Canada, Geology of Canada, no. 5, p. 505-562.

Lane, L.S.
1996: Geometry and tectonics of Early Tertiary triangle zones, northeastern Eagle Plain, Yukon Territory; Bulletin of Canadian Petroleum Geology, v. 44, no. 2, p. 337-348.
1998: Latest Cretaceous-Tertiary tectonic evolution of northern Yukon and adjacent Arctic Alaska; American Association of Petroleum Geologists Bulletin, v. 82, no. 7, p. 1353-1371.
Langhus, B.G.
1980: Generation and migration of hydrocarbons in the Parsons Lake area, N.W.T., Canada; *in,* Facts and Principles of World Oil Occurrence, A.D. Miall (ed.); Canadian Society of Petroleum Geologists, Memoir 6, p. 523-534.
Lawrence, J.R.
1973: The Old Crow Basin; *in,* Future Petroleum Provinces of Canada, R.G. McCrossan (ed.); Canadian Society of Petroleum Geologist, Memoir 1, p. 307-314.
Leckie, D.A., Potocki, D.J., and Visser, K.
1991: The Lower Cretaceous Chinkeh Formation: A frontier-type play in the Liard Basin of western Canada; American Association of Petroleum Geologists Bulletin, v. 75, no. 8, p. 1324-1352.
Lee, P.J.
1998: Oil resources of western Canada; Geological Survey of Canada, Open File 3674, 142 p.
Link, C.M. and Bustin, R.M.
1989: Organic maturation and thermal history of Phanerozoic strata in northern Yukon and northwestern District of Mackenzie; Bulletin of Canadian Petroleum Geology, v. 37, no. 3, p. 266-292.
Link, C.M., Bustin, R.M., and Snowdon, L.R.
1989: Petroleum source potential and depositional setting of Phanerozoic strata in northern Yukon and northwestern District of Mackenzie; Bulletin of Canadian Petroleum Geology, v. 37, no. 3, p. 293-315.
Long, D.G.F.
1978: Lignite deposits in the Bonnet Plume Formation, Yukon Territory; *in,* Current Research, Part A, Geological Survey of Canada, Paper 78-1A, p. 399-401.
1987: Coal in Yukon; *in,* Mineral Deposits of Northern Cordillera, J.A. Morin (ed.); Canadian Institute of Mining and Metallurgy, Special Volume 37, p. 311-318.
MacLean, B.C.
in press: The sub-Phanerozoic basement surface under the Great Slave Plain of the Northwest Territories and its influence on overlying strata; *in,* Potential for Carbonate-hosted Lead-zinc Mississippi Valley-type Mineralization in Northern Alberta and Southern Northwest Territories, Geoscience Contributions, Targeted Geoscience Initiative; P. K. Hannigan (ed.); Geological Survey of Canada, Bulletin 591, p. xxx-xxx.
MacLean, B.C. and Cook, D.G.
1992: The influence of Proterozoic structures on the development of Laramide structures, northern Interior Plains, Northwest Territories, Canada; Bulletin of Canadian Petroleum Geology, v. 40, no. 3, p. 207-221.
1999: Salt tectonism in the Fort Norman area, Northwest Territories, Canada; Bulletin of Canadian Petroleum Geology, v. 47, no. 2, p. 104-135.
MacLean, B.C. and Morrow, D.W.
2004: Bovie Structure: Its evolution and regional context; Bulletin of Canadian Petroleum Geology, v. 52, no. 4, p. 302-324.
Majorowicz, J.A. and Hannigan, P.K.
2000a: Stability zone of natural gas hydrates in a permafrost-bearing region of the Beaufort-Mackenzie Basin; study of a feasible energy source; Natural Resources Research, v. 9, no. 1, p. 3-25.

2000b: Natural gas hydrates in the offshore Beaufort-Mackenzie Basin - Study of a feasible energy source II; Natural Resources Research, v. 9, no. 3, p. 201-214.

Majorowicz, J.A. and Osadetz, K.G.

2001: Gas hydrate distribution and volume in Canada; American Association of Petroleum Geologists Bulletin, v. 85, no. 7, p. 1211-1230.

Martin, H.L.

1972: Upper Paleozoic stratigraphy of the Eagle Plain Basin, Yukon Territory; Geological Survey of Canada, Paper 71-14, 54 p.

1973: Eagle Plain Basin, Yukon Territory; *in,* Future Petroleum Provinces of Canada, R.G. McCrossan (ed.); Canadian Society of Petroleum Geologist, Memoir 1, p.275-306.

Mathews, W.H. and Bustin, R.M.

1984: Why do the Smoking Hills smoke? Canadian Journal of Earth Sciences, v. 21, p. 737-742.

Meding, M.G.

1994: Analysis of selected Northwest Territories hydrocarbon pool data; Department of Energy, Mines and Petroleum Resources, Government of the Northwest Territories.

Meijer-Drees, N.C.

1993: The Devonian succession in the subsurface of the Great Slave and Great Bear plains, Northwest Territories; Geological Survey of Canada, Bulletin 393, 222 p.

Moore, P.F.

1993: Devonian, Subchapter 4D; *in*, Sedimentary Cover of the Craton in Canada, D.F. Stott and J.D. Aitken (eds.); Geological Survey of Canada, Geology of Canada, no. 5, p. 150-201.

Morrell, G. and Dietrich, J.R.

1993: Evaluation of the hydrocarbon prospectivity of the Old Crow Flats area of the northern Yukon; Bulletin of Canadian Petroleum Geology, v. 41, no. 1, p. 32-45.

Morrow, D.W.

1989: Lower Paleozoic stratigraphy of the White Mountains, Yukon and Northwest Territories, and sedimentological evidence for a 'White Mountains platform'; *in,* Current Research, Part G; Geological Survey of Canada, Paper 89-1G, p. 77-84.

1991: The Silurian-Devonian sequence in the northern part of the Mackenzie shelf, Northwest Territories; Geological Survey of Canada, Bulletin 413, 121 p.

1999: Lower Paleozoic stratigraphy of northern Yukon Territory and northwestern District of Mackenzie; Geological Survey of Canada, Bulletin 538, 202 p.

Morrow, D.W. and Cook, D.G.

1987: The Prairie Creek Embayment and Lower Paleozoic strata of the southern Mackenzie Mountains; Geological Survey of Canada, Memoir 412, 195 p.

Morrow, D. W., Cumming, G. L., and Aulstead, K. L.

1990: The gas-bearing Devonian Manetoe facies, Yukon and Northwest Territories; Geological Survey of Canada, Bulletin 400, 54 p.

Morrow, D.W., Cumming, G.L., and Koepnick, R.B.

1986: Manetoe facies-A gas-bearing, megacrystalline, Devonian dolomite, Yukon and Northwest Territories, Canada; American Association of Petroleum Geologists, Bulletin, v.70, no. 6, p. 702-720.

Morrow, D.W. and Geldsetzer, H.H.J.

1992: Lower and Middle Devonian assemblages; *in*, Cambrian to Middle Devonian assemblages, Chapter 7; *in*, Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (eds.); Geological Survey of Canada, Geology of Canada, no. 4, p. 196-210.

Morrow, D.W., MacLean, B.C., Tzeng, P. and Pana, D.
2002: Subsurface Paleozoic structure and isopach maps and selected seismic lines in southern Northwest Territories and northern Alberta: Implications for mineral and petroleum potential; Geological Survey of Canada, Open File 4366, 22 p., CD-ROM.
Morrow, D.W., Potter, J., Richards, B., and Goodarzi, F.
1993: Paleozoic burial and organic maturation in the Liard Basin region, northern Canada; Bulletin of Canadian Petroleum Geology, v. 41, no. 1, p. 17-31.
Mountjoy, E.W.
1967a: Upper Cretaceous and Tertiary stratigraphy, northern Yukon Territory and northwestern District of Mackenzie; Geological Survey of Canada, Paper 66-16, 70 p.
1967b: Triassic stratigraphy of northern Yukon Territory; Geological Survey of Canada, Paper 66-19, 44 p.
National Energy Board
1998: Probabilistic estimate of hydrocarbon volumes in the Mackenzie Delta and Beaufort Sea discoveries; http://www.neb-one.gc.ca/NorthOffshore/FrontierActivities/HydrocarbonVolumes_e.pdf, 8 p.
2000a: Petroleum resource assessment of the Peel Plateau, Yukon Territory, Canada; Energy Resources Branch, Yukon Economic Development, 66 p.
2000b: Petroleum resource assessment of the Eagle Plain, Yukon Territory, Canada; Energy Resources Branch, Yukon Economic Development, 78 p.
2001: Petroleum resource assessment of the Liard Plateau, Yukon Territory, Canada; Energy Resources Branch, Yukon Economic Development, 63 p.
2003: Canada's energy future: Scenarios for supply and demand to 2025; http://www.neb.gc.ca/energy/SupplyDemand/2003/index_e.htm, 93 p.
Norford, B.S.
1997: Ordovician and Silurian, Chapter 6; *in*, Geology and mineral and hydrocarbon potential of northern Yukon Territory and northwestern District of Mackenzie, D.K. Norris (ed.); Geological Survey of Canada, Bulletin 422, p. 119-162.
Norris, D.K.
1984: Geology of the northern Yukon and northwestern District of Mackenzie; Geological Survey of Canada, Map 1528A, scale 1:500,000.
1985: Eastern Cordillera foldbelt of northern Canada: Its structural geometry and hydrocarbon potential; American Association of Petroleum Geologists Bulletin, v. 69, no. 5, p. 788-808.
1997: Geological setting, Chapter 3; *in*, Geology and mineral and hydrocarbon potential of northern Yukon Territory and northwestern District of Mackenzie, D.K. Norris (ed.); Geological Survey of Canada, Bulletin 422, p. 21-64.
Norris, D.K. and Hopkins, W.S., Jr.
1977: The geology of the Bonnet Plume Basin, Yukon Territory; Geological Survey of Canada, Paper 76-8, 20 p.
Norris, D.K. and Hughes, O.L.
1997: Mineral and hydrocarbon potential; *in*, Geology and mineral and hydrocarbon potential of northern Yukon Territory and northwestern District of Mackenzie, D.K. Norris (ed.); Geological Survey of Canada, Bulletin 422, p. 369-396.
Osadetz, K.G., Chen, Z., and Bird, T.D.
in press(a): Petroleum resource assessment, Eagle Plain Basin and environs, Yukon Territory, Canada; Geological Survey of Canada, Open File XXXX, 103 p.
Osadetz, K.G., Chen, Z., and Morrow, D.W.
2003: Petroleum resource assessment of the Tlogotsho Plateau, Nahanni karst, and adjacent areas under consideration for expansion of Nahanni National Park Reserve, northern Cordillera and

District of Mackenzie, Chapter 8; *in*, Mineral and Energy Resource Assessment of the Tlogotsho Plateau, Nahanni karst, Ragged ranges, and adjacent areas under consideration for expansion of Nahanni National Park Reserve, Northwest Territories, C.W. Jefferson and W.A. Spirito (eds.); Geological Survey of Canada, Open File 1686, CD-ROM.

Osadetz, K.G., Dixon, J., Dietrich, J.R., Snowdon, L.R., Dallimore, S.R., and Majorowicz, J.A.
2005: A review of Mackenzie Delta-Beaufort Sea petroleum province conventional and non-conventional (gas hydrate) petroleum reserves and undiscovered resources: A contribution to the resource assessment of the proposed Mackenzie Delta-Beaufort Sea Marine Protected areas; Geological Survey of Canada, Open File 4828, 33 p.

Osadetz, K.G., MacLean, B.C., Morrow, D.W., Dixon, J., and Hannigan, P.K.
in press (b): Petroleum resource assessment, Peel Plateau and Plain, Yukon Territory, Canada; Geological Survey of Canada, Open File 4841.

Osadetz, K.G. and Snowdon, L.R.
1995: Significant Paleozoic petroleum source rocks in the Canadian Williston Basin: Their distribution, richness and thermal maturity (southeastern Saskatchewan and southwestern Manitoba); Geological Survey of Canada, Bulletin 487, 60 p.

Osadetz, K.G., Stockmal, G., and Lebel, D.
2000: Resource analysis of natural gas in the Foreland Belt; *in*, Structure and hydrocarbon occurrence, Rocky Mountain Foothills and Front Ranges, Turner Valley to Waterton Lakes; GeoCanada 2000, Field Trip Guidebook No. 11, p. 137-155.

Potter, J., Richards, B.C., and Goodarzi, F.
1993: The organic petrology and thermal maturity of Lower Carboniferous and Upper Devonian source rocks in the Liard Basin, at Jackfish Gap-Yohin Ridge and North Beaver River, northern Canada: Implications for hydrocarbon exploration; Energy Sources, v. 15, p. 289-314.

Poulton, T.P.
1992: Lower and Middle Jurassic strata of the Foreland Belt; *in*, Part A. Ancestral North America; Upper Devonian to Middle Jurassic assemblages, Chapter 8; *in*, Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (eds.); Geological Survey of Canada, Geology of Canada, no. 4, p. 276-281.

Price, R.A. and Fermor, P.R.
1985: Structure section of the Cordilleran foreland thrust and fold belt west of Calgary, Alberta; Geological Survey of Canada, Paper 84-14, 1 sheet.

Pugh, D.C.
1983: Pre-Mesozoic geology in the subsurface of Peel River map area, Yukon Territory and District of Mackenzie; Geological Survey of Canada, Memoir 401, 61 p.

Reinson, G.E., Lee, P.J., Warters, W., Osadetz, K.G., Bell, L.L., Price, P.R., Trollope, F., Campbell, R.I., and Barclay, J.E.
1993: Devonian gas resources of the Western Canada Sedimentary Basin; Part I: Geological play analysis and resource assessment; Geological Survey of Canada, Bulletin 425, p. 1-127.

Richards, B.C., Bamber, E.W., Higgins, A.C., and Utting, J.
1993: Carboniferous, Subchapter 4E; *in*, Sedimentary Cover of the Craton in Canada, D.F. Stott and J.D. Aitken (eds.); Geological Survey of Canada, Geology of Canada, no. 5, p. 202-271.

Richards, B.C., Bamber, E.W., and Utting, J.
1997: Upper Devonian to Permian, Chapter 8; *in*, Geology and mineral and hydrocarbon potential of northern Yukon Territory and northwestern District of Mackenzie, D.K. Norris (ed.); Geological Survey of Canada, Bulletin 422, p. 201-251.

Ricketts, B.D.
1988: The Monster Formation: A coastal fan system of Late Cretaceous age, Yukon Territory; Geological Survey of Canada, Paper 86-14, 27 p.

Snowdon, D.M.
1977: Beaver River gas field: A fractured carbonate reservoir; *in*, The Geology of Selected Carbonate Oil, Gas and Lead-zinc Reservoirs in Western Canada, I.A. McIlreath and R.D. Harrison (eds.); Canadian Society of Petroleum Geologists, Core Conference, no. 5, p. 1-18.

Snowdon, L.R.
1980: Resinite - A potential petroleum source in the Upper Cretaceous/Tertiary of the Beaufort-Mackenzie Basin; *in*, Facts and Principles of World Petroleum Occurrence, A.D. Miall (ed.); Canadian Society of Petroleum Geologists, Memoir 6, p. 509-521.
1988: Petroleum source rock potential and thermal maturation reconnaissance in Eagle Plain, Yukon Territory; Geological Survey of Canada, Open File 1720; 115 p.

Snowdon, L.R., Brooks, P.W., Williams, G.K., and Goodarzi, F.
1987: Correlation of the Canol Formation source rock with oil from Norman Wells; Organic Geochemistry, v. 11, no. 6, p. 529-548.

Snowdon, L.R. and Powell, T.G.
1979: Families of crude oils and condensates in the Beaufort-Mackenzie Basin; Bulletin of Canadian Petroleum Geology, v. 27, no. 2, p. 139-162.

Snowdon, L.R. and Price, P.R.
1994: Rock-Eval/TOC data for three wells in the Kandik Basin, western Yukon Territory; Geological Survey of Canada, Open File 2899, 31 p.

Snowdon, L.R. and Williams, G.K.
1986: Thermal maturation and petroleum source potential of some Cambrian and Proterozoic rocks in the Mackenzie Corridor; Geological Survey of Canada, Open File 1367, 14 p.

Stasiuk, L.D. and Fowler, M.G.
2002: Thermal maturity evaluation (vitrinite and vitrinite reflectance equivalent) of Middle Devonian, Upper Devonian, and Mississippian strata in the Western Canada Sedimentary Basin; Geological Survey of Canada, Open File 4341, CD-ROM.

Stasiuk, L.D., Fowler, M.G., and Addison, G.
2002: Thermal maturity evaluation of Lower Cretaceous Mannville Group and equivalent coals in the Western Canada Sedimentary Basin: A compilation of vitrinite reflectance data; Geological Survey of Canada, Open File 4342, CD-ROM.

Stasiuk, L.D., Fowler, M.G., Stirrett, A., and Snowdon, L.
2006: Thermal maturity, source rocks and hydrocarbons in Cretaceous and Devonian strata within Summit Creek B-44 exploration well, central Mackenzie valley, N.W.T., Canada; 2006 CSPG-CSEG-CWLS Convention, abstract, CD-ROM, p. 115.

Stelck, C.R.
1944: Final geological report on “The Upper Peel River Area”, Yukon Territory (Canada); Imperial Oil Limited, Canol Project Assignment No. 23.

Stott, D.F., Dixon, J., Dietrich, J.R., McNeil, D.H., Russell, L.S., and Sweet, A.R.
1993: Tertiary, Subchapter 4J; *in*, Sedimentary Cover of the Craton in Canada, D.F. Stott and J.D. Aitken (eds.); Geological Survey of Canada, Geology of Canada, no. 5, p. 439-465.

Stott, D.F., Yorath, C.J., and Dixon, J.
1992: The Foreland Belt; *in*, Upper Jurassic to Paleogene Assemblages, Chapter 9; *in*, Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (eds.); Geological Survey of Canada, Geology of Canada, no. 4, p. 335-344.

Warters, W.J., Cant, D.J., Tzeng, H.P., and Lee, P.J.
1997: Mannville gas resources of the Western Canada Sedimentary Basin; Geological Survey of Canada, Bulletin 517, 101 p.

Wielens, J.B.W.
1987: Study of pre-Mesozoic stratigraphy and structure of Tuktoyaktuk Peninsula, Phase 1, March 1987; Geological Survey of Canada, Open File 1513, 50 p.
1992: The pre-Mesozoic stratigraphy and structure of Tuktoyaktuk Peninsula; Geological Survey of Canada, Paper 90-22, 90 p.

Wielens, J.B.W., von der Dick, H., Fowler, M.G., Brooks, P.W., and Monnier, F.
1990: Geochemical comparison of a Cambrian alginite potential source rock, and hydrocarbons from the Colville/Tweed Lake area, Northwest Territories; Bulletin of Canadian Petroleum Geology, v. 38, no. 2, p. 236-245.

Williams, G.K.
1986: Kee Scarp play, Norman Wells area, N.W.T.; Geological Survey of Canada, Open File 1228, 5 p.
1988: A review of the Bonnet Plume area, east-central Yukon Territory (including Snake River, Solo Creek, Noisy Creek and Royal Creek areas); Geological Survey of Canada, Open File 1742, 70 p.

LIST OF FIGURES

LIST OF TABLES