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Infrastructure and Resources of the Northern Canadian Mainland Sedimentary Basin

D.W. Morrow[1], A.L. Jones[2], and J. Dixon[1]

2006

[1] Geological Survey of Canada (Calgary), 3303-33rd Street, N.W., Calgary, Alberta, Canada T2L2A7
[2] Northwest Territories Geoscience Office (NTGO), Box 1500, 4601-B 52nd Ave, Yellowknife, Northwest Territories X1A2R3

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

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INTRODUCTION

This report summarizes infrastructure and resource information for an area of northwestern Canada extending between 60 and 70° north latitudes and 110 and 141° west longitudes. It represents a potential chapter contribution to a future geological atlas compendium entitled "Geological Atlas of the Northern Canadian Mainland Sedimentary Basin". This report, and future atlas contribution, represent a contribution to the Geological Survey of Canada project entitled "Mackenzie Corridor: Access to Northern Resources" under the Northern Resources Development Program (NRD), Earth Sciences Sector (ESS), Department of Natural Resources (NRCan). The resource and infrastructure information synthesis provides resource exploration companies and northern communities with a concise overview of the existing transportation, pipeline, and power distribution networks, as well as the magnitude of discovered energy and mineral resources. Pertinent literature references are cited, as well as webpage hyperlinks (current as of Dec 2005) to sources of more detailed information for which appropriate literature sources are not available.

This report is intended to facilitate efficient resource exploration and improved decision-making capacity for northern communities concerned with resource exploration and development. This is a direct contribution to the NRD Program outcome that Canadians and, in particular, northern Canadians derive socio-economic benefits from responsible development of mineral and energy resources of the North.

ACKNOWLEDGMENTS

Critical readers Mr. L.P. Gal, of the C.S. Lord Northern Geoscience Office of the Government of the Northwest Territories, and Dr. E. Zaleski, formerly of the Geological Survey of Canada (Calgary) provided comprehensive reviews of the manuscript, which resulted in considerable improvements. The cooperation and assistance of the C.S. Lord Northern Geoscience Office itself is gratefully acknowledged. Finally, we acknowledge the support of the Earth Sciences Sector (ESS) Northern Resources Development (NRD) Program of the Department of Natural Resources Canada (NRCan) as represented by Dr. D.J. Scott, NRD Program Manager.

POLITICAL SUBDIVISIONS AND LAND CLAIMS STATUS

Northern Territories

The report encompasses parts of the three territories of northern Canada (Fig.1). The northeast corner of the report area includes a portion of the territory of Nunavut, created in 1999. But most of the area dealt with belongs to the Northwest Territories and the Yukon Territory (Figs. 1, 2), and encompassing both of their respective capital cities, Yellowknife and Whitehorse. The major difference in governance between a Canadian province and a territory is that a province receives powers directly from the Constitution Act of 1867, whereas a territory is delegated powers by the federal government. Thus, the federal government has more direct control over the territories, while provincial governments have many more inherent competences and rights. In general, legislative powers, programs and responsibilities for management of land, water, mines, minerals, oil and gas, the environment and archaeological resources in these territories are administered by the Department of Indian and Northern Affairs (DIAND). In May 2001, Leaders of an Intergovernmental Forum in Inuvik, signed a Memorandum of Intent (MOI) to devolution of legislative powers, including resource revenue sharing to the Northwest Territories (www.gov.nt.ca/MAA/devolution.htm). The three parties involved in these negotiations are; the Government of Canada, the Government of the Northwest Territory (NWT), and the Aboriginal Summit. Memorandum of Intent specifies that all resource revenues will be used for government purposes and that the net fiscal benefit to the NWT will be shared between the Government of the Northwest Territories and Aboriginal Governments.

First Nations

In 1977, the Berger Commission Report recommended a 10-year moratorium on pipeline construction while native land claims are settled, and a permanent ban on any pipeline from Alaska across the northern Yukon. Since that time, land claim agreements have been reached between the Federal Government of Canada, territorial governments and several northern First Nations groups, and discussions are on-going with others.

Settlement regions within the Northwest Territories (www.gov.nt.ca/MAA/index_aboriginal.htm, www.ainc-inac.gc.ca/pr/agr/index_e.html) include:

The Inuvialuit region (Inuvialuit Final Agreement (1984)),
The Gwich'in region (The Gwich'in Agreement (1992)),
The Sahtu region (The Sahtu Dene and Metis Agreement (1994)) and,
The Tlicho region (Tlicho Agreement (1993)).

The Sahtu Settlement Region is subdivided into three districts, the K'asho Got'ine, the Déline, and the Tulita Districts (Fig. 1). The boundaries of the proposed Dehcho and Akaitcho settlement regions are under discussion at present. The Inuvialuit Settlement Region includes part of northernmost Yukon Territory as well (Fig. 1).

The Yukon Territory is home to more than a dozen Aboriginal groups (Inuvialuit, Vuntut Gwich'in, Tetlit, Nacho Nyak Dun, Selkirk, Little Salmon/Carmacks, Liard, Ross River and Kaska, Teslin Tlingit, Ta'an Kwach'an, Carcross/Tagish, Kwanlin Dun, Champagne and Aishihik, Kluane and White River, and Tr'on Dek Hwech'in). The Yukon First Nations Land Claims Settlement Act of 1994 (laws.justice.gc.ca/en/Y-2.3/112116.html#rid-112125, www.ainc-inac.gc.ca/pr/agr/index_e.html, www.ainc-inac.gc.ca/ps/clm/brieff_e.pdf) was negotiated between the Federal Government and:

- The Carcross/Tagish First Nation,
- The Champagne and Aishihik First Nations,
- The Kluane First Nation,
- The Kwanlin Dun First Nation,
- The Liard First Nation,
- The Little Salmon/Carmacks First Nation,
- The First Nation of Nacho Nyak Dun,
- The Ross River Dena Council, the Selkirk First Nation,
- The Ta'an Kwach'an Council,
- The Teslin Tlingit Council,
- The Tr'ondëk Hwëch'in,
- The Vuntut Gwitchin First Nation, and
- The White River First Nation.

This included final land claims settlements for four groups:

- The Champagne and Aishihik First Nations,
- The First Nation of Nacho Nyak Dun,
- The Teslin Tlingit Council, and
- The Vuntut Gwitchin First Nation.

Subsequently, self-government agreements were reached with:

- The Little Salmon/Carmacks First Nation in 1997,
- The Selkirk First Nation in 1997,
- The Tr'ondëk Hwëch'in First Nation in 1998,
- The Ta'an Kwach'an Council in 2002,
- The Kluane First Nation in 2003, and

- The Kwanlin Dun First Nation in 2005.

The final agreements up until 2005 assigned the Yukon First Nations with 41,595 km^2 of land, of which 25,900 km^2 includes mineral rights. The Carcross/Tagish First Nation and White River First Nation signed Memoranda of Understanding (MOU) with government representatives in 2002, and the self-government documents are in the drafting process. The Liard First Nation and Ross River Dena Council did not sign MOU, and land claims negotiations were discontinued.

The newly created Territory of Nunavut is covered by a single land claims settlement, the Nunavut Land Claims Agreement (1993), which is the single largest land claims settlement in Canada. This land claim settlement provides the Inuit with 351,000 km^2 of which 37,000 km^2 include mineral rights.

INFRASTRUCTURE

Petroleum Pipeline Network

The route for the proposed 1220 kilometre long Mackenzie Valley Pipeline traverses the Northwest Territories (Fig. 3), across a major portion of the northern Canadian mainland sedimentary basin. The proposed pipeline would supply natural gas from gas fields in the Mackenzie Delta (www.mackenziegasproject.com/) to the major markets in southern Canada and in the United States of America. The two main groups involved in the Mackenzie Gas Project are the Aboriginal Pipeline Group (APG) representing the interests of the aboriginal peoples of the Northwest Territories, and the Producers Group of petroleum companies, comprised of Imperial Oil Resources Ventures Limited, ConocoPhillips Canada (North) Limited, Shell Canada Limited, and ExxonMobil Canada Properties. Each of the participants in the Producers Group has an interest in one or more of the three Mackenzie Delta gas fields (Niglintgak, Taglu and Parsons Lake; Fig. 3). The prospect of a MVP has heightened petroleum exploration activity across the entire mainland Northwest Territories, starting in the mid 1990's and continuing to the present day.

Another proposed gas pipeline, the Alaska Highway Pipeline (AHP), would cross the southwest corner of the Yukon (Fig. 3), essentially following the route of the Alaska Highway, built during the Second World War (www.foothillspipe.com/ahpp/index.html). This pipeline would connect the existing gas handling facilities at Prudhoe Bay on the north coast of Alaska with Fairbanks in the Alaskan interior, and with the existing gas distribution systems in southern Canada. The large Prudhoe Bay Oil Field with 13 billion barrels of oil produced to end of 2005 and 26 trillion cubic feet (Tcf) of accompanying discovered gas reserves (Sherwood and Craig, 2001) would provide the natural gas feedstock for the AHP.

The existing petroleum energy infrastructure includes one oil pipeline, the Enbridge-owned Norman Wells Pipeline (Figs. 3, 4). In operation since 1985, this was the first completely buried oil pipeline in permafrost terrain in Canada (http://sts.gsc.nrcan.gc.ca/permafrost/pipeline.html). This pipeline carries crude oil 869 km from the large oil field at Norman Wells, NWT (Fig. 4) to gathering facilities at Zama, northwestern Alberta. By the end of 2003, cumulative production from Norman Wells field reached 34.8 x 10^6 m^3 (215.6 million barrels).

Gas pipelines include the Ikhil Pipeline (Fig. 3, 5), which supplies the town of Inuvik, NWT with natural gas from the Ikhil gas field (http://www.ainc-inac.gc.ca/oil/ann/ann2003/dev_e.html) in the Mackenzie Delta near Caribou Hills, 50 kilometres to the north. Originally discovered in 1983, the field remained undeveloped until 1999. The reservoir is in the Aklak sands (Reindeer Formation) of Eocene Age at a depth of about 1100 metres. Production in 2002 was 15.2 x 10^6 m^3 (0.54 billion cubic feet-BCF) with cumulative production totalling 73.6 x 10^6 m^3 (2.6 BCF).

Two other gas pipelines are located near Fort Liard in the extreme southwest corner of the Northwest Territories (Figs. 3, 5). The Duke Energy Pointed Mountain Gas Pipeline moves gas produced from deep reservoirs in the Liard gas fields just west of Fort Liard to markets in southern Canada and in the United

States. Cumulative field production from the Liard Field to the end of 2004 was 3684 x 10^6 m^3 (130.1 BCF). Immediately south of Fort Liard, a small diameter (324 mm) pipeline, the Shiha Pipeline, carries the gas from the Paramount F-36 Gas Field south 24 kilometres to a processing plant near Maxhamish Lake, British Columbia where it enters the North American gas distribution system. The nearby, older Beaver River and Pointed Mountain Fields in the Liard area previously supplied gas via the Duke Energy Gas Transmission Pointed Mountain Pipeline and the Westcoast Gas Pipeline system (noms.wei-pipeline.com/GMSFS/web/html/companyinfo/operational_info/systems_map/maps.shtml).The Kotaneelee Field, also in the Liard area, is the only producing gas field in the Yukon Territory. It has a cumulative production of over 6,000 x 10^6 m^3 and also feeds into the Duke Energy Pointed Mountain Pipeline.

Gas and oil produced from Paramount's Cameron Hills Oil and Gas field (Figs. 4, 5), south of Tathlina Lake, flow through a small diameter pipeline that runs 15 kilometres to a central processing plant near Bistcho Lake, in northern Alberta. Gas production from the field commenced in March 2002. By the end of 2004 five wells (A-73, C-50, B-08, N-28, and H-58) were producing gas with cumulative production (http://www.ainc-inac.gc.ca/oil/ann/ann2003/dev_e.html) of 291.8 x 10^6 m^3 (10.3 BCF). Sustained oil production started in March 2003. For most of the remainder of the year oil was being produced from four wells (C-74, K-74, H-03, and F-73) with total year-end production at 78,148 m^3 (491,500 barrels). In 2004 the F-73 well was shut in.

Hydroelectric Power Grid

Hydroelectric transmission line networks radiate locally from a few centres in the Yukon and Northwest territories (Fig. 3). In the Northwest Territories (www.ntpc.com/grey/supply/hydro.htm) the NWT Power Corporation runs two hydro-powered generating systems. One north of Yellowknife, with several generating plants along the Snare River, supplies Rae-Edzo, Dettah and Yellowknife with up to 31 megawatts of power. The other, near Fort Smith, supplies Fort Smith, Fort Resolution, Hay River and Enterprise with up to 21 megawatts.

Yellowknife is the major NWT centre for hydroelectric power usage. A network of transmission lines supported the precious metal mining industry that developed north of Yellowknife, as well as the city of Yellowknife itself (Fig 6). Recently however, only the Giant and Con gold mines near Yellowknife remained in production, and these closed in 2004.

The Taltson Hydroelectric Plant at Fort Smith supplies power to the communities of Fort Smith, Fort Resolution and to Hay River. The only other hydroelectric transmission network of note in the Northwest Territories was centred on the now closed, Pine Point Mine on the south shore of Great Slave Lake east of the community of Hay River (Figs. 3, 6). Electric power in most other NWT communities is locally supplied using on-site petroleum fuel powered generators.

Hydro electricity has been used in the Yukon since 1906. Significant hydroelectric transmission line networks radiate from the cities of Whitehorse and Dawson in support of precious and base metal mining in surrounding areas (Figs. 3, 6). Currently, four utility-owned hydroelectric facilities provide a total of approximately 76 Megawatts (MW) of power, along with three privately owned small hydroelectric facilities (www.emr.gov.yk.ca/energy/hydro.html). There are two electric utilities in the Yukon: the Yukon Energy Corporation, owned by the Yukon Development Corporation of the Yukon government, and the privately owned Yukon Electrical Company Ltd. (YECL). . Yukon Energy owns and generates most of the electricity in the Yukon and owns distribution lines in the communities of Dawson, Mayo and Faro. YECL, which manages the Yukon's electrical system, is a private utility owned by Alberta Power Limited, in turn, owned by Canadian Utilities of Alberta. Yukon Utility Hydro hydroelectric facilities include the Whitehorse Rapids, Aishihik Lake, Mayo Lake, and Fish Lake hydroelectric plant complexes. The Whitehorse Rapids and Aishihik Lake facilities account for the bulk of the hydroelectric power production in the Yukon at 40 and 30 megawatts of power per year respectively. The largest single factor influencing fluctuations in electrical demand in the Yukon is the mining industry. For example, when the Faro mine is operating, it accounts for 40% of the Whitehorse-Aishihik-Faro system load.

Railroad Network

Two railroads of historical and present day importance extend northward into the Yukon and Northwest territories. The famous “White Pass” narrow gauge railway line, built in 1898, extends from the American seaport of Skagway on the Alaskan panhandle through northwestern British Columbia along the shore of Lake Bennett to its northern terminus at Whitehorse in the Yukon Territory (Fig. 3). This rail line represented one of the great engineering feats at the turn of the century and, in 1994, it was chosen as a Designated Historic Civil Engineering Landmarks by the American Society of Civil Engineers (http://www.asce.org/history/landmark/projects.cfm?menu=loc). It was designed to complement and ultimately to replace the Chilkoot Pass haul route for access to the Klondike goldfields of the Whitehorse region (Minter, 1988). The modern day White Pass and Yukon Railroad operates as a scenic passenger tour.

The other almost equally famous railway is the Canadian National Railway's Great Slave Lake line from Manning, Alberta to Hay River on the southwest shore of Great Slave Lake (Fig. 3). The line previously continued eastward from Hay River to the Cominco-owned Pine Point Lead-Zinc Mine (www.canadianrockhound.ca/2003/01/cr0307103_pinepoint.html; Fig. 6). It was built specifically to transport lead-zinc concentrate from the Pine Point Mine to the Cominco-owned smelter at the community of Trail in southern British Columbia (ra.tapor.ualberta.ca/cocoon/atlas/Chapters-13-1/). After the closure of the Pine Point Mine in 1991, rail service along the branch line between Hay River and Pine Point Mine ended and the tracks were removed. The Great Slave Lake railway continues to provide a significant freight service to and from the community of Hay River.

Highway and Trail Network

As famous and redolent of history as the northern railroads are, the northern road system is now the primary means of commercial and recreational transportation. Perhaps the best known of these roads is the Alaska Highway, built in 1942 between Edmonton, Alberta and Fairbanks, Alaska in response to the perceived need for a wartime road connection between Alaska and the lower 48 states. “Mile 0” now officially located at the town of Dawson Creek in northern British Columbia, and the highway passes through the communities of Watson Lake and Whitehorse in the southwestern Yukon Territory (Fig. 3). Other important highways in Yukon Territory include the Robert Campbell Highway, the Klondike Highway, the “Top of the World” Highway, The Canol Road, and most recently, the Dempster Highway in northern Yukon extending from Dawson northward to Inuvik, NWT (www.bellsalaska.com/ykhwy5.html; Fig. 3).

The Canol Road was built during World War II, like the Alaska Highway, and runs 320 kilometres from Macmillan Pass in easternmost Yukon Territory, to Norman Wells in the Northwest Territories. It was intended to be a service road for the short-lived Canol Oil Pipeline that supplied oil from Norman Wells to equipment along the Alaska Highway, then under construction (www.llbean.com/parksearch/parks/html/1622llt.htm). The Canol Road is now the Canol Heritage Trail. It is primarily a hiking trail, but still provides vehicle access to the important Mactung tungsten deposit at the Yukon-Northwest Territory border.

In the NWT, the modern day counterpart of the Alaska Highway is the Mackenzie Highway. Begun prior to World War II, it runs from Grimshaw, Alberta through Hay River, NWT around southwestern Great Slave Lake and north to the community of Wrigley on the Mackenzie River, a distance of about 1200 km (www.gov.nt.ca/Transportation/travel/index.html; Fig. 3). A branch highway, known as the Great Slave Highway, connects to Yellowknife. Hay River and the Fort Smith and Fort Resolution highways are connected with the Mackenzie Highway at the community of Enterprise via the short stretch of road (Fig. 3). The recently completed (1984) Liard Highway extends from just south of Fort Liard to Checkpoint, where it joins the Mackenzie Highway. Southward, the Liard Highway connects with the Alaska Highway approximately 27 kilometres west of Fort Nelson, British Columbia. The Mackenzie Delta community of Inuvik lies at the northern extension of the Dempster Highway from the Yukon (Fig. 3).

Supplementing the formal all-weather road or highway system is an extensive ice road (i.e. winter road) and trail network. In some cases, ice roads provide the only land surface access to communities, such as Déline on Great Bear Lake and the community of Colville Lake on Colville Lake (Fig. 3). Other ice roads service the communities of Rae Lakes, Wekweti and Aklavik.

The longest ice road is the Yellowknife to Contwoyto Lake Ice Road, a 568 km link that is the only vehicular route into Nunavut from the South (Fig. 3). It is the world's longest heavy haul ice road and services several mines, such as the Ekati Diamond Mine at Lac de Gras and the inactive Lupin Mine at Contwoyto Lake (Fig. 6). It is open from February to March each year for commercial mine traffic only.

Waterborne Transportation Network

In the Northwest Territories, heavy freight such as fuel for household and industrial uses and transportation is transported during summer by barge from the community of Hay River down the Mackenzie River. Because the river channel is shallow, freight is carried on flat-bottom barges pushed (not pulled) by shallow-draft tugboats. Barge trains are uncoupled at Tuktoyaktuk at the end of the Mackenzie's wide delta, the only natural harbour on the western coast of the Arctic Ocean. From Tuktoyaktuk, the barges are moved by ocean-going tugboats to communities in the high Arctic (www.ccge.org/ccge/english/Resources/rivers/tr_rivers_mackenzieRiver.asp).

From 1939 until 1993 before the construction of the Norman Wells Oil Pipeline, oil from the Norman Wells Oil Field was refined locally. During this period, petroleum products from the Norman Wells refinery were barged to local communities along the Mackenzie River. Turner (1975), in an account of life in the Nahanni, Fort Simpson and Fort Nelson regions in the early part of the twentieth century, describes the historical importance of barge, canoe and other boat traffic in these areas.

Airline Transportation Network

Commercial airlines (www.northerncanada.worldweb.com/Transportation/Airlines/index.html) service most communities of the northern mainland. Major carriers, such as Air Canada, First Air, Canadian North and Air North offer large-scale, modern, commercial jet passenger and freight service between larger northern communities, such as Yellowknife, Hay River, Fort Simpson, Norman Wells, Inuvik, Whitehorse, Dawson City and Old Crow, and the cities of southern Canada, such as Edmonton, Calgary and Vancouver. Many smaller carriers, as well as major carriers, provide freight and passenger service between northern communities and provide support for the northern tourist industry.

PHYSIOGRAPHIC AND GEOLOGIC SETTING OF PETROLEUM EXPLORATION REGIONS

Introduction

The vast region of the northern Canadian mainland included in this report is largely underlain by sedimentary rocks in areas west of the Canadian Shield and that are prospective for petroleum exploration (Figs. 2, 7). The Northern Canadian Mainland Sedimentary Basin itself may be defined as this domain of dominantly sedimentary bedrock, which includes the Interior Plains, Mackenzie Arc, Northern Yukon, Beaufort-Mackenzie Basin and Selwyn-Cordillera Exploration Regions. The Northern Canadian Mainland Sedimentary Basin is bordered on its east side almost entirely by the characteristically low relief and low-lying Canadian Shield, which is underlain exclusively by Precambrian metamorphic and igneous rocks that are not considered prospective for petroleum resources. The Northern Canadian Mainland Sedimentary Basin consequently occupies the northern Yukon, parts of southern Yukon underlain by sedimentary rocks, and most of the Northwest Territories (NWT) west of the Canadian Shield. In a broad sense the Northern Canadian Mainland Sedimentary Basin is simply the northern continuation of the Western Canada Sedimentary Basin (Mossop and Shetson, 1994).

The Phanerozoic succession is divisible into two principle terrain types, the undeformed to mildly deformed platform underlying the plains area of the NWT, and the fold-and-thrust belt of the Cordillera in the western part of NWT and most of the Yukon (Fig. 7). The Phanerozoic rocks throughout most of the area are underlain by a thick, highly deformed, Proterozoic sedimentary to metasedimentary succession. In the southern part of the interior plains area, metamorphic and igneous rocks of the Precambrian basement underlie the Phanerozoic succession.

The major petroleum-bearing and petroleum exploration areas in the northern Canadian mainland sedimentary basin are contained, for the most part, within five distinctive physiographic, or exploration, regions, the Interior Plain Region, the Mackenzie Arc Region, the Northern Yukon Region, the Selwyn-Cordillera Region and the Beaufort-Mackenzie Basin (Fig. 7).

The distribution and relative abundance of petroleum exploration wells (Fig. 7), and of exploration seismic data (Fig. 8) indicate historical exploration interest by the petroleum industry within the northern mainland. It is immediately apparent that petroleum industry activity was focused almost exclusively within the Beaufort-Mackenzie Region, the Interior Plains Region, within the Liard Plateau and Mackenzie Plain areas of the Mackenzie Arc Region and within the Eagle Plain Area of the Northern Yukon Region.

The Canadian Shield west of 110° longitude is formed almost entirely by two divisions of the Kazan Physiographic Region, the Kazan Upland north of Great Slave Lake and the Bear-Slave Upland south of great slave Lake (Bostock, H.S., 1970; Stott and Klassen, 1993). These areas are physiographically similar with maximum elevations of about 500 metres and rolling to hilly, lake spattered, terrain with relief of about 100 metres, with some parts of up to about 300 metres relief exhibited by some monadnocks (i.e., erosional remnants) in the Bear-Slave Upland. The Coronation Hills physiographic division north of the Bear-Slave Upland, an area of broad hills ranging in elevation from 250 metres to 600 metres, forms the northwestern edge of the Canadian Shield where it borders the Arctic Ocean at Coronation Gulf.

Canadian Shield

The Canadian Shield is composed of Precambrian crystalline igneous and metamorphic rocks that together form the ancestral core of the North American continent. These rocks are the storehouse of most of Canada's mineral wealth in the form of base and precious metals, ferro-alloy metals, nuclear metals and of industrial and precious minerals (Lang et al., 1970). Recently, to the known mineral wealth was significantly augmented by a major find in the Slave Province several hundred kilometres northeast of Yellowknife. Numerous diamondiferous kimberlites were discovered the Lac de Gras area (Fig. 9). Two diamond mines are now in full production, the Ekati Mine at Lac de Gras and the nearby Diavik Mine. Other diamond-bearing kimberlite deposits, such as the Snap Lake Deposit, are anticipated to go into production within the next several years (www.iti.gov.nt.ca/diamond/timeline.htm).

Hydrocarbon-based energy resources have not been found in the Canadian Shield. Fluid hydrocarbons, or petroleum, reside within microscopic to macroscopic pore spaces of subsurface rock strata are remarkably non-porous and nearly impermeable. The low porosity of Precambrian strata prevents the accumulation of economic concentrations of petroleum, and their low permeability prevents subsurface migration of petroleum fluids from potential Precambrian hydrocarbon source rocks to petroleum reservoirs.

Another, equally significant reason for the absence of petroleum resources in the Canadian Shield is the general absence of hydrocarbon sources in Precambrian strata. The geothermal heating of residual organic material, or “Kerogen” in sediments and sedimentary rocks is generally acknowledged to be the primary process causing the development of petroliferous hydrocarbons, or petroleum (Tissot and Welte, 1984). Although it is recognized that life had its origins in pre-Proterozoic Archean time (Bengston, 1994), life forms were not generally abundant until Phanerozoic time (Bamber et al., 1970).

Significant hydrocarbons, however, may have been generated during organic maturation of some organic-rich Neoproterozoic (Late Proterozoic) strata. The strong tendency for upward movement of fluid hydrocarbons by buoyancy in water-saturated rocks of the subsurface would favour upward migration of hydrocarbons from Neoproterozoic source rocks into more porous, overlying Phanerozoic strata. There may be situations where older Precambrian strata may have undergone geologically later secondary porosity development by brecciation, or by means of subsurface dissolution. Such porous Precambrian strata could then serve as reservoirs for later-formed petroleum.

Exploration Areas in the Beaufort-Mackenzie Region

The Beaufort-Mackenzie Region, unlike other exploration regions contains only a single exploration area, the Beaufort-Mackenzie Basin (Figs. 2, 7). This basin contains the clastic sedimentary succession laid down in the region of the present Mackenzie Delta from mid-Mesozoic time to the modern day. It is confined to the onshore Mackenzie Delta, the Tuktoyaktuk Peninsula and to the adjacent offshore strata that extend into the Beaufort Sea to the edge of the continental shelf at about 200 metres water depth (Figs. 2, 7). A multitude of lakes and channels dissect the modern delta plain, and the older landward part of the delta is punctuated by scores of ice-cored pingos (Stott and Klassen, 1993).

Exploration Areas in the Interior Plains Region

The Interior Plains Region spans the low, topographically subdued plains lying between the Canadian Shield and the mountains of Canadian Cordillera (Fig. 2). The eastern margin of the Canadian Cordillera coincides with the eastern limit of the Mackenzie Arc Region, and the northern margin is bounded bythe Northern Yukon Region. The Interior Plains Region comprises a relatively undeformed westward-thickening prism of Phanerozoic- sedimentary strata. This succession unconformably overlies a thick succession of variably folded and faulted Proterozoic strata (e.g. Cook and MacLean, 2004).

A large grouping of geographically extensive exploration areas, including the Great Slave Plain, Great Bear Plain, Colville Hills, Horton Plain, Anderson Plain, Peel Plain and Peel Plateau comprise the low elevation broad flatlands of the Interior Plains (Figs. 2, 7; Stott and Klassen, 1993). The main communities in this region are Fort Simpson at the confluence of the Liard and Mackenzie Rivers, Hay River at the mouth of the Hay River, and Fort Liard on the Liard River, all in the Great Slave Plain exploration area. Déline on Great Bear Lake is the largest community in the Great Bear Plain area. The communities of Fort Good Hope and Tsiigehtchic (formerly Arctic Red) are located on the Mackenzie River along the junction of the Anderson and Peel plains.

Great Slave Plain has little relief, generally below 325 metres in elevation. However, it includes a portion of the slightly more elevated Alberta Plateau physiographic region of Bostock (1970) in the vicinity of Trout Lake and south of Tathlina Lake (Fig. 2). The dense northern boreal forest contains many poorly drained areas of swamp and muskeg. Horn Plateau forms another area of high ground in the centre of Great Slave Plain (Fig. 2). The south-facing escarpment of the Cartridge Mountains marks the boundary between Great Slave Plain and Great Bear Plain.

Great Bear Plain is characterized by gently rolling, glacial drift-covered topography, generally below 300 metres elevation, with some small plateaux and hills, such as the Scented Grass and Grizzly Bear mountain rising to 500 metres (Fig. 2). The northern boreal forest south of Great Bear Lake is characterized by short trees and, north of Great Bear Lake, grades to mainly treeless, hummocky moraine.

The Franklin Mountains form the western limit of Great Bear Plain. The northern and southern limits are controlled by upwarped underlying Paleozoic strata. The Colville Hills area north of the Great Bear Plain is dominated by several large linear asymmetrical ridges and hills consisting of structurally deformed and uplifted Paleozoic strata. In the Colville Hills, lakes and drainages occupy the low areas between ridges and hills up to 725 metres in elevation.

Further north and west of the Mackenzie River the low relief and low elevation Peel Plain extends west to Peel Plateau (Fig. 2). Southwestern Peel Plain averages only 125 metres in elevation, rising to 450 metres elevation in the Grandview Hills in the northeast. Glacial drift covers most of this area, along with numerous northwest-trending lakes, bogs and swamps.

Peel Plateau is an upland surface up to 975 metres in elevation, bounded on the west by the Richardson Mountains, on the southwest by the Mackenzie Mountains, and on the northeast by the Mackenzie River and Anderson Plain (Fig. 2). The Plateau is underlain primarily by an exhumed and eroded surface of resistant Upper Cretaceous sandstone that dips moderately northeastward towards Peel Plain, and is extensively covered by hummocky moraine and glacial outwash. The deeply entrenched Peel and Arctic Red rivers traverse parts of both Peel Plateau and Peel Plain.

Anderson Plain is a broad gently undulating plain generally below 300 metres in elevation, and mantled by glacial drift. Stunted trees of the northern boreal forest give way northward and northeastward to treeless tundra. East of Anderson Plain, the treeless tundra of Horton Plain ranges in elevation up to 600 metres. Bedrock of Paleozoic and Mesozoic age are exposed across both Anderson Plain and Horton plains. Neoproterozoic strata are also exposed across parts of Horton Plain. Both the Anderson and Horton rivers traverse Anderson Plain and drain towards the Arctic Ocean but only Horton River traverses Horton Plain.

Exploration Areas in the Mackenzie Arc Region

Mackenzie Arc Region containing the Liard Plateau, the Mackenzie Mountains, the Franklin Mountains and the Mackenzie Plain forms a large indentation into the south-central Interior Plains (Figs. 2, 7). Mackenzie Arc coincides with part of the Mackenzie Fold Belt of Gabrielse (1992), and its eastern boundary coincides with the eastern limit of the mountain front of the northern Canadian Cordillera. The regional orientation of the Mackenzie Arc and its constituent mountain ranges changes from north trending in the south and central parts of the Arc to nearly west trending in the north part of the Arc. Mackenzie Fold Belt (Gabrielse, 1992) includes the Ogilvie-Wernecke Mountains exploration area farther west that is not included in the Mackenzie Arc as defined here (*see* section entitled “Exploration Areas in the Northern Yukon Region”).

The Mackenzie Arc Region belongs to the broadly defined Foreland Belt, which includes all the mountain ranges and foothills of the eastern Canadian Cordillera (Gabrielse et al., 1992). It is composed primarily of folded Proterozoic and Phanerozoic sedimentary successions separated by thrust faults.

South of the Mackenzie Mountains, the Liard Plateau comprises an upland area of treed and tundra hills 1000 to 1500 metres in elevation, underlain by broadly folded Paleozoic and Mesozoic strata. The broad hills and small plateaux, such as Tlogotsho Plateau, are separated by narrow, incised valleys. On the east, the Liard Plateau is bordered by the Great Slave Plain lowlands. North of the South Nahanni River, Liard Plateau rises to the Mackenzie Mountains, with elevations up to 2800 metres in the central Backbone Ranges. Both Liard Plateau and the Mackenzie Mountains lie in the rain shadow of the Selwyn Mountains to the west and, consequently, have a dry climate and low altitude timberline.

Mackenzie Mountains expose faulted and folded carbonate and siliciclastic bedrock of Proterozoic, Paleozoic and Mesozoic age that typically forms bare, felsenmeer-covered, lichen-carpeted slopes with relatively few large cliffs.

Mackenzie Plain and Franklin Mountains are an extension of Mackenzie Arc between the Interior Plains and Mackenzie Mountains (Figs. 2, 7). Mackenzie Plain, which separates the Mackenzie and

Franklin Mountains, forms a broad, rolling, tree-covered and glacial drift mantled plain along which the Mackenzie River is incised. A westward-thickening wedge of Cretaceous-Tertiary strata underlies the plain and, in turn, overlies lower Paleozoic strata folded into a broad asymmetric syncline. The gently west-dipping eastern limb of the syncline crop outs to the east, forming the lower Paleozoic strata of the Franklin Mountains. The Franklin Mountains themselves are a series of curvilinear bedrock ridges that range up to 1600 metres in height. The western limb of the regional syncline beneath Mackenzie Plain dips steeply eastward and is abruptly upturned to form the eastern margin of the Mackenzie Mountains.

The towns of Norman Wells, Tulita, and Wrigley are located along the east side of Mackenzie River in the Mackenzie Plain.

Exploration Areas in the Northern Yukon Region

The Northern Yukon Region is an extension of the Foreland Belt of the eastern Canadian Cordillera (Gabrielse et al., 1992). Its complex geological history is reflected in the diverse array of exploration areas that it encompasses. Lowland areas separate discordantly oriented mountain belts, in contrast to the subparallel trends of the Mackenzie Arc region. Lowland areas of the Northern Yukon Region include Eagle Plain, Bonnet Plume Basin, Kandik Basin, Old Crow Basin and Blow Trough. These separate the mountainous areas of the Ogilvie-Wernecke Mountains, Richardson Mountains, Northern Ogilvie Mountains, Keele Range and the British Barn Mountains.

The Ogilvie-Wernecke Mountains have previously been regarded as part of the Mackenzie Fold Belt (Gabrielse, 1992) based on the continuity of some Laramide structural trends. However, the Ogilvie-Wernecke Mountains and the Mackenzie Mountains are separated by major cross faults, such as the Snake River Fault, and show profound differences in their Proterozoic and Phanerozoic geology. Conversely, all areas of the Northern Yukon Region including the Ogilvie-Wernecke Mountains show comparable Proterozoic and Phanerozoic geology (Norris, 1997; Morrow, 1999), indicating that the Ogilvie-Wernecke Mountains are most logically grouped with the Northern Yukon Region.

The Ogilvie-Wernecke Mountains in north-central Yukon trend westerly for about 400 kilometres from the Mackenzie Mountains to the Tintina Trench, near the Alaskan border. Maximum elevations generally are less than 1500 metres, but range up to 2100 metres in the rugged and glaciated Wernecke Mountains immediately west of Mackenzie Mountains. The Ogilvie-Wernecke Mountains are underlain mainly by Proterozoic and Paleozoic carbonate and clastic sedimentary rocks.

Eagle Plain is a lowland in the centre of the Northern Yukon Region. Gently rolling hills locally attain 800 metres in elevation. Sparsely lowland forest is replaced by open tundra at high elevations or more northern latitudes. The Mesozoic clastic strata that underlie Eagle Plain are surrounded by uplifted Paleozoic and Proterozoic strata in the surrounding Ogilvie-Wernecke, Northern Ogilvie and Richardson Mountains (Figs. 2, 7).

The Northern Ogilvie Mountains lie along the Alaska-Yukon border north of the Ogilvie-Wernecke Mountains and west of Eagle Plain, and they surround the Canadian part of the Kandik basin (Figs. 2, 7). The Northern Ogilvie Mountains are a northward continuation of the western Ogilvie-Wernecke Mountains. The juncture occurs where the dominantly west-trending Ogilvie-Wernecke Mountains turn abruptly northward. Mountain peaks in the Northern Ogilvies range from 1500 to 2100 metres in elevation and are largely unglaciated. Paleozoic and Mesozoic carbonates and clastic sedimentary rocks are the dominant bedrock and mountain slopes are weakly forested or exposed bedrock.

Kandik Basin is a structural depression comprising rolling terrain at about 1000 metres in elevation. Kandik Basin is underlain by complexly thrust-faulted and folded, Paleozoic and Mesozoic strata (Norris, 1997).

Richardson Mountains, on the east side of Eagle Plain, trend northward from Bonnet Plume Basin for about 350 kilometres to the Beaufort-Mackenzie Basin (Figs. 2, 7). The Dempster Highway (Figs. 2, 3) passes through the centre of Richardson Mountains. Elevations vary greatly with peaks up to 1800 metres and valley bottoms below 500 metres. South of the Dempster Highway, mountain ranges in the Richardson Mountains are lower, narrower and exhibit smooth, more rounded aspect and the highway itself passes through the narrow central part of the Richardson Mountains. This southern part is formed of a single large eroded anticlinorium of Paleozoic carbonates and shales. The part north of Dempster Highway is composed of dominantly clastic, tightly faulted and folded, Proterozoic, Paleozoic and Mesozoic strata.

Keele Range, extending from the Alaska border east to the Richardson Mountains, separates Eagle Plain from Old Crow Basin (Figs. 2, 7). It is characterized by large rounded hills, up to 1000 metres in elevation, and commonly crowned with castellated outcrops of granitic rock. The range comprises uplifted, folded and faulted Precambrian and Paleozoic sedimentary, volcanic and intrusive rocks.

Old Crow Basin, a strikingly flat area of about 75,000 km^2 in area, lies north of the Keele Range and south of the British-Barn Mountains (Figs. 2, 7). This structural and physiographic depression is sometimes referred to as the Old Crow-Babbage Depression (Norris, 1997). It is a sparsely forested, flat lowland with extensive muskeg and numerous shallow lakes. Seismic interpretation indicates the existence of a Tertiary depocentre beneath Old Crow Basin and other more minor basins south of Old Crow Plain. The town of Old Crow is the only population centre, but has no road access to the Dempster Highway.

The British-Barn Mountains in the northwest corner of the Yukon Territory border the Beaufort Mackenzie Basin and Blow Trough (Figs. 2, 7) rising abruptly from the Yukon Coastal Plain and then steadily losing elevation toward the south. Typically, v-shaped valleys separate branching ridges. However, many streams have cut across ridges, for example the Firth River extends across the entire range. Near the Alaska Border, some unglaciated, rugged areas attain elevations of up to 1800 metres. The British-Barn Mountains are charactized by block faults of Tertiary age that uplifted highly deformed Paleozoic cherts and argillites with subordinate quartzite and limestone.

Blow Trough, near the north coast of the Yukon, lies between the British-Barn and Richardson Mountains, and the Beaufort-Mackenzie Basin (Figs. 2, 7). It is about 65 kilometres long, with its south end at the headwaters of the Blow River, and broadens northward towards the Arctic or Yukon Coastal Plain. Blow Trough is a structurally controlled depression filled with mid-Cretaceous turbidite sandstones and conglomerates up to 300 metres thick. On the flanks of the trough, this flyschoid succession thins dramatically where it unconformably overlies Paleozoic Ellesmerian units. It is overlain by 1200 metres of Upper Cretaceous and Tertiary clastic sedimentary rocks.

Bonnet Plume Basin, another strikingly flat area covering about 1800 km^2, is a relatively small but pronounced physiographic and structural depression partly enclosed by the Richardson Mountains and bounded on the south by the Ogilvie-Wernecke Mountains (Figs. 2, 7). The Peel River marks the northern margin, and the Knorr Range along Bonnet Plume River forms its eastern boundary. The basin developed during differential tectonic subsidence across fault blocks of the Richardson fault array in early Late Cretaceous time. Local reversals of fault displacements from Late Cretaceous to Tertiary time subsequently caused deposition of 1500 metres of coarse clastic sediments.

Exploration Areas in the Selwyn-Cordillera Region

This region is a composite of several diverse physiographic and tectonic elements that lie west of the Mackenzie Arc Region and south of Northern Yukon Region (Figs. 2, 7). Tintina Trench, which lies along the western boundary of the Yukon Plateau-Selwyn Mountains exploration area, is the topographic expression of a prominent fault of crustal dimensions, the Tintina Fault. This fault system is extremely significant in that it generally separates what are known as “in place” sedimentary rocks of ancestral western North America from the geologically transported, accreted and variably displaced “allochthonous terranes” farther west (Gabrielse et al., 1992; Gabrielse, 1992). Bedrock in the Pelly and Cassiar

Mountains and part of the Yukon Plateau immediately west of Tintina Trench (Fig. 7) is part of the Omineca Belt of regionally uplifted, pericratonic, metamorphic and granitic rocks, which separate ancestral North America from the accreted terranes of the Intermontane Belt (Gabrielse et al., 1992).

The morphogeological Intermontane Belt west of the Omineca Belt includes the Yukon Plateau and Whitehorse Trough ((Gabrielse et al., 1992; Fig. 7). The Coast and Insular morphogeological belts of the Canadian Cordillera, including the western part of the Yukon Plateau and the St. Elias Mountains, lie west of the Whitehorse Trough Exploration Area (Figs. 2, 7) and the Omineca Belt. The Selwyn-Cordillera Exploration Region is composed primarily of three exploration areas, the Yukon Plateau-Selwyn Mountains, the Tintina Trench and the Whitehorse Trough areas (Fig. 7).

The Yukon Plateau-Selwyn Mountains Exploration Area lies east of Tintina Trench, south of the Northern Yukon Region and West of the Mackenzie Arc Region. This area coincides approximately with the Selwyn Fold Belt, which geologically is dominated by broadly to isoclinally folded and faulted strata of mainly Proterozoic and Paleozoicage. Fine-grained, dark coloured, basinal strata are dominant and large Cretaceous granitic batholiths are common within the southern part of this area (Gabrielse, 1992). The northern part of this area is formed of a broad treed plateau with subdued topography at an average elevation of about 1300 metres. The Selwyn Mountains in the southern part of this area were strongly glaciated by the Cordilleran ice-sheet, which carved the underlying bedrock into rugged mountains of up to about 3000 metres elevation.

Tintina Trench, bordering the west side of the Yukon Plateau-Selwyn Mountains Area, is a narrow, straight, steep-sided valley ranging from one kilometre to 25 kilometres in width. It is the northern continuation of the Rocky Mountain Trench of the southern Canadian Cordillera. The Yukon, Stewart, Pelly, Hoole, Black and Liard rivers all flow along the Trench for part of their length. Relief between the valley floor and walls is as much as 600 metres. Coal-bearing Tertiary siliciclastic rocks underlie the valley floor. As described previously, Tintina Trench has developed along the trend of the major transcurrent, or strike-slip, Tintina Fault (Gabrielse, 1992).

Whitehorse Trough, located in the Intermontane Belt west of the Pelly and Cassiar Mountains, is characterized by moderately rugged topography with elevations ranging from 700 to 1400 metres. The forested valley bottoms, containing numerous lakes and muskeg, are mantled by Quaternary glacial and recent alluvial deposits. Folded and faulted Mesozoic and Tertiary siliciclastic and carbonate sedimentary rocks form bedrock, and coal deposits are common. Variably metamorphosed sedimentary and igneous rocks that are not prospective for petroleum exploration surround Whitehorse Trough.

PETROLEUM RESOURCES OF EXPLORATION REGIONS

Introduction

The petroleum potential of each exploration area within the five petroleum exploration regions (Fig. 7) is discussed here in some detail. Within the northern mainland sedimentary basin, the most significant discoveries are in the oil and gas fields in the Beaufort-Mackenzie Basin, the large gas fields in the Liard Plateau, the oil field at Norman Wells and recently discovered oil and gas southwest of Tulita in the Mackenzie Plain. Lesser discoveries have been identified in the Colville Hills of the Interior Platform and in Eagle Plain within the Northern Yukon Region.

Beautiful-Mackenzie Basin Region

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

Introduction

The Beaufort-Mackenzie Basin (Figs. 2, 7) underlies Tuktoyaktuk Peninsula, Mackenzie Delta, outer Yukon Coastal Plain and the adjacent offshore area. In the offshore it extends from Amundsen Gulf westward to the US border, with deposits extending into the deepwater of Canada Basin. The 1967 discovery and subsequent development of the Prudhoe Bay Field on the north coast of Alaska was followed by many petroleum discoveries in the Mackenzie Delta and Beaufort Sea during the decade of 1970 to 1980. This was a period of generous Canadian federal government incentives for frontier exploration.

Geological Setting

In a strict sense the Beaufort-Mackenzie Basin refers to only latest Cretaceous to Recent sedimentary rocks (Dixon et al., 1992), but is commonly used to include all sedimentary strata underlying the relevant geographic area (Figs. 2, 7). These strata range from Proterozoic to Recent age (Fig. 10)

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

The lower Paleozoic succession is poorly known due to a lack of well penetrations and few outcrops. Based on regional comparisons and the limited available data, Paleozoic rocks are a continuation of those seen on the Interior Platform, with the exception of the Cambrian succession, which does not extend into the Beaufort-Mackenzie area. A thick carbonate succession of latest Cambrian to Middle Devonian age is present, grading laterally westward, and probably northwestward, into shale of the Road River Group (Fig. 10). These are overlain by a dominantly clastic, late Middle Devonian to Late Devonian succession of the Canol and Imperial formations. Carboniferous and Permian carbonate and siliciclastic beds are preserved only under the southwest part of Mackenzie Delta and extend into outcrops of the northern Cordillera (Richards et al., 1997; Dixon et al., 1994; Dixon, 1998). Triassic sandstone, siltstone and carbonates are absent under the Mackenzie Delta and are relatively thin in the adjacent mountain areas (Dixon, 1998). Jurassic to Recent strata are dominantly shale and sandstone successions formed by a series of deltaic and shoreline deposits with deep-water sediment gravity-flow beds periodically prevalent (Dixon, 1982, 1986).

The Phanerozoic succession is punctuated by a number of major unconformities (Fig. 10) that mark the end of major tectonic phases. These include:

1. Base of Paleozoic succession (Lower or Middle Cambrian),
2. Latest Devonian,
3. Earliest Jurassic (Hettangian-Sinemurian),
4. Early Cretaceous (Late Hauterivian),

5. Mid-Cretaceous (Late Albian),
6. Late Cretaceous (Late Maastrichtian),
7. Early Tertiary (Late Eocene) and,
8. Late Tertiary (Late Miocene).

Other widespread unconformities of lesser tectonic significance are also present.

There are four broad structural domains in the Beaufort-Mackenzie area (Lane and Dietrich, 1996). Under Tuktoyaktuk Peninsula down-to-basement extensional faults are the prevalent structures (Fig. 11, Eskimo Lakes Fault Zone; Lane and Dietrich, 1995). Offshore from the northern Tuktoyaktuk Peninsula, Tertiary strata are undeformed to mildly deformed. Under Mackenzie Delta and the adjacent offshore the structural style is dominated by listric faults and associated folds (Fig. 11, Tarsiut-Amauligak Fault Zone; Lane and Dietrich, 1995). Under the western Beaufort Sea thrust faulted anticlines are the prevalent structural features, forming an arcuate foldbelt that extends from the US to the western margin of Mackenzie Delta (Lane and Dietrich, 1995). In the latter area the folds are cut by listric faults.

Exploration History

The first well drilled in the area was the Atkinson H-25 well in 1969, which recovered oil, prompting an initial phase of exploration that resulted in a number of significant discoveries in Cretaceous and Tertiary sandstone reservoirs, such as Parsons Lake and Taglu (Table 1). In the late 1970s, exploration shifted to the offshore areas where a number of oil and gas wells were drilled (e.g., Kopanoar, Amauligak, Tarsiut; Table 1). Exploration activity slowed during the late 1980s and virtually ceased in the 1990s. However, the increased demand for gas and increased prices in the North American market made the frontier areas look attractive and a new round of exploration began in 2001.

About 260 wells have been drilled in the area and several hundred thousand line kilometers of seismic data have been recorded, much of it now publicly available (Figs. 7, 9).

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

Source Rocks

In early studies of the geochemical characterization of source rocks and oils, three principle sources were identified; the Middle Jurassic to Lower Cretaceous Husky Formation, the Upper Cretaceous Boundary Creek and Smoking Hills formations and the Eocene Richards Sequence (Fig. 10; Langhus, 1980; Creaney, 1980; Snowdon and Powell, 1979; Brooks, 1986a, b). The two Upper Cretaceous source rocks have organic carbon contents of up to 12% by weight, whereas the Richards Sequence, primarily only the basal few tens of metres of shale, has only 1.2 to 1.5% by weight of organic carbon. While the Upper Cretaceous source rocks contain oil-prone marine kerogen, the Eocene strata contain predominantly terrigenous, gas-prone kerogen. To explain the abundance of oil as well as gas in Tertiary reservoirs the presence of resinite in the Eocene shale was hypothesized to be the material from which oil was generated (Snowdon, 1980).

Subsequent work in Tertiary strata has revealed that the geochemical biomarker signature that first identified the Richards Sequence as a source rock is present in the organic matter of other Tertiary coaly and shale successions (Snowdon, pers. comm., 2002). This increases the number of potential source intervals to include some of the more organic rich, coaly units in deltaic beds, such as the Fish River, Aklak, Taglu and Kugmallit sequences. While the Tertiary succession is gas-prone, the abundance of resinite is still a valid hypothesis for the common occurrence of liquid hydrocarbons.

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

Reservoir Rocks

Reservoirs are present in the following units (see Fig. 10):

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

Other potential reservoir units could include:

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

Maturation and Generation

In general, Lower Paleozoic rocks tend to be highly mature to overmature (dry gas), Carboniferous to Albian strata mature to immature, and Upper Cretaceous to Tertiary strata range from mature to immature. The level of organic maturation in these strata is a function of the maximum subsurface paleotemperatures experienced by these strata, which generally reflects their maximum burial depths. In general the Tertiary succession has a low maturity with respect to oil generation (0.25 to 0.65 %Ro), commonly even at depths of up to 4500 m (in places as low as - 0.4 to 0.65 %Ro), although Issler and Snowdon (1990) suggest that thermal maturation gradients should increase dramatically about one kilometre deeper.

Migration and Accumulation

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

Exploration Plays

Known Play Types

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

Potential and/or Untested Play Types

1. Turbidite sandstones in the Devonian Imperial Formation,
2. Pinch out against unconformities in Jurassic through Tertiary strata,
3. Anticlines associated with thrust faults in the western Beaufort, and
4. Gas hydrate occurrences.

Reserve Estimates

Estimates of reserves in the discoveries, as published by Morrell (1995) are:

- Gas - 360.2 x 10^9m^3(12.72 Tcf),
- Oil - 223.2 x 10^6m^3(1460.5 MMbl),
- Condensate - 17.5 x 10^6m^3

The NEB (1998) numbers for recoverable hydrocarbons (at the 90% confidence level; Figs. 4, 5) are:

- Gas - between 186 x 10^9m^3 and 349 x 10^9m^3(6.568 Tcf to 1.235 Tcf) and,
- Oil - between 93 x 10^6m^3 and 229 x 10^6m^3(585 MMbl to 1440.4 MMbl).

NEB (1998) gave a best estimate of the total discovered resource in the basin of 161 x 10^6m^3 (1.01 billion barrels) of recoverable oil and 255 x 10^9m^3 (9.00 Tcf) of marketable gas.

Hydrocarbon Potential

The potential for additional resources is high and the area is likely to be a major source of gas in the near future. In 1994 the Geological Survey of Canada published estimates of potential resources (Dixon et al., 1994) and gave the following median values:

- Gas - 1.49 x $10^{12}m^3$ (53.3 Tcf), and
- Oil - 862.4 x 10^6m^3 (5.39 billion barrels).

See also NEB (1998). The gas hydrate resource in the Beaufort-Mackenzie area is highly speculative, with values ranging from 2.4x10^{12} to 87x10^{12} m^3 of raw natural gas (Majorowicz and Osadetz, 2001).

Interior Plains Region

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

Introduction

The Interior Plains Region, including the Great Slave Plain, Great Bear Plain, Colville Hills, Anderson Plain, Peel Plain and Plateau exploration areas, is a low relief lowland that lies between the granitic Canadian Shield to the east and the mountainous Canadian Cordillera to the west. Petroleum exploration began here after the Second World War and led to the initial discovery of natural gas at the Rabbit Lake Field in the Great Slave Plain southwest of Great Slave Lake in 1955.

Geological Setting

Cambrian to Upper Devonian strata underlie most the Interior Plains, with a thin veneer of Albian rocks throughout much of the area, and locally preserved Upper Cretaceous and Lower Tertiary rocks (Figs. 12, 13). The Phanerozoic strata are underlain by a very thick succession of deformed Proterozoic sedimentary and low-grade metasedimentary rocks (Cook and MacLean, 2004). South of Bulmer Lake, in southern Great Bear Plain and northern Great Slave Plain, igneous and metamorphic rocks of the Precambrian Basement underlie Phanerozoic strata.

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

The Cambrian succession generally is characterized by a basal transgressive sandstone (Mount Clark Formation, the “Old Fort Island” Formation of Dixon and Stasiuk, 1998) gradationally overlain by interbedded shale, sandstone and thin carbonates of the Mount Cap Formation. These, in turn, are unconformably overlain by the Saline River Formation, a succession of interbedded shale, carbonate and evaporites (anhydrite and halite). The Cambrian sandstones appear not to extend across Peel Plain and are absent under most of Great Slave Plain (Dixon and Stasiuk, 1998). Gradationally succeeding the Saline River Formation is a thick succession of platform carbonates, dominated by dolostone, that range from Upper Cambrian to Middle Devonian in age, and which contain a number of regionally extensive unconformities. In the western Peel Plain and Plateau, these carbonates pass laterally westward into basinal shales of the Road River Group in the Richardson Mountains. Most of the carbonates are dolostone (Franklin Mountain, Mount Kindle, Peel, Tsetso, Arnica and Keg River formations; Pugh, 1983, 1993; Meijer-Drees, 1975, 1993; Morrow 1999) with some anhydrite (Mirage Point, Camsell, Fort Norman, Bear Rock and Chinchaga formations; Meijer-Drees, 1975, 1993; Morrow, 1991, 1999). Parts of the Middle Devonian succession contain shale and limestone deposits (Horn River Group; Hare Indian, Landry, Hume, Ramparts, Slave Point, Sulphur Point and Watt Mountain formations, and the Kee Scarp reef; Pugh, 1983, 1993; Meijer-Drees, 1975, 1993). Carbonate deposition ended in the late Middle Devonian with the widespread deposition of the Canol shale, followed by deposition of syntectonic clastic rocks of the Imperial and Tuttle formations (Pugh, 1983, 1993).

Carboniferous to earliest Cretaceous strata are absent across most of the Interior Plains. Some Carboniferous to Triassic-aged strata are preserved in the southwest part of Great Slave Plain (Fig. 12) possibly preserved in the westernmost parts of Peel Plateau (Fig.13). A thin Jurassic succession is preserved, probably in buried grabens within Anderson Plain (Fig. 13; Dixon, 1999). Albian strata rest unconformably on Paleozoic rocks throughout most of the Interior Plains (Dixon, 1997, 1999). The Albian is a shale-dominant succession (Arctic Red Formation) containing a thin but laterally extensive, upper Aptian basal sandstone (Martin House Formation, Dixon, 1999). Late Cretaceous strata are preserved in Anderson Plain (Mason River Formation-shale) and across the Peel Plateau (Trevor Formation - interbedded sandstone and shale; and Boundary Creek Formation - organic-rich shale; Dixon, 1999).

Proterozoic strata are folded and thrust faulted, but the overlying Phanerozoic is generally only mildly deformed into very broad, open synclines and anticlines, with the overall succession dipping and thickening to the west and southwest (Fig. 14). Some minor normal faults are present throughout the area. In the Colville Hills, Phanerozoic rocks are more intensely deformed. Here, Early Tertiary deformation has created a number of tight, thrust faulted anticlines (Cook and Aitken, 1971 and 1973), which are underlain by large Proterozoic structures (MacLean and Cook, 1992). Others have interpreted the Colville Hills structures as strike-slip features (Davies and Willott, 1978). The same deformation extends into Peel Plateau, where thrust faulted anticlines extend into Albian and Upper Cretaceous strata.

Exploration History

Approximately 400 exploratory wells have been drilled on the Interior Plains (Fig. 7), with most of the drilling concentrated in the Great Slave Plain and lower density of drilling in Colville Hills, Peel Plain and Plateau and the Anderson and Horton plains. The most significant discoveries in the northern part of the Interior Plains have been in the Colville Hills area (Table 2), where gas and some condensate have been recovered from Cambrian strata in four wells (Tedji lake K-24, Tweed Lake M-47, and Bele O-35, completed in 1974, 1985 and 1986, respectively). There was also a significant gas show in Nogha O-47, drilled in 1986.

In the Great Slave Plain area (Table 2), several important discoveries have been made. The gas discovery in 1968 within porous limestone and dolostone of the Middle Devonian Sulphur Point Formation (Fig. 12) at the HB Cameron A-05 well led to the development of the mixed oil and gas field at Cameron Hills (Fig. 5; Table 1), which commenced production in 2002 from nine wells (Gal and Jones, 2003). This production comes from several intervals within the Middle Devonian Keg River, Sulphur Point and Slave Point formations. A large gas discovery was also made in 1961 in reefal, shelf-edge limestone of the Slave Point Formation at the Sun Netla C-07 (F-07) well in southwestern Great Slave Plain. In the Cretaceous strata, a significant gas discovery was made in 1989 at the Arrowhead B-41 well, also in southwestern Great Slave Plain.

Minor gas shows have been reported from many wells in Peel Plain and Peel Plateau, the most significant being at the Tree River H-38 well (Table 2). Also, gas shows in southern Great Slave Plain and several smaller gas fields (Celibeta H-78, Grumbler G-63, Tathlina N-18 and the Rabbit Lake field) were discovered in the period between 1960 and 1980 in the Devonian Keg River to Slave Point interval (Gal and Jones, 2003; Table 2).

Seismic coverage is extensive in Great Slave Plain; limited in parts of Great Bear, Anderson and Horton plain; moderate in western Peel Plain and the Peel Plateau; and more extensive in Colville Hills and eastern Peel Plain (available through the NEB in Calgary). In general the density of publicly available coverage is low throughout the entire area (Fig. 8).

Source Rocks

There are at least seven known potential source rocks (Figs. 12, 13):

1. Scattered, thin beds of algal-rich shale in the Cambrian Mount Clark-Mount Cap succession (Wielens et al., 1990; Dixon and Stasiuk, 1998),
2. Middle Devonian Bluefish Member of the Hare Indian and Horn River formations, and the Late Devonian Muskwa Formation (Feinstein et al., 1988),
3. The Middle to, possibly, Late Devonian Canol shale (Feinstein et al., 1988, 1991),
4. The basal part of the Late Cretaceous shale (Slater River Formation equivalent in Great Bear Plain; Fig. 13),
5. The Triassic Toad and Grayling formations,
6. The Early Cretaceous Garbutt Formation (Leckie et al., 1991), and
7. The Late Cretaceous Smoking Hills formation (Snowdon, 1990).

Other potential source rocks may be present in the Albian shales (Snowdon, 1990), but there are insufficient data to determine the significance of these. Only the Cambrian Canol and Bluefish source rocks are known to have been correlated to pooled hydrocarbons. The limited distribution and thickness of Cambrian source rocks probably limits the amount of hydrocarbons generated. Typically they occur as laminae to beds of a few centimetres in thickness at several stratigraphic horizons within the upper Mount Clark and lower Mount Cap formations. Middle Devonian Canol strata are more extensive and form a cohesive stratigraphic interval a few metres to about 122 metres thick. In the Norman Wells area in the Mackenzie Plain farther west, the Canol shale has contributed to the major reserves at the oil field. It subcrops under western Anderson Plain and eastern Peel Plain and dips gently westward to southwestward under Peel Plain and Peel Plateau. The Triassic Toad-Grayling and the Early Cretaceous Garbutt formations have some source rock potential and are both proximal to oil shows in the Chinkeh Formation in British Columbia near the border with the Northwest Territories. Slater River shale and equivalent strata are present in parts of Mackenzie Plain and Peel Plateau farther west. Smoking Hills strata are present only under a small area of Anderson Plain where they are 20 to 50 m thick. Both Late Cretaceous units are generally high in organic carbon (up to 12 % by weight) and contain type II marine kerogen.

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

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

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

Reservoir Rocks

The basal Cambrian sandstones of the Colville Hills, the Devonian Kee Scarp reef, the Devonian reefal and dolomitized Keg River to Slave Point interval across the southern Great Slave Plain within the Presqu'ile Barrier, the Cretaceous Chinkeh sandstones in southwestern Great Slave Plain and the Cambro-Ordovician vuggy dolostone of the Franklin Mountain Formation in Great Bear Plain all contain hydrocarbons (Fig. 12). Bitumen commonly occurs in Cambrian sandstones, in the basal Cretaceous sandstones across Great Slave Plain, and in many lower Paleozoic carbonates, indicating that oil was once present.

Other potential reservoirs include:

1. Vuggy or fractured dolostone in the extensive developed lower Paleozoic platform carbonates (possibly at Tree River H-38) particularly beneath the “sub-Cretaceous unconformity”,
2. Platform carbonate to shale transitions in the lower Paleozoic succession of Peel Plain and Plateau (Osadetz et al. 2005),
3. Isolated, “pinnacle” reef mounds of the Horn Plateau type (Fig. 12) developed along the upper surface of the Devonian Lonely Bay or Nahanni formations (Gal and Jones, 2003),
4. Porous, shelf-edge facies transitions to basinal shale of Late Devonian and Carboniferous platform carbonates, such as the Jean Marie, Kakisa, Tectho, Kotcho and Flett formations (Fig 12; Gal and Jones, 2003),
5. Secondary porosity (leaching, dolomitization) in Devonian and Carboniferous platform carbonates (Jean Marie, Kakisa, Tectho, Kotcho and Flett formations; Gal and Jones, 2003), and in solution-collapse breccias (Bear Rock Formation),
6. Sandy turbidites and other coarse clastic rocks in the Devonian Imperial Formation and Carboniferous Tuttle Formation (Osadetz et al., 2005),
7. The basal sandstone of the Albian succession (Martin House Formation), and
8. Sandstones in the Albian to Santonian strata of Peel Plateau and Mackenzie Plain (Dixon, 1999; Osadetz et al., 2005).

Maturation and Generation

Thermal maturity of Cambrian source rocks is marginal to mature in the north Colville Hills, and show increasing maturity towards the south (Dixon and Stasiuk, 1998). Throughout most of the Interior Platform, sedimentary rock thickness and burial is moderate, consequently any source rocks in these areas would likely be immature to marginally mature. However, as the succession thickens towards the west and southwest, thermal maturity increases, with overmature Cambrian strata in the lower Paleozoic succession under parts of Peel Plain, Peel Plateau (Osadetz et al. 2005) and Mackenzie Plain.

Oil and gas have been generated from Cambrian source rocks (e.g., Tweed Lake A-67, ~ 0.9-1.0% Ro vitrinite equivalent) and the extensive occurrence of bitumen in Cambrian sandstone indicates that oil generation occurred. However, the recovery of gas and condensate from the sandstone at Tweed Lake A-67 (Fig. 14) within a late mature oil zone suggests that most of the gas likely migrated from elsewhere (Dixon and Stasiuk, 1998), possibly from the south and west.

Thermal maturity of the Devonian strata in Mackenzie Plain has been assessed and mapped regionally, but for vast areas are without thermal maturity and source rock data (Feinstein, 1988; Stasiuk and Fowler, 2002). Thick, good quality Middle to Late Devonian Bluefish Member and Canol Formation marine source rocks are mature over a large area and can be expected to have generated large volumes of hydrocarbons. Large areas of these source rocks are in the gas zone (Stasiuk and Fowler, 2002). Canol shale is known to be the source for oil at Norman Wells, in nearby Mackenzie Plain (Feinstein et al., 1988, 1991), but no known reservoirs with Canol-derived oil have been yet discovered in the Interior Plains. No known oil discoveries have been attributed to the Bluefish shale. But oil staining in the underlying Hume Formation just south of Norman Wells has been linked to a local thermally mature Bluefish source rock (Feinstein et al., 1988), suggesting that this unit charges underlying reservoirs. Devonian Horn River source rock shale ranges widely in maturity across Great Slave Plain from submature at the top of the oil window east of 119 degrees longitude, to overmature in the dry gas generation zone west of about 123 degrees longitude (Stasiuk and Fowler, 2002).

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

Migration and Accumulation

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

Oil that charged the Norman Wells reservoir farther west was probably generated from the thermally mature Canol shale (Stasiuk and Fowler, 2002). There is some possibility that these oils may have migrated into porous Kee Scarp reefal limestone in Great Bear Plain in the Interior Plains region immediately east of the Norman Wells Field (Fig. 4). Also, oils generated during thermal maturation of the organic-rich Middle Devonian Bluefish Member of the Hare Indian Formation (Fig. 12) could have migrated into underlying Hume reservoirs (Feinstein et al., 1988).

The unconformity surface on which the Cambrian sandstones rest has significant topographic relief, and sandstone pinch out against topographic highs may have provided traps for the initial liquid hydrocarbons. Tertiary structures may have enhanced such traps or created new traps into which hydrocarbons were remobilized. Seal rocks are present in the shales of the Mount Cap and Saline River formations and the evaporite of the Saline River Formation.

Gas in the numerous Devonian gas fields and shows within the Presqu'ile Barrier across Great Slave Plain was probably generated further west from lower Paleozoic source rocks, such as the Horn River and Muskwa shales. This gas migrated eastward and up-dip through the barrier during Mesozoic to Cenozoic time. More locally generated oil-phase hydrocarbons are present in some fields, such as at Cameron Hills (Figs. 4, 5), where eastward gas migration failed to flush locally generated, less mature oil from reservoirs.

Exploration Plays

Cambrian Sandstone Reservoirs

1. Early Tertiary thrust faulted anticlines,
2. Up-dip pinch out of sandstones against paleotopographic highs, and
3. Enhanced trap combining trap types 1 and 2.

Paleozoic Platform Carbonates

1. Up-dip pinch out of porous intervals,
2. Fault traps,
3. Carbonate to shale transition and possible development of shelf-edge reefs or biostromes in western Peel Plain, Peel Plateau, and along the Presqu'ile Barrier in Great Slave Plain,
4. Dolomitization of Devonian and Carboniferous platform carbonates,
5. Reef mounds developed on Middle Devonian carbonates and encased in Middle/Late Devonian shale.
6. Kee Scarp reefs sealed by Devonian Canol Formation shale, and
7. Porous Hume carbonates sealed by Bluefish Member shale.

Paleozoic Siliciclastic Rocks

1. Stratigraphic up-dip pinch outs of porous sandstones,
2. Up-dip pinch outs of porous sandstones beneath sub-Cretaceous unconformity,

3. Up-dip porosity terminations against high angle faults, such as Trevor Fault in Peel Plateau, and
4. Anticlines in the Peel Plateau.

Basal sandstone of the Albian succession

1. Lateral/up-dip pinch out of porous sandstone, and
2. Anticlines in the Peel Plateau.

Upper Cretaceous sandstone

1. Anticlines in the Peel Plateau and Mackenzie Plain.

Reserve Estimates

A median value of $11.345 \times 10^9 m^3$ (400 billion cubic feet) of gas has been attributed to the three Colville Hills Cambrian discoveries (Morrell, 1995). A median value of $121.19 \times 10^9 m^3$ (4.28 Tcf) of gas has been attributed to the scattered gas fields across the southern Great Slave Plain (Morrell, 1995), although production of gas at the Cameron Hills Field of over $170 \times 10^6 m^3$ (6.0 billion cubic feet) (Gal and Jones, 2003) has already exceeded previous published reserve estimates for this field (e.g. Morrell, 1995). It is very likely that the reserve estimates for most gas fields in this area (Fig. 5) will be revised drastically upwards in the future.

Hydrocarbon Potential

Qualitative assessments of the Interior Plains indicate low to moderately high hydrocarbon potential, varying throughout the area (e.g. Gal and Jones, 2003; Gal, 2005; Osadetz et al. 2005). The Colville Hills and southern Great Slave Plain remain the most prospective exploration areas with known oil, gas and condensate discoveries, and the possibility of more discoveries. Large areas remain relatively untested with only a few wells, such as the Peel Plain and Peel Plateau (Osadetz et al., 2005). In the western parts of the latter areas, the possibility of petroleum-bearing shelf-edge reefs and/or biostromes or dolomitised and porous shelf-edge carbonates or porous sandstones has yet to be tested in detail.

Mackenzie Arc Region

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

Introduction

The Liard Plateau, the Mackenzie Mountains, the Mackenzie Plain and the Franklin Mountains together comprise the Mackenzie Arc, which forms a broad convex arc of mountain ranges that face northeast toward the Interior Plains. Mackenzie Arc changes orientation from north-trending near Liard Plateau to northwest-trending near the Ogilvie-Wernecke Mountains in the Northern Yukon Region (Figs.

2, 7). Immediately west of the NWT-Yukon Territory border, the Ogilvie-Wernecke Mountains trend nearly due west.

These arcuate semicontinuous mountain ranges have been referred to collectively as the Mackenzie Fold Belt, a continental-scale, northeast-facing arc of mountain ranges bordering the broad Interior Platform and the Northern Yukon Fold Complex (Gabrielse et al., 1992). As discussed previously, profound differences between the sub-Mesozoic geology of Mackenzie Mountains and the Ogilvie-Wernecke Mountains (Norris, 1997; Morrow, 1999) have led to their separation as exploration areas into different exploration regions. Discovery of the Norman Wells oil field in 1920 provided the definitive petroleum exploration model for this region until recent oil and gas discoveries, such as in the Summit Creek area near the eastern limit of the Mackenzie Mountains (Figs. 4, 5), suggested additional new exploration models.

Geological Setting

Mackenzie Arc is the northern continuation of the Rocky Mountains (Rocky Mountains Foreland Belt) of western Canada. It is bounded on the east by the relatively undisturbed strata of the Interior Plains and on the west by the more intensely deformed strata of the Selwyn Fold Belt (Figs. 2, 7). The dominant structural style of Mackenzie Arc is one of eastward and westward verging, regionally continuous concentric folds and high angle thrust faults, in contrast to the low angle thrust-dominated Rocky Mountains south of 60 degrees latitude. The amount of structural shortening associated with deformation in the Mackenzie Mountains has been estimated to be about 50 kilometres (Gordey, 1981; Cecile et al., 1982), much less than the 200 kilometres of shortening estimated for the southern Rocky Mountains (Price and Fermor, 1985).

Moderately folded and faulted Proterozoic to Late Devonian strata are exposed across most of the Mackenzie Mountains (Figs. 14, 15, 16). For the most part, Carboniferous to Cretaceous strata are exposed only on Liard Plateau at the south end of the Mackenzie Arc (Bamber et al., 1992; Stott et al., 1992). Post-Devonian strata are absent across the entire Mackenzie Mountains except for a local graben of preserved Early Cretaceous strata (Mackenzie Mountains (north) column in Fig. 15; Blusson, 1971). Late Cretaceous strata are present across Mackenzie Plain (Slater River Formation - shale; Little Bear Formation - interbedded sandstone and shale; East Fork Formation - shale, and lower part of the Summit Creek Formation - interbedded sandstone, conglomerate and shale). Minor thicknesses of Early Tertiary strata are preserved in Mackenzie Plain (upper part of Summit Creek Formation in Mackenzie Plain column in Fig. 15- interbedded sandstone, shale and coal).

Up to five kilometres of Neoproterozoic strata of the Mackenzie Mountain and Windermere supergroups are exposed along the 400 km length of the Plateau Thrust (Fig. 16) in the Mackenzie Fold Belt. This succession of Neoproterozoic shale, carbonate, sandstone, volcanic rocks and diamictite is not significantly metamorphosed and is exposed across large areas in the northern Mackenzie Mountains (Fig. 14; Gabrielse and Campbell, 1992).

Cambro-Ordovician sandstone and carbonate with an aggregate but very variable thickness of up to 20 kilometres, unconformably overlie Proterozoic strata across most of the Mackenzie Fold Belt (Fig. 15). Mackenzie Arch formed a linear landmass along the central axis of the Mackenzie Mountains in Cambrian time. This landmass separated a Cambrian depocentre in the eastern Mackenzie Plain, containing siliciclastic rocks and evaporite of the Mount Clark, Mount Cap and Saline River formations, from the much thicker siliciclastic and carbonate succession of the Cambrian Backbone Ranges, Vampire, Sekwi and Rockslide formations in Selwyn Basin (Mackenzie Mountains (north) column in Fig. 15; Dixon and Stasiuk, 1998).

Platform carbonate deposits of the Franklin Mountain and Mount Kindle formations (i.e. Ronning Group, Pugh 1993) with an aggregate thickness of up to 2000 metres, extended across almost the entire Mackenzie Fold Belt in Early Cambrian to mid-Silurian time, following the basal Cambrian transgression that inundated Mackenzie Arch (Aitken et al., 1974). South of Mackenzie Arch, deeper water deposition of carbonate and shale of the Sunblood and Whittaker formations, and of the Road River Group, occurred in Root Basin and in the Meilleur River Embayment within the southern Mackenzie Mountains and Liard Plateau (Fritz et al., 1992; Morrow and Cook, 1987).

Widespread exposure across Mackenzie Arc in late Silurian time caused development of the "sub-Devonian unconformity". Early Devonian transgression was accompanied by deposition of up to 400 metres of thick yellowish-orange siliciclastic, carbonate and evaporate strata of the Delorme Group (Tsetso, Camsell and Cadillac formations in Fig. 15; Morrow, 1991) across the Mackenzie Mountains and Liard Plateau (Morrow and Geldsetzer, 1992).

By late Early and Middle Devonian time, platform carbonate and evaporite deposits of the Arnica, Sombre, Bear Rock, Fort Norman, Landry, Nahanni and Hume formations, up to 2000 metres in thickness, blanketed the Mackenzie Mountains, Mackenzie Plain, and Franklin Mountains areas and the eastern Liard Plateau. At this time, gray and buff shale of the Road River Group and the Funeral Formation accumulated farther west in the Selwyn Mountains and across the western part of Liard Plateau. Diagenetic dolomitization of the Landry and Nahanni limestones in the southern third of the Mackenzie Arc formed the coarsely crystalline and porous Manetoe Dolomite, an important petroleum reservoir facies (Fig. 15; Morrow and Geldsetzer, 1992).

At the close of Middle Devonian time, organic-rich black, gray and greenish-gray shales of the Horn River Group (including the Hare Indian Formation and the organic-rich Bluefish Member) and of the Canol Formation blanketed underlying Middle Devonian platform carbonates. Platform carbonate deposition during this time is represented by the Ramparts Formation limestone and the Kee Scarp Member reefal reservoir limestone in the Mackenzie Plain and Franklin Mountain areas. In addition, in the extreme eastern part of the Mackenzie Mountains west of Norman Wells, limestones of the Tetcho and Kotcho formations were deposited in the eastern part of the Liard Plateau area (Fig. 15; Geldsetzer and Morrow, 1992). By Late Devonian time, the entire Mackenzie Arc was blanketed by shale, siltstone and sandstone of the Imperial and Fort Simpson formations. Deposition of the organic-rich black shale source rock of the Exshaw Formation in Liard Plateau marked the passage from Devonian to Carboniferous time.

Carboniferous and Permian strata are preserved only within Liard Plateau. None have been found within the Mackenzie Mountains, Mackenzie Plain or Franklin Mountains (Bamber et al., 1992). In Liard Plateau, the Carbo-Permian succession is up to 3000 metres thick. Carboniferous platform carbonates of the Flett and Prophet formations extend westward from the Interior Platform into the eastern part of Liard Plateau, as does the important reservoir sandstone of the Carboniferous Mattson Formation. These are overlain unconformably by siltstones and cherts of the Permian Kindle and Fantasque formations. Triassic strata, represented by the siltstones of the Grayling and Toad formations, occur only in the southern part of the Liard Plateau where they are mapped together as a single map unit, the "Grayling and Toad undivided" (Fallas et al., 2004).

Jurassic strata are absent across the entire Mackenzie Arc. Cretaceous strata are absent across almost the entire Mackenzie and Franklin Mountains where deformed Proterozoic and Paleozoic strata are either exposed at surface, or lie unconformably beneath a thin cover of Quaternary drift (Fig. 15; Stott et al., 1992). However, Cretaceous strata are preserved in Mackenzie Plain between the Franklin and the Mackenzie Mountains, and along the axes of north-trending synclines in Liard Plateau at the south end of the Mackenzie Arc (Fig. 15).

In Mackenzie Plain, slightly more than 1000 metres of alternating sandstones (Martin House, San Sault, Little Bear) and shales (Arctic Red, Slater River and East Fork) are capped by the Late Cretaceous to Early Tertiary Summit Creek conglomerate (Dixon, 1999; Fig. 15). The aggregate preserved Cretaceous succession in Liard Plateau is up to 1500 metres thick. These strata include the alternating sandstones and shales of the Fort St. John Group, overlain by the resistant Dunvegan Formation sandstone and the more recessive Kotaneelee Formation shale and Wapiti Formation sandstone. The Chinkeh Formation, a transgressive shoreline conglomeratic sandstone at the base of the Cretaceous succession, forms the reservoir facies for the Maxhamish gas field in northeast British Columbia a short distance southeast of Liard Plateau (Leckie et al., 1991). A thin unnamed Paleocene siliciclastic succession that unconformably overlies Paleozoic strata is mapped in a few small areas. Quaternary drift and outwash that unconformably overlie the Paleozoic and Mesozoic strata cover broader areas along the modern rivers and streams in the extreme western part of the Liard Plateau (Fig. 15; Fallas et al., 2004).

Intermittent igneous intrusive and extrusive rocks of the Eocene Beaver River alkaline complex are present mainly as small volcanic plugs across the southwestern part of Liard Plateau (Fallas et al., 2004). Larger igneous bodies in this area include the Neoproterozoic Pool Creek Syenite and a Tertiary syenite body (Fig. 15; Pigage and Mortensen, 2004).

Exploration History

The most significant discoveries in the northern part of the Mackenzie Arc occurred at Norman Wells in Mackenzie Plain where oil has been produced from the Middle Devonian reefs of the Kee Scarp Member for over 80 years (Figs. 14, 15; Table 2). A significant occurrence of heavy oil (20° API) was identified in 1971 in the Ordovician Franklin Mountain Formation at the East MacKay B-45 well in Mackenzie Plain. Several recent oil and gas discoveries near Summit Creek southwest of Tulita followed the initial oil and gas discovery at the Summit B-44 well in 2004 (Fig. 7; Table 2). About 90 wells have been drilled in Mackenzie Plain, but only a very few exploratory wells have been drilled in the adjacent Mackenzie and Franklin Mountains.

Exploration within Liard Plateau led to a succession of large gas field discoveries in the southeast Plateau in both the Yukon and Northwest territories (Table 2). The Beaver River gas field, discovered in 1957 (Pan Am A-1 Beaver River) in British Columbia just south of the British Columbia – Yukon border, extends into the Yukon (Davidson and Snowdon, 1978). Subsequent finds of gas fields at the Pointed Mountain (Pan Am Pointed Mountain P-53 discovery well completed in 1966) and Kotaneelee (Pan Am et al A-1 Kotaneelee YT P-50 discovery well completed in 1962, Table 2) had a sporadic production history in the period from the mid 1960s until the mid 1980s (NEB, 1996, 2001; Morrell, 1995). All these gas fields are closely grouped along the Duke Energy Pipeline (Figs. 3, 5).

The hydrothermally dolomitized limestone of the Early to Middle Devonian Landry and Nahanni formations, the "Manetoe Dolomite" (Morrow et al., 1990), forms the porous reservoir rock in faulted anticlines at the Beaver River, Kotaneelee and Pointed Mountain gas fields (Fig. 17). All of these pre-1990 discovered gas fields have all experienced severe production problems due to the influx of groundwater into the reservoir (NEB, 2001&1996; Morrell, 1995).

The Northcor et al. Liard F-25A well drilled in 1985 was the discovery well for the Liard K-29 gas field northeast of the Pointed Mountain Field (Fig. 17, Table 2), but production did not begin until 2000 shortly after the spectacular Chevron et al. Liard K-29 well was drilled. The Ranger Fort Liard P-66A well drilled in 1997 was the discovery well for the Liard P-66A Field a short distance north of the Pointed Mountain and Liard K-29 fields (Fig. 17). This field was brought into production in 2000. The reservoir rock in all these fields is also the "Manetoe Dolomite" in faulted anticlinal culminations associated with regional Tertiary (Laramide) compression.

A single well (CPOG La Biche F-08) gas pool straddling the Yukon and Northwest Territories border (Fig. 17) was discovered in 1971 (NEB, 1996, 2001; Morrell, 1995). This gas pool occurs in silicified detrital carbonates that have been interpreted to be paleocavern sediment fills within the Nahanni Formation (Morrow and Potter, 1998).

In addition to the production from the Devonian "Manetoe Dolomite" gas fields, gas shows have been noted in the Fantasque, Prophet, and Besa River formations above these gas fields within Liard Plateau (NEB, 1996). Also, since 2000, the Fort Liard F-36 gas field has produced gas from the Mattson and Fantasque formations from two wells near Fort Liard. The Fort Liard F-36 gas field (Fig. 17) is located slightly east of Liard Plateau on the western edge of the Great Slave Plain subdivision of the Interior Platform, but is described here because the eastern limit of its main producing interval, the Mattson Formation, is restricted mainly to the Liard Plateau region (Fig. 15).

Approximately a dozen scattered exploration wells have been drilled along the eastern edge of the Mackenzie Mountains (Fig. 7), but none have yielded commercially exploitable hydrocarbons. Most of these wells bottomed in Devonian strata such as the Arnica and Bear Rock formations. A small amount of seismic coverage is available through the NEB for the extreme eastern slopes of the Mackenzie Mountains, and in Liard Plateau in the area of the gas fields (Fig. 8).

Source Rocks

There are at least 10 known, probable or potential source rocks in Mackenzie Arc (Fig. 15):

1. Scattered, thin beds of algal-rich shale in the Cambrian Mount Clark-Mount Cap succession (Dixon and Stasiuk, 1998) are probable source rocks in the Mackenzie Mountains, Mackenzie Plain and Franklin Mountains,
2. Organic-rich cherty and shaly dolostones and organic-rich shales of the Upper Ordovician and Lower Silurian Whittaker Formation and the Duo Lake Formation (Fritz et al., 1992) are probable source rocks in the Mackenzie Mountains,
3. Organic-rich gray to black shale intervals within the Road River Group (Fritz et al., 1992) are probable source rocks throughout the Mackenzie Mountains and Liard Plateau,
4. Organic-rich siliceous black shales within the Horn River Group, including the Bluefish Member of the Hare Indian Formation (Feinstein et al., 1988; Morrow et al., 1993), are known and documented source rocks in the Mackenzie Mountains, Mackenzie Plain and Franklin Mountains,
5. Organic-rich black shale in the lower part of the Besa River Formation, equivalent to that the Horn River Group, (Morrow et al., 1993) is a known and documented source rock throughout the Mackenzie Mountains and Liard Plateau,
6. The Middle and Late Devonian, Canol Formation black shale (Feinstein et al., 1988, 1991) is a known and documented source rock throughout the Mackenzie Mountains, Mackenzie Plains and Franklin Mountains,
7. The latest Devonian to earliest Carboniferous Exshaw Formation (Fowler et al., 2000; Creany and Allen, 1990) or its lateral equivalent, the first black shale within the Besa River Formation are known and documented source rocks throughout the Mackenzie Mountains and Liard Plateau,
8. Carboniferous black shale of the Clausen Formation (Richards, 1989) is a probable source rock in Liard Plateau,
9. Carboniferous black shales of the Golata Formation and within the overlying Mattson Formation (Richards, 1989, Morrow et al., 1993) are probable source rocks in Liard Plateau,
10. Cretaceous shales in the Garbutt and Lepine formations are probable source rocks in Liard Plateau (Dixon, 1999, Snowdon, 1990).

The documented source rocks described here (e.g. Bluefish Member) have been linked to any known hydrocarbon accumulations within the Mackenzie Arc, but have been correlated with oil and gas pools in the Interior Plains. Probable source rocks are black shales that contain TOC (total organic carbon) values of more than 1.0% and/or may be associated with hydrocarbon pools or fields in the adjoining Interior Plains. Potential source rocks are black shale or basinal limestone rich in organic material.

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

Reservoir Rocks

Many stratigraphic units in Mackenzie Arc exhibit porosity and permeability sufficient to serve as potential hydrocarbon reservoir rocks. However, the high structural elevation of strata across Franklin Mountains has precluded entrapment of hydrocarbons. Proterozoic and Paleozoic strata are exposed at surface across these areas (Gabrielse et al., 1992) and most potential hydrocarbon reservoirs are either breached or have had their contained liquid hydrocarbons flushed by shallow groundwater. Groundwater flow in the Mackenzie Mountains has also been interpreted to have caused Tertiary brecciation of the Devonian Bear Rock and Camsell formations, as observed in outcrop and in the shallow subsurface of eastern Mackenzie Mountains (e.g. in the Amoco Candex Shell A-1 Red Dog K-29 well; Morrow, 1991).

Liard Plateau is the only part of the Mackenzie Arc where lower and middle Paleozoic strata, and any contained potential reservoirs, are buried beneath a thick cover of both upper Paleozoic and Mesozoic strata. Farther north in Mackenzie Plain, immature heavy oil in Paleozoic carbonate reservoirs at the MacKay B-45 well in Mackenzie Plain was probably generated locally from shale source rocks of the unconformably overlying Cretaceous Slater River Formation. The oil and gas pools recently discovered in the Mackenzie Plain southwest of Tulita (e.g. Summit Creek B-44; Figs. 4, 5) may also occur in folded and faulted lower Paleozoic carbonate strata near the eastern margin of Mackenzie Mountains.

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

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

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

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

8. Porous deltaic sandstone of the Carboniferous Mattson Formation,
9. Possible fractured reservoirs within the Permian chert of the Fantasque Formation, and
10. Porous sandstones of the Cretaceous Chinkeh and Scatter formations.

Maturation and Generation

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

The Middle Devonian Hume and Nahanni formations in the Mackenzie Mountains and Liard Plateau range in levels of organic maturation from about 1.4 %R_o up to at least 2.6 %R_o, and are thus well into the dry gas stage of hydrocarbon generation maturation (Tissot and Welte, 1984). Hume Formation maturation ranges from 0.4 %R_o on the east side of the Franklin Mountains and increases westward across Mackenzie Plain to 1.4 %R_o. This range of maturation embraces the oil window and is consistent with locally sourced oil for the Norman Wells field from Canol source rocks. Higher stratigraphic levels exhibit progressively lower levels of organic maturation. The overlying Late Devonian Imperial Formation exhibits levels of organic maturation that range from about 1.6 %R_o up to at least 2.2 %R_o in the Mackenzie Mountains, hence still in the zone of gas generation.

Determination of the post-Devonian history of thermal organic maturation of most of Mackenzie Arc is precluded by the paucity of post-Devonian strata (Fig. 15). Carboniferous and Permian strata are present only in Liard Plateau, where Carboniferous strata range in organic maturation from about 0.8 %R_o (Mattson Formation) up to 1.5 %R_o (Prophet Formation; Potter et al., 1993). This range of maturation straddles the oil to wet gas generation zone. Cretaceous strata that unconformably overlie Paleozoic strata are present locally in Liard Plateau, and are estimated to range in maturity between 0.6 %R_o and 0.8 %R_o, within the upper part of the oil window (Stasiuk et al., 2002).

The large gas fields (Beaver River, Pointed Mountain, Kotaneelee and Liard gas fields) in Middle Devonian strata of Liard Plateau (Figs. 5, 15, 17) indicate that tremendous volumes of gas were generated in Paleozoic organic-rich shaley source rocks during progressively deeper burial (Morrow et al., 1990). The prevalence of solid reservoir bitumen in lower Paleozoic platform carbonates, such as in the Mount Kindle and Arnica formations (Morrow et al., 1990), is consistent with oil and gas generation and migration through these strata.

Migration and Accumulation

Bitumen in the Cambrian Mount Clark sandstone, documented farther east in the Interior Platform and as discussed with regard to the Interior Platform, indicates oil generation and probable eastward petroleum migration in post-Cambrian time. Bitumen in vuggy carbonates of the lower Paleozoic Franklin Mountain and Mount Kindle formations of the Mackenzie Mountains and Liard Plateau may have been emplaced during lateral eastward migration of oils generated from correlative basinal Road River shale source rocks. Similarly, bitumen in vugs and intercrystalline pores of the Early Devonian Arnica and Bear Rock formations (Morrow, 1991) may indicate up-dip eastward passage of liquid hydrocarbons from basinal source rocks of the Road River Group (Fritz et al., 1992; Morrow and Geldsetzer, 1992).

Oil in the Norman Wells Field is believed to have been generated from the adjacent, thermally mature Canol shale, with minimal vertical or lateral migration required (Stasiuk and Fowler, 2002). The oil-bearing Kee Scarp reef (Mackenzie Plain-Franklin Mountains column in Fig. 15) lies on the north limb of a synclinal feature, with surrounding shale acting as a lateral and up-dip seal. The location of the Norman Wells field near an oil seep suggests that the seal rock is leaky and that a considerable amount of hydrocarbons may have escaped.

Oil generation gave way to gas generation during deeper burial in the central and western parts of the Mackenzie Arc, and gas may be confined in up-dip stratigraphic traps where Paleozoic strata lie unconformably beneath the impermeable Cretaceous shale. This occurs in areas with Cretaceous cover, such as across parts of Liard Plateau, Mackenzie Plain, Franklin Mountains, and the extreme eastern parts of the Mackenzie Mountains. Gas generated from lower Paleozoic source rocks may also have accumulated in weakly deformed lower Paleozoic carbonates beneath the upper plate of the Plateau Thrust in the central Mackenzie Mountains (Fig. 16; Cecile et al., 1982).

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

Oil and gas generated from Late Devonian and Carboniferous source rocks (Besa River, Exshaw, Clausen and Golata shales) probably migrated eastward into Late Devonian and Carboniferous platform carbonates of the Tetcho, Kotcho, Prophet and Flett formations and, notably, into Carboniferous sandstone of the Mattson Formation, a significant gas producer at the F-36 well in the Interior Platform near Fort Liard (Fig. 17; Gal and Jones, 2003).

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

Exploration Plays

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

1. Fault traps in Cambrian Mount Clark sandstone structurally juxtaposed with Paleozoic shale source rocks,
2. Stratigraphic traps where porous lower Paleozoic Franklin Mountain, Mount Kindle, Arnica, Landry and Hume carbonates pass laterally up-dip to Road River and/or Canol shale source rock,
3. Structural anticlinal traps where porous bioclastic strata or reef build-ups in the upper part of the Devonian Hume and Nahanni formations are overlain and sealed by Horn River shale source rocks,
4. Combined structural-stratigraphic traps where fractured, hydrothermal, white, coarsely crystalline dolomite masses within the Landry and Nahanni formations are overlain and sealed by Horn River-Besa River shale source rocks and involved in Laramide faults or folds, and
5. A regional sub-thrust play where lower Paleozoic carbonates are overlapped and sealed by Proterozoic strata that form the hanging wall of the Plateau Thrust in the central part of the Mackenzie Mountains (Fig. 16).

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

Unlike the Mackenzie Mountains, the thick early Paleozoic to Mesozoic successions covering Liard Plateau provide more potential for the preservation of traps in Early Paleozoic strata. These include:

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

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

Reserve Estimates

About $37.5x10^6 m^3$ (235.9 MMbl) of recoverable oil is present at Norman Wells (Fig. 4; Morrell, 1995). A very approximate estimate of $50x10^9 m^3$ (1.77 Tcf) of gas can been attributed collectively to the four main Manetoe gas fields in Liard Plateau, including the recently discovered Liard gas field (Morrell, 1995; Gal and Jones, 2003). No reserve estimates are yet available for the new oil and gas discoveries in the Summit Creek area of the western Mackenzie Plain north of Keele River (Figs. 4, 5; Table 2), but there is little doubt that they will be substantial. In Table 2, new discoveries have been assigned minimal oil and gas reserves but are very likely to be much higher in reality.

Hydrocarbon Potential

Although there have been many exploration programs in the Mackenzie Plain, efforts to find another Norman Wells-type oil field have been unsuccessful. The Franklin Mountains are considered to have a poor potential due to inferred high levels of thermal maturity and extensive exposure of potential reservoir rocks.

Gas in the "Manetoe Dolomite" in Liard Plateau remains, arguably, the most attractive target for exploration both in structural and stratigraphic traps. Paleozoic platform carbonate and chert higher in the succession are also prospective, but probably for much smaller gas fields. Consequently, the remaining hydrocarbon potential for Liard Plateau is moderate to high. Both the Ogilvie-Wernecke and Mackenzie Mountains have low potential for hydrocarbons, with the possible exception of the sub-Plateau Thrust play in the Mackenzie Mountains (Fig. 16).

Northern Yukon Region

Geology.........................	Paleozoic to Tertiary strata
Proven source rocks......	Devonian Canol Formation; Carboniferous Blackie and Ford Lake formations; Late Cretaceous Parkin Formation.
Reservoir rocks.............	Paleozoic carbonate; Carboniferous carbonate and sandstone; Permian sandstone; Cretaceous sandstone
Discoveries...................	Oil and gas from Devono-Carboniferous and Permian strata in Eagle Plain
Hydrocarbon potential...	Low in most areas, but moderate to high in Eagle Plain

Introduction

The Northern Yukon Region extends from the Ogilvie-Wernecke Mountains north to the Yukon coastal plain. This region coincides with all of the Northern Yukon Fold Complex (Gabrielse, 1992) with the addition of the Ogilvie-Wernecke Mountains, which as discussed previously, was included in the Mackenzie Fold Belt by Gabrielse, (1992), but is here regarded here as part of the Northern Yukon Region. This region extends east to include the Richardson Mountains and, on the west, the fold complex continues into Alaska. Within this area there are five areas with significant hydrocarbon potential. These are (Figs. 2, 7):

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

Although the intervening mountainous areas, such as the Ogilvie-Wernecke Mountains, Keele Range and British Barn Mountains (Figs. 2, 7) may have some hydrocarbon potential, their high levels of thermal maturation, degree of deformation, structural elevation and exposure of potential reservoir rocks, and high degree of compaction make them less prospective.

Geological Setting

The areas of significant petroleum potential are large tectonic depressions surrounded by highly deformed Proterozoic through Cretaceous strata. Cretaceous clastic deposits commonly form the youngest fill, although in the case of the Bonnet Plume (Norris and Hopkins, 1977) and Old Crow basins, Lower Tertiary and Quaternary strata are present (Figs. 18, 19). The depressions are located where major structural elements change trend, for example, Bonnet Plume Basin is located where the north-trending structures of the Richardson Mountains pass southward to the east-trending structures of the Ogilvie-Wernecke Mountains (Fig. 2). Deformation within these depressions is generally less intense than in the surrounding mountains. In Kandik Basin and Blow Trough, the youngest sedimentary rocks are Albian, whereas under Eagle Plain the youngest strata are probably Campanian, but possibly as young as Santonian.

The folded and faulted Ogilvie-Wernecke Mountains contain the most complete stratigraphic succession exposed in the mountainous areas of the Northern Yukon Region. The Proterozoic succession exposed across the Ogilvie-Wernecke Mountains includes Mesoproterozoic strata of the metasedimentary Wernecke Supergroup and Pinguicula Group. The Neoproterozoic Ekwi Supergroup is exposed across large areas of eastern Ogilvie-Wernecke Mountains. The aggregate thickness of the Proterozoic succession is up to 20 kilometres (Gabrielse and Campbell, 1992; Stott, 1993). Cambrian carbonates and sandstones of the Illtyd and Slats Creek formations are exposed in the Ogilvie-Wernecke Mountains. During Silurian time, Road River shale was deposited across most of the Ogilvie-Wernecke Mountains, with deposition of platform carbonates of the Ogilvie Formation during Early to Middle Devonian time. The Carboniferous succession is up to one kilometre thick. The Carboniferous shale and limestone succession of the Ford Lake, Hart River, Blackie and Ettrain formations, and the unconformably overlying sandstones and cherts of the Permian Jungle Creek and Takhandit formations, are underlain by Devonian strata in the western part of the Ogilvie-Wernecke Mountains (Fig. 18; Richards et al., 1997).

The Proterozoic and Paleozoic succession exposed across the Ogilvie-Wernecke Mountains is also found in the subsurface of the Eagle Plain, where it is truncated by an important regional sub- Cretaceous angular unconformity (Dixon, 1992).

Exploration History

Eagle Plain is the most explored area with about 40 wells, and with several hydrocarbon discoveries in Carboniferous (Chance sandstone in Hart River Formation) and Permian strata and some lower Paleozoic gas shows (Figs. 4, 5, 18; Yukon Economic Development, 1994; Morrell, 1995; Table 2). Of the other four potentially prospective areas, only Blow Trough has had any drilling, one well within the depression and two wells on the perimeter. Kandik Basin has only three wells, all in close proximity along the eastern flank of the basin. There were no hydrocarbon shows in the Blow Trough and Kandik wells.

Seismic coverage is mainly confined to Eagle Plain, with some older, poor quality data along the Yukon coastal plain intersecting the Blow Trough (Fig. 8). A few seismic lines are located on the eastern margin of Kandik Basin, associated with the three wells drilled in this area. The wells located on the eastern side of Kandik Basin were drilled on surface anticlines. To date, no wells have been drilled in the Ogilvie-Wernecke Mountains.

Source Rocks

Potential source rocks in the subsurface of Eagle Plain include the lower Paleozoic Road River Group and Prongs Creek shales, the Devonian Canol Formation, the Carboniferous Ford Lake, Hart River and Blackie shales, Albian shale of the Whitestone River Formation, and the basal beds of the Shale member, Upper Cretaceous Parkin Formation.

Under Blow Trough and Kandik Basin, thick shale strata are found in the Albian and throughout parts of the Early Cretaceous and Jurassic successions. Old Crow and Bonnet Plume basins are the least known areas, but subcropping Paleozoic shale beds may represent potential source rocks and, in the case of Old Crow Basin, some Jurassic and Lower Cretaceous shales.

Reservoir Rocks

Potential and known reservoir rocks (Figs 18, 19) for each of the areas are listed as follows:

Bonnet Plume Basin

1. Albian conglomerate and sandstone.

Eagle Plain

1. Lower Paleozoic platform carbonates of the Ogilvie and Bouvette formations - gas shows,
2. Late Devonian turbidite (Imperial Formation),
3. Late Devonian/Early Carboniferous marine sandstone and conglomerate (Tuttle Formation) - gas tested,
4. Canoe River Member (limestone) in the Carboniferous Hart River Formation - gas and oil recovered,
5. Chance Sandstone Member (marine), in the Carboniferous Hart River Formation - gas and oil recovered,
6. Lower member (marine sandstone) of the Permian Jungle Creek Formation - gas tested, and

7. Marine and non-marine sandstones in the Upper Cretaceous Eagle Plain Group - gas tested from the Fishing Branch Formation.

Kandik Basin

1. Albian marine sandstone and conglomerate,
2. Early Cretaceous non-marine to marine sandstone (Kamik Formation), and
3. Carboniferous and Permian carbonates.

Old Crow Basin

1. Carboniferous carbonate, and
2. Cretaceous marine sandstone.

Blow Trough

1. Albian marine sandstone and conglomerate, and
2. Early Cretaceous marine sandstone (Kamik Formation).

Ogilvie-Wernecke Mountains

Many potential reservoir rocks of the Eagle Plain subsurface are well exposed in the adjacent Ogilvie-Wernecke Mountains (Morrow, 1999; Bamber et al., 1992; Hamblin, 1990; Morrell, 1995). These include:

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

Maturation and Generation

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

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

In Eagle Plain, maturation levels range from immature in the youngest Cretaceous rocks to overmature in some of the lower Paleozoic strata (Snowdon, 1987; Link and Bustin, 1989). Oil and gas generation has occurred, probably in Carboniferous source rocks, although other unidentified sources may have contributed. In the Ogilvie-Wernecke Mountains, the level of organic maturation at the top of the Hume-equivalent Ogilvie Formation ranges from about 2.0 $\%R_o$ up to 4.0 $\%R_o$, which indicates that the overlying Canol Formation shale is overmature and in the gas generation zone (Link and Bustin, 1989; Morrow, 1999).

Migration and Accumulation

The bulk of the known hydrocarbon occurrences are in the Carboniferous Chance Sandstone, a lenticular conglomeratic sandstone within the Hart River Formation (Figs 4, 5, 18). Its situation in Tertiary anticlines in the mature or oil zone of hydrocarbon generation, and its stratigraphic proximity to source rocks in the Blackie and Ford Lake formations represent a highly favourable setting for hydrocarbon migration and accumulation in reservoirs. Porous reservoir quality, Paleozoic strata exposed in the Ogilvie-Wernecke Mountains, have not been observed to contain sufficient oil or bitumen to be regarded as “reservoir bitumen”, a term indicating bitumen produced through thermal “cracking” of oil to gas. However, gas shows have been recorded from the Permian Jungle Creek Formation conglomerate and Devonian Ogilvie Formation reefal limestone within Eagle Plain (Fig. 18; Morrell, 1995; Morrow, 1999).

A lack of data and observed hydrocarbons in the other prospective areas in the Northern Yukon Region precludes assessment of potential migration and accumulation.

Exploration Plays

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

1. Early Tertiary anticlinal traps formed during Laramide and pre-Laramide deformation,
2. Stratigraphic pinch out of Late Paleozoic sandstone and conglomerate in combination with structural closure,
3. Stratigraphic up-dip subcrop traps of Late Paleozoic sandstone and conglomerate beneath the sub-Cretaceous unconformity in the subsurface of Eagle Plain,
4. Porous Carboniferous and/or Permian carbonates in structural and stratigraphic traps including and subcrop traps beneath the sub-Cretaceous unconformity in the subsurface of Eagle Plain, and
5. Early Paleozoic porous shelf-edge carbonate reservoirs, probably limited to the margins of Eagle Plain, in structural and stratigraphic traps.

Carboniferous shaley siltstones and shales of the Ford Lake, Hart River and Blackie formations are all potential or probable source rocks (Hamblin, 1990, Snowdon, 1990). Permian shaley beds within the Jungle Creek Formation are also potential source beds for these play types (Hamblin, 1990, Snowdon, 1990).

Exploration plays in the Ogilvie-Wernecke Mountains would only be viable in areas where Late Paleozoic strata of sufficient thickness and lateral continuity cover potential Neoproterozoic and Early Paleozoic reservoir rock. Most potential reservoirs in these near-surface strata lie within the zone of modern day fresh groundwater recharge, and any hydrocarbons may have been flushed from these rocks.

Possible petroleum play situations in this region might include:

1. Fault traps created by structurally juxtaposition of Cambrian Slats Creek sandstone and Paleozoic shale source rocks,
2. Stratigraphic traps where porous Early Paleozoic Bouvette or Ogilvie carbonates pass laterally up-dip to Road River and/or Canol shale source rock,
3. Anticlinal traps in which porous bioclastic strata in the upper part of the Devonian Ogilvie Formation are overlain and sealed by Canol shale source rocks,
4. Combined structural-stratigraphic traps in which fractured, hydrothermal, white, coarsely crystalline, dolomite masses within the Bouvette and Ogilvie formations are overlain and sealed by Canol shale source rocks and involved in Laramide faults or folds, and

5. Stratigraphic traps in which porous crinoidal limestones are sealed within silty shale source rocks of the lower part of the Hart River Formation (Canoe River Member).

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

Reserve Estimates

Morrell (1995) cites reserve estimates (Figs. 4, 5) at the 50% confidence level in Eagle Plain as:

- Gas - $2.524 \times 10^9 m^3$ (0.089 Tcf), and
- Oil - $1.86 \times 10^6 m^3$ (11.7 MMbl).

Hydrocarbon Potential

Eagle Plain remains the area in the Northern Yukon Region with the highest potential for more discoveries. Elsewhere, high levels of thermal maturity indicate that any hydrocarbons present would most likely be gas.

Selwyn-Cordillera Region

Geology.........................	Proterozoic, Paleozoic, Mesozoic and Cenozoic sedimentary and metamorphic rocks, Paleozoic and Mesozoic igneous rocks
Proven source rocks.......	No proven source rocks but Mesozoic siltstone and shale of the Tantalus and Richtofen formations in Whitehorse Trough are possible source rocks
Reservoir rocks.............	Mesozoic conglomerate and sandstone of the Laberge Group in Whitehorse Trough
Discoveries.....................	None
Hydrocarbon potential....	Low

Introduction

The Selwyn-Cordillera occupies most of the southwest corner of the Yukon Territory in northwestern Canada (Fig. 7). It extends westward from the Ogilvie-Wernecke and Mackenzie Mountains of the Mackenzie Arc Region to the international border with Alaska, U.S.A and to the St. Elias Mountains in the extreme southwest corner of Yukon Territory (Fig. 7). Exploration areas within this region include the Yukon Plateau- Selwyn Mountains Area, Tintina Trench, and Whitehorse Trough and collectively are referred to here as the “Selwyn-Cordillera Exploration Region” and, as such, do not include the entire Selwyn-Cordillera although these areas are contained entirely within the Selwyn Cordillera (Fig. 7). The Selwyn-Cordillera is, in general, characterized by mountainous, high relief terrain transected by the northwest-trending, broad valley of Tintina Trench, which separates Yukon Plateau- Selwyn Mountains in the eastern Selwyn-Cordillera from the Pelly-Cassiar Mountains in the western part of the Selwyn-Cordillera. The smaller Shakwak Trench separates the St. Elias Mountains from the Selwyn-Cordillera to the east (Fig. 2, 7). Whitehorse Trough is the northern extreme and terminus of the Intermontane Belt of the Canadian Cordillera. Intermontane sedimentary basins, such as Bowser Basin in British Columbia, lie in the Intermontane Belt to the south (Gabrielse et al. 1992).

Geological Setting

The Selwyn-Cordillera is diverse composite of geologically distinct regions. It includes parts of in-place Ancestral North America as well as the allochthonous Ancient Phanerozoic Terranes of western North America (Gabrielse and Yorath, 1992), separated by Tintina Trench, which marks a fundamental, continental scale, tectonic suture. The allochthonous Ancient Phanerozoic Terranes west of Tintina

Trench, originated west of continental North America and were successively accreted to western North America during Mesozoic and early Cenozoic plate collisions driven by sea floor spreading (Gabrielse et al., 1992). These allochthonous Ancient Phanerozoic Terranes were subsequently disrupted, smeared out northwestward by dextral transcurrent movements along the former continental margin. Large volumes of igneous rock were emplaced both during continental accretion and during subsequent Late Cretaceous and Tertiary, dominantly dextral, transtensional and transpressive deformation (Gabrielse et al., 1992).

Exploration History

Only one exploration well has been drilled (East Watson Lake YT G-79), and no seismic data have been acquired in the Selwyn-Cordilleran Region (Fig. 7, 9). The petroleum potential of Whitehorse Trough was recognized early on, and hydrocarbon exploration began in about 1950 (NEB, 2001). In the period 1961 to 1981, a total of 50 exploration permits were granted, and regional geological studies to assess petroleum prospectivity were conducted. In 1985 Petro-Canada fieldwork in the Whitehorse area included a geochemical sampling and reservoir analysis program which identified several areas with oil and gas potential (Morrell, 1995; NEB, 2001).

In the early 1900s, significant coal resources of bituminous to anthracite grade were found in Whitehorse Trough, principally in the Late Jurassic to Early Cretaceous Tantalus Formation (NEB, 2001).

Source Rocks

There are no proven source rocks in Whitehorse Trough. However, Templeman-Kluit (1978, 1984) noted that the back-reef facies of the Lewes River Group (Hancock Member of the Aksala Formation) is locally bituminous, with up to 1.0% TOC (NEB, 2001), and could source hydrocarbons in coeval reefal and shoal belt carbonate facies of the Lewes Group (Fig. 19). Other possible source rocks include shales in the Jurassic Richtofen Formation and in the Jurassic/Cretaceous Tantalus Formation, both of which contain more than 1.0% TOC in northern British Columbia (English et al., 2003). No source rock data have been acquired for the stratigraphically lower Cache Creek Group, but some dark algal dololaminites and dark argillaceous limestones are reported to emit a fetid odour when struck (NEB, 2001).

Reservoir Rocks

Potential petroleum reservoir strata (NEB, 2001; Fig. 19) in Whitehorse Trough include:

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

Maturation and Generation

The geological history of the Selwyn-Cordilleran Region, apart from Whitehorse Trough, has generally precluded the preservation of commercial quantities of hydrocarbons. Potential source rocks have been deformed and metamorphosed to relatively high grade through burial and igneous intrusive activity. Metamorphic heating exceeded the limits of hydrocarbon preservation in metasediments and graphitic schists across large parts of the Selwyn-Cordilleran Region. Even less deformed and metamorphosed rocks east of the Tintina Trench have been subjected to widespread high heat flow during Mesozoic igneous activity. Paleothermal indicators equivalent to a vitrinite reflectance of 4.5%R_o indicate that sub-Mesozoic strata have been uniformly heated to at least 300^{0}C (Gordey and Anderson, 1993). Paleotemperatures of this magnitude preclude the preservation of significant quantities of hydrocarbons, even dry gas hydrocarbons (Tissot and Welte, 1984; Dougherty et al., 1991). The pervasive and long-lived brittle deformation history of the Selwyn-Cordillera during continental accretion and shearing is also unfavourable for the preservation of pre-existing hydrocarbon traps.

In contrast, the unmetamorphosed strata within the intermontane Whitehorse Trough exhibit a wide range of organic maturity levels. The background level for much of the Tantalus Formation is estimated to be about 1.7% (NEB, 2001; Hunt and Hart, 1993) or near the lower limit of the oil generation window. Generally, Tantalus strata along the eastern and western flanks of Whitehorse Trough are in the lower part of the oil window, but entered the zone of gas generation along the axis of the trough (NEB, 2001). Much of the sedimentary fill of Whitehorse Trough is in the gas generation window of organic thermal maturity, with dramatically higher values near igneous bodies.

Migration and Accumulation

Little information is available concerning possible hydrocarbon migration pathways within strata that occupy Whitehorse Trough. No observations of pore-filling bitumen have been recorded. Therefore, migration pathways are inferred on the basis of unproven conceptual hydrocarbon exploration plays (*see* Exploration Plays).

Exploration Plays

Exploration plays in the Selwyn-Cordilleran Region would only be viable in areas where upper Paleozoic to Cenozoic strata are of sufficient thickness and lateral continuity to provide a seal for potential reservoirs in lower Paleozoic to Mesozoic strata. However, the organic maturity of most potential reservoirs exceeds the limits for the preservation of hydrocarbons. In addition, potential reservoirs commonly lie within the zone of modern day fresh groundwater recharge, so that any hydrocarbons generated may have been flushed from these rocks or biodegraded.

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

1. Gas in leached porosity and interfragment porosity in breccia in Cache Creek limestone in unconformity pinch outs sealed by unconformably overlying Lewes River Group strata (Fig. 19),
2. Gas in stratigraphically controlled, primary porosity in reefal carbonate mounds within the Triassic Hancock Member of the Aksala Formation. Mandanna Member siliciclastic rocks provide the surrounding and overlying seal for these Reef mounds (Fig. 19),
3. Oil and gas in stratigraphically controlled, up-dip pinch outs of primary and secondary porosity within conglomeratic sandstone of the Jurassic “Conglomerate Formation” enhanced by structural development of local anticlines and faults. Intertonguing shale of the coeval Richtofen Formation (Fig. 19) may act as a reservoir seal for this possible play,
4. Stratigraphically controlled, up-dip pinch outs of primary and secondary porosity within conglomeratic sandstone of the Jurassic “Conglomerate Formation” interfingered with less permeable volcanic rocks of the Nordenskiold Formation that could act as reservoir seals (Fig. 19),
5. Structural closures of oil and gas trapped in primary porosity in fluvial conglomeratic sandstone bodies within the Jurassic Tanglefoot Formation,
6. Stratigraphic up-dip and lateral facies pinch outs and structural closures of oil and gas trapped in primary porosity in fluvial conglomeratic sandstone bodies within less permeable fine grained siliciclastic rocks in the Jurassic/Cretaceous Tantalus Formation, and
7. Stratigraphic up-dip and lateral facies pinch outs and structural closures of oil and gas trapped in primary porosity in coarse sand bodies encased within less permeable, finer grained Cenozoic strata.

Reserve Estimates

No hydrocarbon resources are reported for the Selwyn-Cordilleran Region.

Hydrocarbon Potential

A recent petroleum assessment indicates mean amounts of recoverable oil of $1.29x10^6 m^3$ (8.12 MMbl) and marketable gas of $5.55x10^9 m^3$ (196 billion cubic feet) for Whitehorse Trough (NEB, 2001).

MINERAL EXPLORATION AND DEVELOPMENT IN THE NORTHERN CANADIAN MAINLAND SEDIMENTARY BASIN AND THE ADJACENT CANADIAN SHIELD AND CANADIAN CORDILLERA

Introduction

Mineral exploration and development is inextricably linked with the development of the Canadian mainland north of 60° north latitude (www.nrcan.gc.ca/mms/hm_e.htm). The rush to the fabulous placer gold fields of the Klondike near Dawson in the Yukon at the end of the nineteenth century in 1897 (Minter 1988) ushered in the twentieth century era of mineral exploration and mine development in the north. The focus of mine development shifted many times in the northern mainland as commodities, such as precious and base metals, underwent cyclical price changes, or as economic reserves were depleted in individual mines. The history of the last decade is very typical of this shifting focus for commodities that were, or are, actively mined (Fig. 20). Many famous gold and silver mines, such as the Con and Giant mines at Yellowknife and the Lupin Mine north of Yellowknife (Fig. 6), closed during the post-1994 decade (Fig. 20) due to low precious metal prices, as well as due to the depletion of ore reserves. This is true also for base metal mines, which have led to the closure in the last decade of famous mines, such as the Faro District mines in the Yukon, not to mention the well known Polaris and Nanisivik mines of the Arctic Islands (Fig. 20). The middle of the last decade, however, has seen the origin and spectacular growth of a diamond mining industry in the NWT with revenues that have far eclipsed anything seen previously in the northern mainland (Fig. 20).

As discussed previously, mine developments have led to large investments in, and incremental increases in northern infrastructure in the form of roads, railways and power generation facilities and transmission grids. Such developments have aided development of successions of mineable commodities near these infrastructure networks. The development of diamond mining in the NWT beginning in 1998 is an example where a winter road from Yellowknife to Contwoyto Lake (Fig. 3), previously built to service the Lupin gold mine (Fig. 6), now services the diamond mines at Lac de Gras.

The history of mining and related mineral exploration in the northern mainland west of 110° longitude is discussed in (www.nwtgeoscience.ca/normin/) for the NWT and at (www.geology.gov.yk.ca/minfile/; Deklerk and Traynor, 2005) for the Yukon.

It is beyond the scope of this report to discuss the socio-economic impact of mineral exploration and mining on the northern mainland and northern communities. Certainly, mining has provided both short-term and long-term employment to nearby communities and have, of course provided considerable economic benefits to these communities during periods of mining production. The world famous Pine Point Mine on the south shore of Great Slave Lake is typical in this regard. This mine produced and shipped 10,785,000 tons (9,783,936 tonnes or metric tons) of lead and zinc concentrates/high-grade ores after mining and milling 69,416,000 tons (62972807 tonnes) of ore material during its production life from 1965 to 1988 (en.wikipedia.org/wiki/Pine_Point_Mine). A northern railway link to southern Canada, originally as part of the Canadian National Railway system was built from Alberta to the Pine Point minesite to haul this ore to smelters in southern Canada. Subsequent to mine closure, the part of the rail link between the town of Hay River, NWT and Pine Point was closed. However, the remainder of this railway, now owned and operated by RailAmerica, and now called the Mackenzie Northern Railway, still operates between the community of Smith, Alberta and Hay River (en.wikipedia.org/wiki/Mackenzie_Northern_Railway). This rail link with southern Canada is an invaluable piece of infrastructure, and commodities, such as agriculture and forest products from northeastern Alberta and the southern Northwest Territories, as well as fuel and supplies destined for Arctic communities are barged across Great Slave Lake to Yellowknife and to many communities along the Mackenzie River to the Beaufort Sea. This is just one example of long term benefits to northern communities of infrastructure put in place originally to service mine development and production.

The reader should be aware, however, that there are spectacular examples of the harmful effects of mining operations on northern communities. Foremost among these is, arguably, the Eldorado Mine (Fig. 6) at the former community of Port Radium on Great Bear Lake. In 1999 the Canadian Government signed a commitment with the Deline Dene Band to have the estimated 1.7 million tonnes of radioactive mine tailings in Port Radium cleaned up (en.wikipedia.org/wiki/Eldorado_Mine). Also, there may be a long-term liability issue with respect to aboriginal miners at Eldorado Mine who have since died from radiation-induced cancers (www.ccnr.org/deline_deaths.html).

Intermediate adverse societal impacts have also been associated with base and precious metal mining and reclamation. For example, the Giant Mine Remediation Project (GMRP; nwt-tno.inac-ainc.gc.ca/giant/index_e.html) sponsored by the Department of Indian and Northern Affairs, is devoted to the creation of a long-term remediation plan for the 237,000 tonnes of toxic arsenic trioxide stored underground at the site, as well as ensuring that the entire site is managed safely to protect northerners and the environment. Thus, although the gold produced and mining operations at the Yellowknife Giant Mine during its 50 year life had a tremendously beneficial economic impact, there were environmentally adverse impacts that have only recently been fully appreciated.

A new realization has made itself felt across the northern mainland, as well as elsewhere, that mining activities must be performed in an environmentally responsible and societally acceptable manner in order to be considered sustainable resource development. This new realization has led to new protocols and regulations for mining activities in the north, which include consideration of environmental and societal impacts, as well as aboriginal issues. To this end, a new policy, “The Mine Site Reclamation Policy for the Northwest Territories” was released by the Department of Indian Affairs and Northern Development in 2002 (www.ainc-inac.gc.ca/ps/nap/recpolnwt/index_e.html). Mine development and reclamation policies in Nunavut are handled mainly through the Nunavut Environmental Impact Review Board in conjunction with federal regulations and Mine Site Reclamation Policies are in the process of being developed for Nunavut in conjunction with those under development for the NWT (www.ainc-inac.gc.ca/nr/prs/m-a2002/02176bk_e.html). At this time, the Yukon Government is designing a new mine reclamation and closure policy (www.emr.gov.yk.ca/mining/info/mine_reclamation_policy.htm).

Mining in the Yukon

Introduction

Much of the following narrative is adapted from the official government of the Yukon webpage concerning the history of Yukon mining (emr.gov.yk.ca/mining/info/mining_history.html).

Mining in the Yukon has a long history, dating back at least to aboriginal peoples who are known to have mined native copper nuggets in the White River area for trading and to fashion arrowheads. Mining became the cornerstone of the Yukon economy after the famous Klondike gold rush of 1896-1898, and continues to the present day. Prospecting for placer gold by settlers began soon after the first reported discovery in 1850 at Fortymile Creek near its confluence with the Yukon River northwest of Dawson (Fig. 6; Gordey and Makepiece, 2003). Since that time, the Yukon has intermittently been a major contributor to the production of precious and base metals in Canada (Fig. 6). The total recorded fine placer gold production from 1885 to date is about 12.5 million ounces (388793.54 kilograms). In the post-1992 years, there has been a decline in Yukon mineral production (http://www.gov.yk.ca/depts/eco/stats/annual/review03.pdf).

All historical and present-day mining activity in the Yukon has been in the Selwyn-Cordillera Region (Fig. 6). Areas of mining (Figs. 6, 9) and petroleum activity (Figs. 4, 5, 7, 9) are almost entirely mutually exclusive in the Yukon, reflecting the very different geological parameters that produce concentrations of metallic and nonmetallic minerals as compared to petroleum.

Precious Metal Mines

Placer gold discovered in the Klondike district near Dawson in 1896 initiated the world's largest 'gold rush', and placer mining was the main contributor to the Yukon economy from that time until the early 1920s. Placer mining was more active from the 1940s to the 1960s, and from 1974 to the present. The cumulative production of fine gold from 1885 to the present day is estimated to be 389,000 kilograms (12.5 million ounces; emr.gov.yk.ca/mining/info/mining_history.html).

High-grade silver-lead veins were first discovered in the Keno Hill area in 1906 (Fig. 6; Gordey and Makepiece, 2003;). The first mill was constructed in 1925, with intermittent development and production until 1941. The mines were reactivated in 1945 and continued until production was suspended in January 1989 due to low silver prices. Total production from 1921 to 1988 is estimated to be 6,769 tonnes of silver, 273,622 tonnes of lead, 153,198 tonnes of zinc and 1,800 tonnes of cadmium from 4.9 million tonnes of ore, with production from 16 underground mines and several open pits. These mines are now closed (e.g. United Keno Hill in Table 3).

Other smaller precious metal mines have operated for short periods in the Yukon. High-grade gold-silver veins at the Venus mine south of Carcross had small production from 1910-11, in 1925, in 1969-70 and again in 1980-81.

Electrum-bearing quartz-carbonate epithermal veins were mined at the Skukum gold mine (Table 3) west of Carcross, which operated at about 300 tonnes per day from 1986 to 1988 when ore reserves were depleted. The Ketza River gold mine, southwest of Ross River, operated at about 350 tonnes per day from 1988 to 1991.

High-grade lead-zinc-silver skarn mineralization was first reported at Mount Hundere (Fig. 6; Gordey and Makepiece, 2003; Table 3) in 1962. The Mount Hundere joint venture group purchased the property early in 1989, and immediately began an intensive exploration and development program, with mining and milling commencing at about 1,200 tonnes per day in 1991 at the Se Dena Hes mine. Production was suspended at the end of 1992 due to low metal prices. In 1993 the property was sold to a consortium (Teck, Cominco, Korea Zinc and Samsung) and has remained on care and maintenance status.

Small-scale mining and milling of high-grade gold-silver veins was conducted at several properties in the Mount Nansen area (Fig. 6; Gordey and Makepiece, 2003; Table 3) from 1945 to 1947, from 1966 to 1969, and again in 1975-76. During 1996, the property was developed for production, including rehabilitation and expansion of the existing mill and construction of a new tailings dam. Gold production commenced in 1996, with mineable reserves estimated at 386,337 tonnes at 5.17 grams per tonne gold and 75.09 grams per tonne silver. Production continued in 1998, but the mine closed in 1999 (Fig. 20).

The Brewery Creek gold property (Figs. 6, 20; Table 3) was discovered in 1987 by Noranda. Between 1988 and 1993, the property was extensively explored. Subsequently, the property was developed the property for production as an open pit, heap-leaching operation and the first bar of gold was poured in 1996. Seasonal mining continued until 2000, and heap leaching until 2002, at which time production ceased and remediation started (www.emr.gov.yk.ca/./mining/info/brewery_creek.pdf).

Base Metal and Non-Metallic Mines

Skarn copper mineralization of the Whitehorse Copper Belt (Dobrowolsky and Ingram (1993); www.geology.gov.yk.ca/publications/openfile/1993/of1993_1(i).pdf) was first discovered in the Whitehorse area in 1897; shipments of high-grade ore prior to 1930 totalled 153,000 tonnes. Following extensive exploration in the 1950s and 60s, a 1,800 tonnes per day mill was constructed in 1966 and open-pit mining followed. Underground mining commenced in 1972 and milling continued at 2,000 to 2,400 tonnes per day until economic ore reserves were depleted in 1982. Total production from 1967 to 1982 is estimated at 123,000 tonnes of copper, 90 tonnes of silver and 7 tonnes of gold from 10.3 million tonnes of ore. The tailings pond is a potential source of magnetite for use as a heavy medium in coal preparation plants.

Massive sulphide zinc-lead-silver mineralization was first discovered near Vangorda Creek (Fig. 6; Gordey and Makepiece, 2003; Table 3) in the Anvil Range in 1953. The huge Faro ore body was discovered in 1965, and mine production commenced in 1970 at 6,000 tonnes per day (Table 3). Cyprus Anvil Mining Corp. operated the mine at rates of up to 11,000 tonnes per day until 1982 when production was suspended due to low metal prices. In 1985 Curragh Inc. reactivated the mine and produced at rates of up to 14,000 tonnes per day until the Faro pit and the smaller Vangorda pit were depleted in 1992. In 1995 the mine was reactivated by Anvil Range Mining Corp. Production was suspended in January 1998.

From 1972 to 1973 underground mining and milling of 540 tonnes per day of high-grade massive sulphide ore took place at the Wellgreen nickel-copper deposit, at which time operations were suspended due to poor ground conditions and low nickel prices (Table 3). Since then the property has been re-evaluated as a potential, large tonnage, low-grade, open-pit mine.

Chrysotile asbestos was first noted in the Fortymile area in 1887 with development work undertaken in the 1950s. The Clinton Creek mine (Fig 9; Table 4) operated from 1967 to 1978, during which period over 63 million tonnes of waste rock and 16 million tonnes of ore were mined from four open pits to produce 940,000 tonnes of cement-grade asbestos fibre.

Coal was produced at the Tantalus Mine (Table 4) at the north end of Whitehorse Trough with about 2722 tonnes mined in 1905, more than 4536 tonnes annually in 1907-09, and at reduced rate until 1922. Adits are now caved and are burning underground. More recently, coal was produced at the Tantalus Butte Mine (Table 4) immediately north of the Tantalus Mine (Fig. 8). Production averaged 454 tonnes/year from 1923-38. It was reopened 1948, producing 118,000 tonnes in the period from 1948-67, and 137,000 tonnes from 1969-76. Fire in 1978 required sealing of the underground workings, but a further 74,000 tonnes was mined on surface from 1978-81.

Mining in the Northwest Territories and Nunavut

Introduction

Much of the following narrative is adapted from the official NWT government webpage concerning the history mining in the Northwest Territories, which has also had a long history (Beales et al., 2002; www.iti.gov.nt.ca/mog/minerals/mins_history.htm). As in the Yukon, it is interesting to note that areas of mining (Figs. 6, 9) and petroleum activity (Figs. 4, 5, 7, 9) in the combined area of the Northwest Territories and Nunavut are, as in the Yukon, almost entirely mutually exclusive with little overlap.

The economy of the NWT is inextricably linked to mining. Base and precious metals were, until recently, the mainstay of the NWT mining industry. However, in recent years the focus has shifted to diamond mining and production of oil and gas. The major mining centres in the NWT and Nunavut within the report area west of 110° longitude are at Yellowknife and Contwoyto Lake. The first major gold discovery in the NWT in 1935 on the west side of Yellowknife Bay heralded over 50 years of precious metal and base metal mining, but with the recent decline of all metal mining, mining activity in the NWT has shifted to the diamond industry with a growing number of diamond mines, such as the Ekati and Diavik mines.

Precious Metal Mines

Introduction

In 1898, B.A. Blakeney, a prospector on his way to the Klondike in the Yukon, staked the first claim in the Yellowknife area (www.iti.gov.nt.ca/mog/minerals/mins_history.htm). Samples assayed at 2,158 ounces per ton (74 kilograms per tonne) gold. In 1905, J. Mackintosh Bell of the GSC conducted the first mineral survey of the north shore of Great Slave Lake. His work indicated that the area was favourable for gold mineralization. In July 1929, Stan McMillan flew Donavan Clark and his party (Dominion Explorers) into the east shore of Yellowknife Bay and they prospected over the site of the future Con Mine (Fig. 6; Table 3). In 1933 two prospectors, Johnny Baker and Herb Dixon, discovered free gold at Quyta Lake. In 1934, Baker found more gold on the east side of Yellowknife Bay. Burwash Yellowknife Gold Mines Ltd was formed and in 1935, some 15 tons (13.6 tonnes) of ore grading around 12 ounces per ton (411.4 grams per tonne) gold was shipped from the Burwash mine south to Fort McMurray, then by rail to Trail, B.C. for refining. This was the first shipment of gold from the Yellowknife area. Burwash Mine was short lived. It produced only 87 ounces (2.706 kilograms) of gold and closed in 1937.

Con Mine

In 1935, a Cominco field party staked the NERCO property following the discovery of gold by N. Jennejohn of the Geological Society of Canada (www.iti.gov.nt.ca/mog/minerals/mins_history.htm). The C-1 Shaft was sunk on Vein-10, a small high-grade quartz vein in the hanging wall of the Con Shear and a 90 tonne per day mill was built. The mill was expanded to 136 tonnes per day and by 1940 gold was being mined from the Con Shear itself.

In 1946, a wide shear zone, the Campbell Shear, was discovered and by 1958, all the gold produced at Con Mine (Fig. 6) was from the Campbell Shear.

In 1974, the Robertson Shaft was sunk to 1,890 metres depth to access the lower levels of the mine. By 1990, the main production shaft extended to a depth of 1,902 metres with 129 kilometres of underground workings.

Milling capacity was 1,043 tonnes per day. In 1998, the Con Mine was closed due to a labour dispute, but operations resumed in July 1999. The Con Mine began processing ore from Giant Mine in 2000 but closed again in 2003. Con Mine has produced over 5 million troy ounces (160,000 kilograms) of gold during its production history.

Giant Mine

Prospectors C.J. Baker and H. Muir on behalf of Burwash Yellowknife Mines Ltd first staked the Giant Mine (Fig. 6; Table 3) property in 1935 (www.iti.gov.nt.ca/mog/minerals/mins_history.htm). Yellowknife Gold Mines Limited was incorporated in 1937 and shortly thereafter acquired the Giant Claims. In 1938, D.W. Cameron discovered a gold bearing schist outcrop at the south end of the mine property now known as the DWC zone. An exploration program conducted from 1944 to 1946 resulted in the location of the subsurface extensions of the zones previously mapped on surface. Development began in 1946 with the sinking of a number of shafts.

During the first 15 years of the mine's life, extensive exploration programs were carried out. The last major new ore zone to be discovered on the Giant mine property (the LAW) was discovered in 1962. By 1964, the Giant orebody was considered to have been totally delineated.

In November of 1985, Giant Mine poured its 10,000th gold brick. In 1995, production began from the Supercrest area adjacent to Giant Mine. The Supercrest added approximately seven to eight years mine-life to Giant. In April 1999, the mine owner up until that time, Royal Oak Mines Inc., went into receivership. Miramar Mining Corp., which operated the Con Mine, acquired Giant Mine in December 1999. The mine was closed in 2004, but over its more than 50 year production history it has produced over 7 million troy ounces (220,000 kilograms) of gold.

Tundra and Salmita Mines

"Canada's most northerly gold mine" is what the Tundra Gold Mine (Fig. 6; Table 3) was called when it went into production in 1964 (www.iti.gov.nt.ca/mog/minerals/mins_history.htm). It was located 200 km northeast of Yellowknife. By the time the mine closed in 1968, the mill had processed approximately 185,000 tons (168,000 tonnes) of ore grading 0.54 ounces per ton (18.5 grams per tonne) of gold. Some 104,000 ounces (3234.76 kilograms) of gold was recovered.

In the 1983, Giant Yellowknife Mines opened the Salmita mine (Fig. 6; Table 3) on Mathews Lake, near the old Tundra Mine. The mine produced approximately 175,000 ounces (5443.11 kilograms) of gold and 12,000 ounces (373.24 kilograms) of silver over four years before closing.

Colomac Mine

The presence of gold in the Indin Lake area 220 km northwest of Yellowknife was known since 1938. However, the area was not fully explored until 1945, when Giant Yellowknife Mines discovered gold mineralization as a result of diamond drilling (www.iti.gov.nt.ca/mog/minerals/mins_history.htm). Further exploration during 1946 led to the discovery of an extensive zone of low-grade gold mineralization. The property was not placed into production at that time, as low gold prices did not make operations economically feasible. In 1974, Cominco conducted an exploratory drilling program at the site. Neptune Resources Corporation obtained an option on the property from Johnsby Mines Ltd in 1986 and exercised this option in 1988. Neptune conducted extensive feasibility studies during 1988, and planned development of the site in 1989.

Production began at Colomac (Fig. 6; Table 3) in 1990 but operations were suspended in 1991 In 1993, Royal Oak Mines Inc acquired the Colomac Mine, and resumed production of the Colomac site in 1994. After depletion of reserves the mine was closed in 1997.

Discovery Mine

A.V. Giauque and sons first staked the Discovery property (www.iti.gov.nt.ca/mog/minerals/mins_history.htm) in 1944. Discovery Yellowknife Mines was formed in 1945, to explore the property. After extensive exploration in 1946, a shaft was sunk and in late 1949 a 90 tonne per day mill was installed. Discovery Mine (Fig. 6; Table 3) operated between 1950 and 1969 but was closed from 1969 to 1980.

In 1980, Newmont Exploration Ltd. optioned the property. Since that time the property has had a succession of owners and extensive ground geophysics, mapping and geochemical studies along with extensive drilling programs (www.tyhee.com/discovery.html). Past production of gold from the Discovery Mine was 1023575 ounces (3843.613 kilograms).

Other Mines in the Yellowknife Area

Ptarmigan Mine (Fig. 6; Table 3), located 19 kilometres north of Yellowknife, began operations in 1941 but closed shortly after. Operations resumed at Ptarmigan in 1987 and continued sporadically up until 1997. The Norma claims, located 75 kilometres east of Yellowknife, were staked in the summer of 1939. In 1945 Beaulieu Yellowknife Mines Ltd was formed to explore the Norma property and the Beaulieu mine (Fig. 6) began operating in October 23, 1947. However, it closed down a month later after 7.5 ounces (233 grams) of gold had been recovered (Beales et al., 2002).

Echo Bay Mines

The Echo Bay claims (www.iti.gov.nt.ca/mog/minerals/mins_history.htm) east of Port Radium were staked in 1930 by Consolidated Mining and Smelting Company of Canada. Some diamond drilling was done in 1932 and two parallel adits were developed in 1934. In 1963, Northwest Explorers optioned the property and drilled eleven holes. Echo Bay Mines (Fig. 6; Table 3) was subsequently incorporated and acquired a mining lease. Production of silver and copper began in 1964. The ore was milled initially using the infrastructure from the old Eldorado Mine, 1.6 kilometres to the southwest. 1972, the mine had six levels and the mill was operating at 90 tonnes per day. During 1971 and 1972 the average ore grade was 2,331 grams per tonne Ag and 0.92% Cu. In 1974, Echo Bay Mines Ltd. reached an agreement with Eldorado Mining and Smelting to exploit the silver ore from the Eldorado Mine (Fig. 6). Eldorado was subsequently re-opened as a silver mine in 1976 and operated by Echo Bay Mines until 1982.

The Echo Bay Mine produced 383,409 tonnes of ore from which 792,888 kilograms of silver and 4,935 tonnes of copper were recovered. The last reported production from the mine was in 1981.

Lupin Mine

The Lupin Gold Mine opened in 1982 on the west shore of Contwoyto Lake in the Northwest Territories, in an area that was subsequently incorporated into the new territory of Nunavut Territory in 1999 (Fig. 6; Table 3; http://www.kinross.com/news/130803-1.pdf). The deposit, hosted in banded iron formation, was discovered in 1960. On commencing production in 1982, the mine pioneered the use of aircraft support for the rotation of employees, transport of perishables and shipment of ore, as well as the transport of other freight over a winter road. This infrastructure was used during the later development of the diamond mines in the Northwest Territories. With the exception of a period of suspension from 1998 to 2000, due to low gold prices, the Lupin mine has operated from 1982-2004 and produced approximately three million ounces (93,310.450 kilograms) of gold, representing a significant contribution to the economy of northern Canada. The mine ceased production briefly in August 2003, but was re-started in early 2004 to recover stope pillars with a reduced crew.

Base Metal and Non-Metallic Mines

Pine Point Mine

Surface showings of lead-zinc mineralization (www.iti.gov.nt.ca/mog/minerals/mins_history.htm) along the south shore of Great Slave Lake were first brought to the attention of Klondike-bound prospectors by local Aboriginal peoples in 1889. Bell (1902) visited the showings in 1889 and Cameron (1917) provided the first description of the dolomitized host rock of this huge Mississippi Valley-type of carbonate-hosted lead-zinc deposit.

In 1929, Northern Lead Zinc Company, formed by Cominco Ltd. and Ventures Ltd. (predecessor to Falconbridge), began to explore the area on the south shore of Great Slave Lake for base metals. In 1951 Pine Point Mines Ltd was formed to further explore the area (Cominco held a 50% interest in Pine Point Mines Ltd). By 1958, Cominco had delineated Canada's richest known lead/zinc deposit. The Canadian Government built a railway (Fig. 3) from Roma, Alberta to Pine Point starting in 1962 and the town of Pine Point was built between 1963 and 1965.

Production from the Pine Point Mine (Fig. 6; Table 3) began in 1964, with the first rail shipment of concentrates taking place after the completion of the railway in early 1965. Pine Point operated until June 1987. Some 3,810,176 tonnes of zinc and 1,179,340 tonnes of lead were produced from 62.6 million tonnes of ore over the mine life. The town was officially closed on September 1, 1987. The site has since been reclaimed. The value of Pine Point ore milled during the final year of large-scale production in 1987 was almost $500 million and represented half of all mineral production in the Northwest Territories during 1987 (Ellis and Hearn, 1990).

Prairie Creek Deposit

The Prairie Creek Deposit (Fig. 6; (www.canadianzinc.com/welcome/index.shtml#2)), although never in production, is an important deposit, which advanced to the point of having considerable infrastraucture installed. Shear zone-hosted zinc, lead and silver mineralization was discovered in 1928 at Prairie Creek on the South Nahanni River in the Mackenzie Mountains, 170 km west of Fort Simpson. Very little exploration was done on the property until 1966 when Cadillac Explorations Ltd. commenced investigating the mineralized zones. Drilling was carried out in 1968 and 1969. From 1970 to 1980, extensive underground exploration was carried out.

In 1980, the Hunt brothers agreed to finance the property into production. A copper concentrator was purchased and brought to the site, and mining and milling facilities were constructed. In May 1982, when the mine facility was nearly complete, the price of silver collapsed and Cadillac Explorations was forced into bankruptcy. A total of $64,000,000 had been spent on the property up to that point.

During 1992, the new operator, San Andreas Resources, discovered stratiform-style lead-zinc mineralization, which opened up the possibility of multiple exploration targets within the deposit. In 1992 and 1993, additional drilling took place and baseline environmental studies were initiated. During 1995, additional step-out holes extended the strike length of the known mineralized zones to 2.1 km. The orebody remains open at depth and along strike.

In 1996, San Andreas Resources negotiated an Impact Benefits Agreement (IBA) with the Nahanni Butte Dene Band. This was followed with a program of mine rehabilitation, re-sampling and resource estimation. In 1999, San Andreas Resources Corporation became "Canadian Zinc Corporation". In 2004, Canadian Zinc Corp. began a 27 hole, 6000 metre drilling program to further delineate the extent, continuity and potential ore grade in the Prairie Creek Deposit.

CanTung Mine

Axel Berglund discovered and staked the CanTung deposit for Northwestern Explorations Ltd. in 1954 as a copper prospect (www.iti.gov.nt.ca/mog/minerals/mins_history.htm). The property, located 360 km west of Fort Simpson near the Yukon border, was mapped and sampled in 1955 and drilled by Kennecott Copper in 1956. It was found to be subeconomic in respect of copper and the claims were allowed to lapse.

Prospectors working for the "Mackenzie Syndicate" (Leitch, Highland Belt, Area Exploration Ltd., Dome Minerals Ltd., Ventures Ltd. and Lake Expanse Gold Minerals Ltd.) discovered scheelite while panning in the Flat River in the late 1950s. In 1958, the Mackenzie Syndicate re-staked the property. The Canada Tungsten Mining Corporation Ltd (CanTung) was formed in 1959 to acquire and develop the property. CanTung drilled 11 holes in 1959 and 41 holes in 1960. Ore reserves of 1.08 million tonnes grading 2.47% WO_3 and 0.45% Cu were defined. Production commenced in 1962. The Pit Zone was mined by open pit, and then subsequently by underground mining. Production from the pit continued until September 1973 with only short interruptions due to low tungsten prices. Milling of underground ore from E Zone began in June 1974.

In 1979, production was increased to approximately 900 tonnes per day following a mill expansion. Production was halted by a strike from November 1980 to May 1981, and for most of 1983 due to low tungsten prices. In August of 1986 operations were suspended indefinitely due to low tungsten prices.

Falconbridge sold its interest in the CanTung mine (Fig. 6; Table 3) in 1966, followed by Dome in 1985. Also in 1985, Amax transferred all tungsten assets, including CanTung and the MacTung project at Macmillan Pass, to Canada Tungsten Inc. but retained majority control. Aur Resources Inc. optioned the property in 1995.

Canada Tungsten and Aur Resources merged in 1996. In 1997, North American Tungsten Corporation Ltd. purchased CanTung, together with the related assets of the former Canada Tungsten, from Aur

Resources. The company re-opened the CanTung mine on December 1, 2001. The mine shut down in December of 2003 and subsequently resumed production in September of 2005 (north.cbc.ca/regional/servlet/View?filename=tungsten-mine-19102005).

MacTung Deposit

J. F. Allen first discovered scheelite showings at the MacTung site (Fig. 6) in 1962, while exploring for molybdenum (www.iti.gov.nt.ca/mog/minerals/mins_history.htm). Southwest Potash Corp., a subsidiary of American Metal Climax Inc. (Amax), staked the area. Geological studies, prospecting and a ground magnetic survey were completed in 1962-63.

Between 1968 and 1973, 10,600m of diamond drilling were completed. In 1983, a preliminary project description and baseline environmental report was released to government. Because of the location of the MacTung orebody on the NWT/Yukon border, the report was released to the federal Department of Indian and Northern Development (DIAND) and both territorial governments.

A 900 tonne pre day open pit and underground mining facility was proposed, with production to begin in 1986. Concentrate would be trucked out along the North Canol Road to Ross River, Yukon Territory, and on to the port at Skagway, Alaska. However, a dramatic drop in tungsten prices caused Amax to shelve these plans.

North American Tungsten Corporation has an ongoing exploration program which, in 2005, included 25 surface diamond drill holes (www.northamericantungsten.com/index.shtml).

Eldorado Mine

In a 1900 expedition to Great Bear Lake, J.M. Bell and Charles Camsell of the Geological Survey of Canada (www.iti.gov.nt.ca/mog/minerals/mins_history.htm) observed “greenstones with numerous interrupted stringers of calcite containing chalcopyrite and the steep rocky shores where they present themselves to the lake are often stained with cobalt bloom and copper”. In 1929 Gilbert Labine followed up on Bell's notes and flew to the east shore of Great Bear Lake to stake the first four claims of what would become the Eldorado uranium mine.

By 1932, the town of Great Bear, later renamed Port Radium, consisted of the partially constructed Eldorado mine, a sawmill, electric power plant, general store, post office, two radio stations, an RCMP post and a mining recorder’s office. The town’s population stood at 200. By the end of 1932, between 2,500 and 3,000 claims were recorded in the area.

Eldorado mines (Fig. 9; Table 4), the first modern mining operation in the NWT, began production in December 1933. The mine initially produced radium and uranium, and subsequently silver (see Echo Bay Mine). The mill operated at a capacity of 50 tonnes per day up until 1940 after which throughput was increased to 125 tonnes per day. The mine became a crown company in 1944. In 1950, the mill capacity was increased to170 tonnes per day. A fire halted production in 1951. However, the mill was re-built in 1952 with the capacity increased to 300 tonnes per day. With the development of other uranium sources in Canada, the mine was no longer profitable and was closed in September 1960.

As discussed previously, there are significant environmental concerns with the estimated 1.7 million tonnes of radioactive mine tailings stored at Port Radium, the former Eldorado mine townsite.

Diamond Mines

Introduction

Small-scale diamond exploration programs conducted in the Northwest Territories in the early 1970s led to the discovery of subeconomic kimberlite pipes on Somerset Island by Cominco Ltd. and Diapros Ltd. (www.iti.gov.nt.ca/mog/minerals/mins_history.htm). The first major find occurred in 1991, when Dia Met Minerals Ltd. and BHP Minerals announced diamondiferour kimberlite pipes at Lac de Gras in the NWT near the eastern margin of the MacKenzie Atlas area. This discovery resulted in the largest staking rush in Canadian history. Since then, several of the world's largest mining companies, including BHP, RTZ and De Beers, have become actively involved in diamond exploration and mining in the NWT.

To date, more than 300 kimberlite pipes have been found in the NWT, including over 20 diamondiferous kimberlites with economic potential. .

BHP-Billiton's Ekati Mine

From 1982 to 1990, geologist Charles Fipke, and the company he founded, Dia Met Minerals, traced kimberlite indicator minerals from the Mackenzie Mountains back to their source in the Lac De Gras area (www.iti.gov.nt.ca/mog/minerals/mins_history.htm). In 1991, BHP Minerals entered into a joint venture with Dia Met Minerals when diamonds were discovered in the vicinity of Lac De Gras at a small lake, subsequently named, Point Lake. The Point Lake kimberlite pipe was the first of over 100 pipes discovered on the Ekati property.

During 1992 the Koala pipe was discovered on the property. Between June 1993 and May 1994, 11,512 line-km of airborne geophysics was flown and over 4000 heavy mineral samples were analysed. Eight holes totalling 2,151 metres were drilled, seven of which intersected kimberlite. Between 1994 and 1995, another 2000 heavy mineral samples were analysed and 28 holes were drilled. In the following year at least 23 diamond drill holes totalling 5,039 metres were drilled, heavy mineral sampling continued and detailed ground geophysics was completed over grids. Bulk sampling of the Koala, Fox, and Panda pipes took place, from 1993 to 1995. During this period BHP Diamonds initiated prefeasibility studies, and an environmental review was undertaken of the proposed mining project. In 1997, BHP and Dia Met received final regulatory approval for a mine with processing facilities. The Ekati mine (Fig. 6; Table 4) was opened on October 14, 1998.

Some 121 kimberlite pipes have been identified on the property, and 20 of these have been bulk sampled. Of the 20 pipes, eight are in the current mine plan. In excess of 70 million tonnes of ore, and approximately 508 million tonnes of waste rock, are scheduled to be mined over the life of the project. Ore grades are in the order of one carat per tonne. Seven of the eight pipes in the mine plan will initially be mined open pit. The Panda and Koala pipes will subsequently be exploited via underground methods because of the higher value of their ore. The Koala North pipe will be exploited by underground methods only.

The ore is currently being processed at a rate of 12,500 tonnes per day, but it is planned to increase this to 18,000 tonnes from 2007 onwards. The mine life is currently pegged at 17 years.

The Ekati Mine (Fig. 6; Table 4) produces around 4 million carats of predominantly gem and industrial quality diamonds a year, about four per cent of current global production by weight, and six per cent by value. Over 20 million carats had been produced from the mine by the end of 2003.

Diavik Mine

During the latter part of 1991 and early 1992, Aber Resources Ltd. (now Aber Diamond Corp.) staked mineral claims in and around the project area (www.iti.gov.nt.ca/mog/minerals/mins_history.htm). In June 1992, Aber Resources completed a joint venture agreement with Kennecott Canada Exploration to further explore the property. Between April 1992 and January 1994, 20,500 line-km of airborne geophysics was flown, 1,700 heavy mineral samples were taken. Ground geophysics tested airborne anomalies and 65 diamond drillholes totalling 6,630m were completed. Twenty-five kimberlites were discovered.

During 1994, three diamondiferous pipes (A21, A154 South, and A154 North pipes) were sampled In 1995, a fourth diamond-bearing kimberlite pipe A418 was discovered. During the summer of 1996, a bulk sample of 6,000 tonnes of kimberlite was taken from A418 and A154 South pipes, yielding 21,000 carats of diamonds. Based on these results, the decision to commence the permitting process for mine development was made.

In 1996, Diavik Diamond Mines Inc. (a wholly owned subsidiary of Rio Tinto plc, which also owns Kennecott Canada Inc.) was created to develop and manage the Diavik Diamonds Project. Permitting and licensing approvals were obtained from the federal government in late 1999 for the Diavik diamond mine. Construction of the mine, completed in January of 2003, cost $1.25 billion. During the 2001 winter road season, 4,089 truckloads of fuel, construction materials and equipment were hauled to the project site.

Diavik Mine (Fig. 6; Table 4) commenced production in January 2003. Reserves are estimated at 25.6 million tonnes grading at 4.15 carats per tonne making the deposit one of the richest in the world. A 20-year mine life is envisaged with diamond production averaging 5.4 million carats per year. In 2003 diamond production was 3.8 million carats.

Other Diamond Projects (Snap Lake, Kennady Lake, Jericho)

Antler Resources Ltd. first staked the Snap Lake Property in 1991. In 1992 a joint venture agreement between Winspear Resources Ltd, Antler Resources Ltd and Aber Resources Ltd was struck to explore the property. By the summer of 1993, kimberlite indicator minerals had been identified at several areas on the property, leading the partners to conclude a kimberlite body lay under Snap Lake. A double-lobed kimberlite pipe was discovered on the property in 1995 and a gently dipping relatively thick kimberlite dyke was also found. In January 1997 Antler Resources amalgamated with Winspear Resources to take full advantage of this discovery.

A decision was made by the joint venture to proceed with bulk sampling of the dyke. During the 1998, a 200 tonne sample was taken. Results from this sample were favourable and a decision was made to commence with the extraction of a 20,000 tonne sample. A three-year, 20,000-tonne bulk sample program was planned and sampling commenced in 1999.

In 2000, De Beers Canada Corp. purchased Winspear. Prior to the successful take-over of the company, Winspear embarked on a large-scale “value recognition program”. The program was designed to define known and projected extensions of the Snap Lake Dyke. Through this program a number of drillholes were completed, as well as an underground decline to the kimberlite. MRDI completed a mineral resource estimate for the dyke. The program succeeded in increasing the total value of the property.

Aber Resources changed its name to Aber Diamond Corporation in early 2000. In December 2000, Aber Diamond Corporation agreed to sell their stake in the property to De Beers Canada Corporation. The transaction was completed on February 1, 2001 and the De Beers Snap Lake diamond mine is expected to commence production in 2006.

The Kennady Lake project, another significant diamond prospect, was originally known as the AK/CJ claims. In 1995, the 5034 pipe was discovered on the property. Macrodiamonds were recovered from samples taken in 1995 and a bulk sampling program was carried out. In March 1997, De Beers Canada Exploration Inc. entered into a joint venture with the claim holders, Mountain Province Mining and Camphor Ventures. Under this venture, De Beers Canada Exploration Inc. assumed immediate operation of the project, with the option of earning up to a 60% interest.

In 1997, the Tesla pipe was discovered on the property, followed by the Hearne and Tuzo pipes in 1997. During 1999, a bulk sample was taken from each of the four pipes to provide a more reliable estimate of diamond grade and value.

During 2000, De Beers studied the feasibility of mining the 5034, Hearne and Tuzo pipes using the data collected to date but deferred a production decision. In 2002, De Beers recovered further bulk samples from the Hearne and 5034 pipes. For the 5034 pipe, a total of 1,215 carats were recovered from 836 tonnes of kimberlite with the three largest diamonds weighing 7.0, 6.6 and 5.9 carats respectively.

Jericho (www.ainc-inac.gc.ca/nr/prs/j-a2005/02573bk_e.html) is a diamondiferous kimberlite deposit located in Nunavut at the north end of Contwoyto Lake, 25 kilometres north of the Lupin gold mine site. It was discovered soon after the initial diamondiferous kimberlite discoveries near Lac de Gras. Benachee Resources Inc., a subsidiary of Tahera Diamond Corporation, is the operator for the Jericho deposit. Potential minable kimberlite including reserves and resources is 5.5 million tonnes averaging 0.85 carats (www.tahera.com/jericho_diamond.html). Construction of a minesite has received all regulatory approvals and is scheduled to begin during the winter of 2005 using (www.cbc.ca/north/story/jericho-start-27012005.html).

CONCLUSION

Mineral development across the northern mainland west of 110° longitude has had a pattern of continuity as a whole and may be regarded as an ongoing activity. Individual mines and mining camps have waxed and waned depending on commodity prices and ore reserve depletion. Mining in each area has been accompanied by permanent additions to the northern infrastructure base, which has provided increased opportunities for development of other mineral and energy resources in the same region. Future mining activity across the north has to be tempered, however, with the realization that there are societal and environmental costs to unregulated mining activity and that potential benefits, such as increased employment, royalty revenues and other community financial benefits, and infrastructure development must be weighed against the cost of environmental degradation and hazards, and of the socio-economic impact of mining activities.

Energy development across the northern mainland has been confined to relatively few local areas, such as at Norman Wells and along the Norman Wells oil pipeline, the Liard Plateau Area and in the Mackenzie-Beaufort Basin. There is every indication that the next decade will see a tremendous expansion in both energy exploration and petroleum production in conjunction with pipeline construction along the Mackenzie Valley. New petroleum discoveries are being found in areas bordering the potential Mackenzie Valley Pipeline right of way. As with mineral exploration and development, energy exploration and development must be tempered with concerns for environmental and societal impacts.

This comprehensive review provides a basic framework for assessment of petroleum potential in northern basins as well as an overview of mineral exploration and mining activities in the northern mainland. As such, this report supports the capacity for informed land-use decisions that will benefit northern Canadians, most of whom are First Nations or Inuit. It is hoped that the report contributes to responsible development of non-renewable mineral and energy resources in the future, to ensure economic sustainability, opportunities and quality of life for northern Canadians.

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TABLES

FIGURES

that shows where Proterozoic strata along the base of the Plateau Thrust overlie Paleozoic strata. Contours of vitrinite $\%R_o$ reflectance within Devonian strata are also shown in 16B.

17. Map showing locations of gas fields in Liard Plateau of the Mackenzie Fold Belt. The western limit of the diagenetic "Manetoe Dolomite" reservoir facies is also shown. Also shown is the F-36 Mattson gas field south of Fort Liard.
18. Table of formations for the Northern Yukon Region. Individual columns represent stratigraphy within exploration areas (note that scaling of time scale for Figures 18 and 19 are different than in the Tables of formations for exploration regions in the Northwest Territories). Legend same as for Figure 10.
19. Table of formations for parts of the Northern Yukon and Selwyn-Cordilleran Regions. Individual columns represent stratigraphy within exploration areas. Legend same as for Figure 10.
20. Historical data from Statistics Canada concerning gross revenue from mining for the Yukon, NWT and Nunavut (post-1998). Low precious and base metal prices caused recent closures of many northern mainland mines. Since 1999, diamond mines have replaced metal mines as the main source of mining-related revenue in the NWT.