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Reviews on Natural Resources in the Arctic: Petroleum, Gas, Gas Hydrates and Minerals

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Abstract : The Arctic consists of numerous sedimentary basins containing voluminous natural resources and two of the world's major oil and gas producing areas. The western Siberia Basin in the Arctic region has the largest petroliferous province with an area of 800 × 1,200 km and produces more than 60% of total Russian oil production. The North Slope of Alaska produces about 20% of the U.S. output, i.e., 11% of the total U.S. consumption. Being small compared to those regions, the Canadian Northwest Territories and the Pechora Basin in Russia produce only fair amount of oil and natural gas. There are also many promising areas in the northern continental shelf of Russia. In addition to Russia, Svalbard and Greenland have been investigated for oil and gas. Gas hydrates are widespread in both permafrost regions and arctic continental shelf areas. The reserves of gas hydrates in the Arctic Ocean are about 20~32% of total estimated amounts of gas hydrates in the world ocean. Mineral mining is well developed, especially in Russia. The major centers are located around the Kuznetsk Basin and Noril'sk. They are major suppliers of gold, tin, nickel, copper, platinum, cobalt, iron ore, coal as well as apatite. There are also some minings of lead-zinc in Alaska and Arctic Canada.

Key words : Arctic, Oil, Gas, Gas hydrate, Mineral mining.

1. Introduction

The Arctic generally includes the area north of 66.5° N and consists of a ring of mainly mountainous continental landmasses that surround the Arctic Ocean (Fig. 1). Since the beginning of the 20th century many geologists have paid increasing attention to the Arctic due to the economic potentialities of natural resources. The Arctic region includes a cluster of giant and supergiant oil and gas fields on the North Slope and Beaufort Shelf near Prudhoe Bay, Alaska; probable supergiant gas fields in the southeastern Barents and southern Kara Seas; and large deposits of bituminous coal beneath the eastern Chukchi Shelf (Hale 1990; Haimila *et al.* 1990).

Recently, gas hydrates are of economic interest because they lie close to the earth' s surface and can be inferred as a major reservoir of natural gas. The presence of gas hydrates in sediment under the permafrost in remote areas of the Siberia and Arctic regions of North America has been reported (Chersky and Makogan 1970; Bily and Dick 1974; Kvenvolden *et al.* 1993). By extrapolating to the entire Arctic, Kvenvolden and Grantz (1990) suggested that more than $10^{15}m^3$ of methane at standard temperature and pressure may be tied up in hydrate deposits beneath the margins of the Arctic Ocean basin. Although there are no technologies for extracting the methane gases from the hydrate deposits, the possible size of the reserve, more than 1,300 times the volume of natural gas in the Prudhoe Bay field, makes acquisition of definitive information very important for the gas hydrate deposits of the Arctic region (National Research Council 1991).

Geophysical surveys and international interests in

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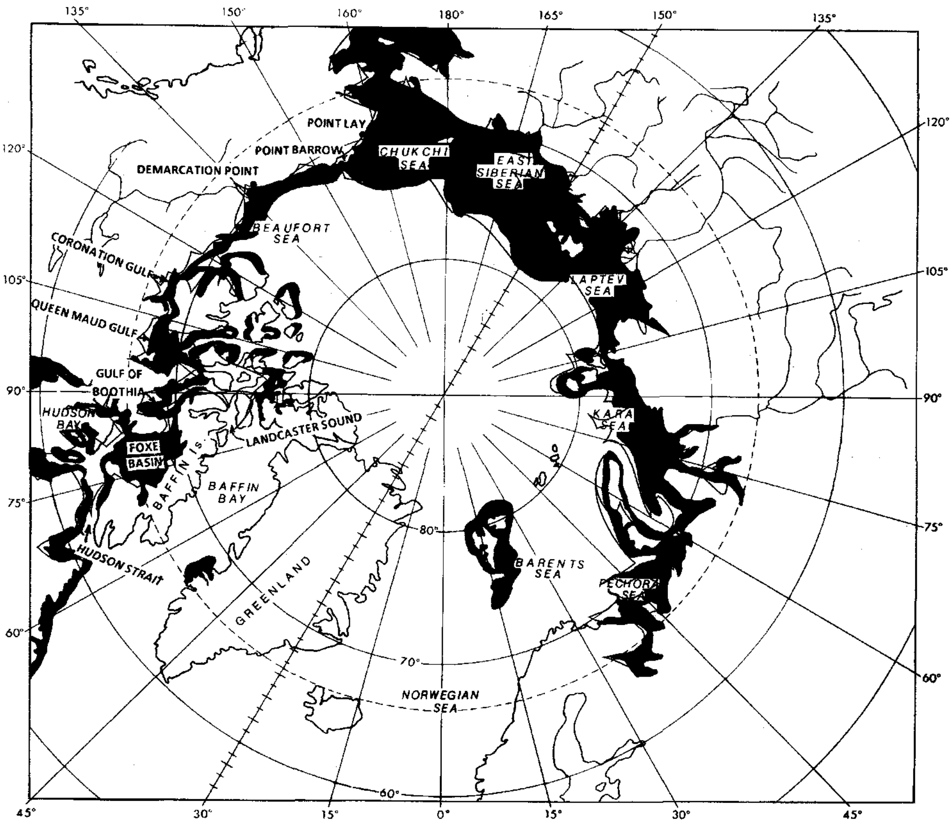

Fig. 1. Map of the Arctic showing areas with water depth less than 100 m deep (Hale 1990).

the Arctic regions are now on an increasing trend after the successive finds of oil and gas in Siberia, which said to include the world' s two largest gas fields, coupled with the discovery of the Sverdrup Basin gas field at 78° N in the Canadian Arctic Archipelago (Dixon and Dietrich 1990; Embry *et al.* 1989; Nassichuk 1983). Therefore, it is necessary to collect and accumulate the basic data for Arctic natural resources to join future resources development in the Arctic region. In this study, assessments of petroleum, gas, gas hydrates and mineral resources in the Arctic regions are reviewed. The understanding of the distribution of natural resources in the Arctic will provide clear research directions for resources development in the Arctic region.

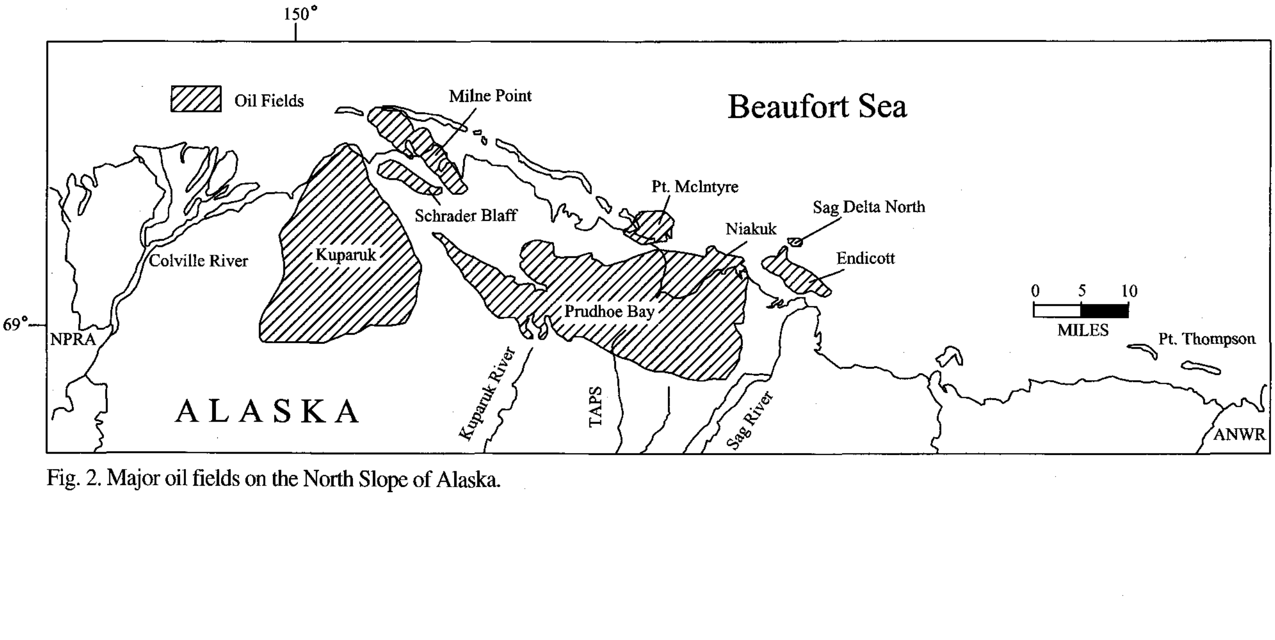

Fig. 2. Major oil fields on the North Slope of Alaska.

2. Petroleum and Gas

Alaska

The North Slope of Alaska accounts for about 25% of U.S. domestic oil production (BP exploration 1999). Prudhoe Bay development led to the discovery and development of other oil fields: Kuparuk, to the west of Prudhoe Bay; Endicott; Lisburne; Point McIntyre; Niakuk; Milne Point; Cascade; Sag Delta North; and West Beach (Fig. 2). A total of 14 oil fields are currently in production on the North Slope with commercial oil reserves exceeding 17.7 billion barrels. On the periphery of the producing fields, there may be 50 more satellite fields which may range from 1 to 100 million barrels each (Miller 1997).

Except for Prudhoe Bay and the Kuparuk fields, little has been published concerning the origin of North Slope oils. Morgridge and Smith (1972) suggested that the source of Prudhoe Bay oil is Cretaceous marine shale. On the basis of chemical analyses of crude oil, Jones and Speers (1975) concluded that oils from the Triassic Ivishak sandstone (Sadlerochit Group), Jurassic Kuparuk River Formation, and the Upper Cretaceous sandstone had a common origin. The trap is an unconformity trap, and the major reserves are in Early Cretaceous, Jurassic, Triassic, and Mississippian sandstones and carbonates below transgressive Late Cretaceous units (Jones and Speers 1975). The oil at Prudhoe Bay is trapped in the Sadlerochit Formation of the late Permian—early Triassic, a sandstone and gravel structure of nearly 2.7 km underground. In some locations, the oil-bearing sandstone is approximately 120 m thick.

The reservoir of Kuparuk oil field is located in a basin between the Colville and Prudhoe highs (Fig. 3). The origin of the oil is believed to be predominantly of lower sequence formations with migration occurring possibly via the Prudhoe Bay field. The dominant trapping mechanism is stratigraphic pinch-out and truncation of the reservoir at a local unconformity along the southern and western flanks of a southeast-plunging antiform (Carman and Hardwick 1983). The producing reservoir is Cretaceous Kuparuk sands at depths of 1.6 to 2 km. The reservoir sandstones occur within sequences that developed from the coarsening-upward, shallow marine area (BP Exploration and ARCO Alaska 1997).

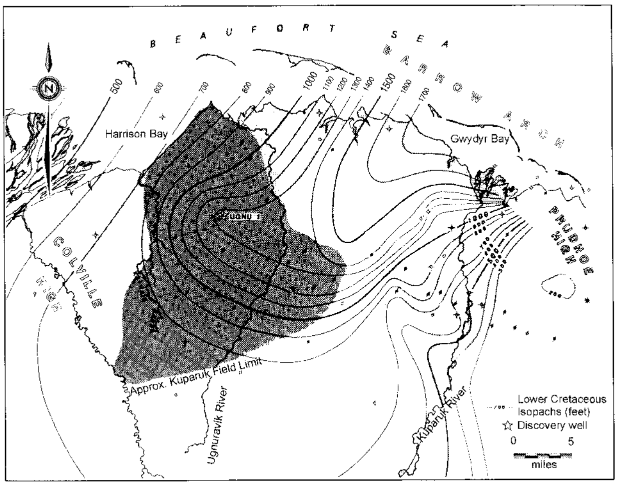

Fig. 3. Isopachs (in feet) of Lower Cretaceous sequence beneath Arctic plain display thinning to the Colville and Prudhoe highs south of Barrow arch (Carman and Hardwick 1983).

In this area, the total natural gas reserves are estimated at 840 billion m³. Several multinational corporations have already extracted 11.6 billion barrels of oil from the North Slope. By 1996, 821 billion m³ of natural gas had been pumped out, however, 90 % of this had been re-injected into the reservoirs to maintain the pres-

Table 1. Representative oil and gas fields in the Alaskan North Slope (modified from BP Exploration, 1999).

Oil Field	Reserves		Cumulative oil production to 1/1999(l)	Current production rate (1/1999)		No. of oil wells
	Oil(l)	Gas(m^3)		Oil(l/day)	Gas(m^3/day)	
Prudhoe Bay	$3.97x10^{12}$	$1,330x10^9$	$1.62x10^{12}$	$109.22x10^6$	$234.89x10^6$	804
Kuparuk	$1.03x10^{12}$	$84.90x10^9$	$0.25x10^{12}$	$42.77x10^6$	$10.19x10^6$	498
Endicott	$0.17x10^{12}$	$39.62x10^9$	$0.060x10^{12}$	$8.11x10^6$	$9.51x10^6$	40
Pt. McIntyre	$0.13x10^{12}$	$25.47x10^9$	$0.042x10^{12}$	$19.08x10^6$	$5.09x10^6$	58
Lisburne	$0.28x10^{12}$	$8.49x10^9$	$0.021x10^{12}$	$1.11x10^6$	$2.83x10^6$	76
Milne Point	$0.83x10^{12}$	-	$0.017x10^{12}$	$8.74x10^6$	$0.74x10^6$	136
Niakuk	$0.032x10^{12}$	$3.68x10^9$	$0.0056x10^{12}$	$3.66x10^6$	$0.51x10^6$	15

sure and to conserve the gas for future use (BP Exploration and ARCO Alaska 1997). The detailed oil and gas productions from the representative oil fields on the North Slope are shown in Table 1.

Canada

The North region which is the northern area of 60° N in the Northwest Territories (NWT) holds about 25% of Canada' s remaining discovered conventional oil and 24% of discovered gas (Fig. 4). Considering undiscovered conventional oil and gas reserves, the importance of the northern basins such as the Sverdrup and Western Canadian Basins (Fig. 5) is even more evident (Table 2). The North is also estimated to contain approximately 40% of both Canada' s undiscovered conventional oil potential and its undiscovered conventional gas potential (Canada Indian Affairs and Northern Development 1999).

In the Alberta or Western Canadian basin, oil and gas reserves are estimated at 11 billion barrels and 1.6 trillion m^3, respectively (Meyerhoff and Meyerhoff 1973). The northern part of the Western Canadian Basin, the most important oil producing basin, extends into the southern NWT and southeastern Yukon between the Rocky Mountains and the Canadian Shield. Other major northern basins are the Mackenzie Delta/Beaufort Sea, Sverdrup Basin, Hudson Bay and Foxe Basin, and the continental shelf bordering the eastern margin of the continent in Baffin Bay, Davis Strait and the northern Labrador Sea (Fig. 5). To date, most oil production has been from the Norman Wells field in the central Mackenzie Valley. The Norman Wells oil field extends beneath the Mackenzie River at 65° 20′ N latitude. Norman Wells oil production in 1998 was 1.56 million m^3, a slight decline from the previous year (Canada Indian Affairs and Northern Development 1999). Major undeveloped resources are also present in the Mackenzie Delta, Beaufort Sea and in the Arctic Islands, and other discoveries await development, for instance, in the Colville Hill north of the Great Bear Lake (Fig. 5).

The Sverdrup Basin covers an area of approximately 320,000 km^2 along the northwestern margin of the Arctic Archipelago (Fig. 5). It is a smaller successor basin to the Franklinian geosyncline, which extended from Melville Island northeast of the Mackenzie delta to the northeastern Greenland, a distance of 1,760 km. The Franklinian geosyncline contains a Proterozoic through Late Devonian sedimentary sequence ranging from 11,000-12,000 m in the miogeosyncline to possibly 18,000 m in the eugeosynclinal section in Axel Heiberg and Ellesmere Islands (Halbouty 1970). The Sverdrup Basin contains an incomplete sequence, 14,000 m thick, of Mississippian—earliest Pennsylvanian through middle Eocene sedimentary rocks with an area of 430 × 1,000 km. Middle Eocene folding terminated basinal sedimentation. In a basin of this size and duration, considerable lateral and vertical variations in lithology are found, however, the section in nearly all the system represents a change from a shelf facies on the southeast

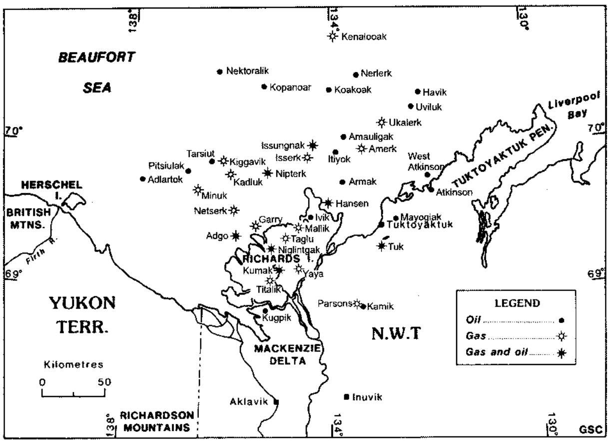

Fig. 4. Map of the significant oil and gas discoveries in the Northwest Territories and Mackenzie Delta-Beaufort Sea (Haimila *et al.* 1990).

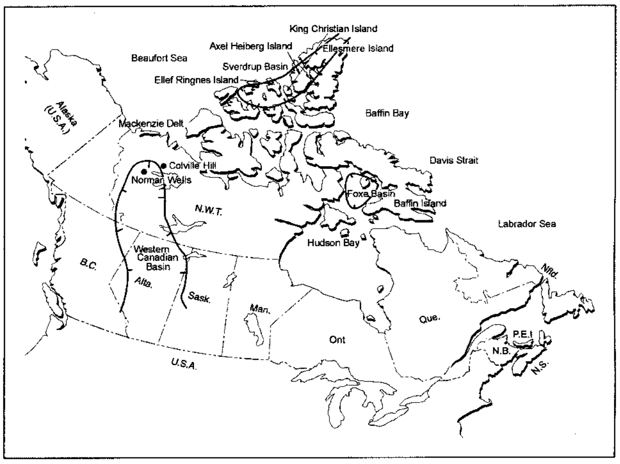

Fig. 5. Map of the important petroleum producing regions in Canada.

to a basinal facies on the northwest. Numerous diapirs in the Sverdrup basin are believed to be formed from evaporites of Pennsylvanian age (Thorsteinsson and

Table 2. Northern remaining reserves as percentage of total Canadian remaining resources (from Indian Affairs and Northern Development 1998).

	Recoverable conventional oil		Recoverable conventional gas	
	Discovered	Undiscovered	Discovered	Undiscovered
Mainland territories	2 %	1 %	1 %	4 %
Mackenzie Delta/ Beaufort Sea	18 %	21 %	12 %	15 %
Arctic Island/ Eastern Arctic offshore	5 %	16 %	13 %	21 %
Northern Canada Total	25 %	38 %	26 %	40 %

Tozer 1970), although evaporities of Cambrian through Devonian ages also may have contributed to the diapirs. Eocene orogeny folded the late Paleozoic, Mesozoic, and early Tertiary rock, and refolded the pre-Mississippian rocks on which the younger sequence lies unconformably. A gas discovery in Triassic sandstone on King Christian Island suggests the presence of a gas field of 150 billion m^3 or more, with possibly 1 billion barrels of liquid hydrocarbons. Subsequently, a gas field was discovered in Kristoffer Bay of Ellef Ringnes Island, 80 km farther north, and gas is trapped in the same sandstone as that at King Christian Island (Heise 1972) (Fig. 5). Oil also had been discovered in other Arctic Archipelago.

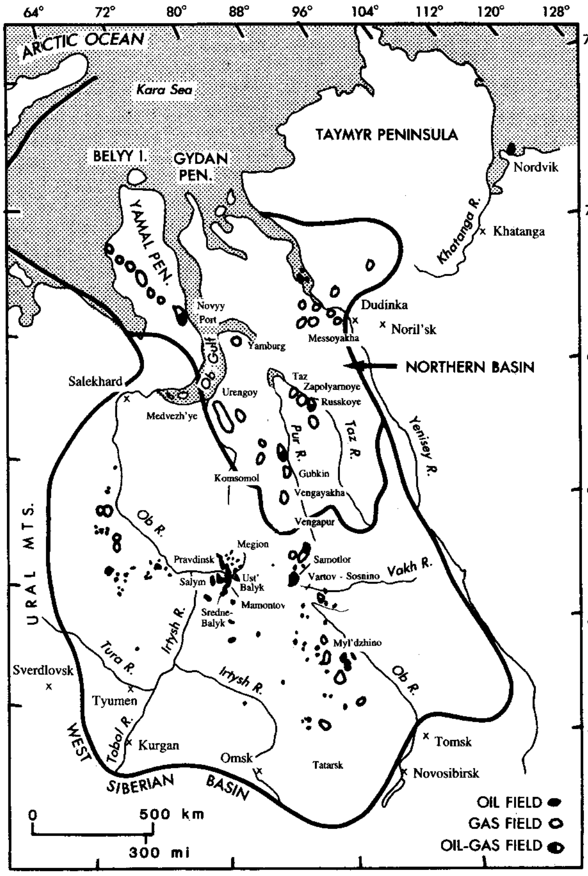

Fig. 6. Oil and gas fields in the West Siberian Basin (modified from Grace and Hart 1986).

Russia

Russia holds one of the world leading positions for unexplored oil and gas reserves. Its original overall reserves in place have been explored so far only by 40%, while unexplored recoverable reserves have been estimated up to several dozens of billions of barrels (Dmitrievsky 1999). These are mainly in the west Siberia and in the Russian shelf.

The West Siberian Basin where the oil and gas resources concentrate in the central and northern part (Fig. 6) is the second-richest petroliferous basin in the world after the Persian Gulf (Meyerhoff 1980). After the beginning of oil production, more than 205 fields and potential fields had been identified in its 1.75 million km^2 area for 10 years (Halbouty 1970). The Samotlor field whose recoverable reserves reach 15.1 billion barrels in the West Siberian Basin is the largest oil field in Russia.

The West Siberian Basin is a composite basin, with Mesozoic-Cenozoic sediment filling the top of Paleozoic sequence that overlies the crystalline Archean-Proterozoic basement. The productive zones in the basin are principally in the Neocomian and Cenomanian sections. These sections are terrigenous sequences of terrestrial and marine Jurassic and Cretaceous rocks that filled a subsiding intra-platform basin. The sediments were deposited on a complex basement which was converted to horst and graben structures by post-Hercynian block faulting. These structures provided ideal sites for hydrocarbon accumulation in the Mesozoic succession. The entire region has been stable since Jurassic time, and its low elevation has prevented erosion that would have facilitated the escape of gas and oil (Meyerhoff and Meyerhoff 1973).

Hydrocarbons in Neocomian reservoirs were generated by thermal maturation of sapropelic organic matter in the Tithonian Bazhenov shale. Methane gas in the Cenomanian section appears to be a combination of thermogenic gas from the Bazhenov Suite and biogenic gas generated from the Cenomanian section itself, although experts disagree over how much gas came from each source (Rice and Claypool 1981).

The gas deposits of the northern West Siberian basin represent the largest single concentration of gas in the world. The 66 fields in the northern West Siberian basin contain at least 22 trillion m^3 of proved gas, almost one-third of the world reserves. These include the largest and second-largest gas fields in the world—Urengoy (8.1 trillion m^3) and Yamburg (4.81 trillion m^3)—as well as most of the ten largest gas fields in the world (Grace and Hart 1986).

A gigantic gas and oil super-province was also discovered in the Barents Sea and the Kara Sea. The original recoverable resources of the region, as of January 1, 1993, are over 70% of the resources of the entire shelf of Russia (Dmitrievsky 1999). There are at least three major areas of strong oil and gas accumulation, i.e., the Central Barents gas bearing area, the South Kara gas bearing area and the Peter Sea oil-gas condensate bearing area. As to their further development, there is a vast yet unused potential; in nine out of the 16 potentially oil-gas bearing basins covering 62% of the promising area, there are no wells at all, and in four potentially oil-gas bearing basins, there are only one or two wells each. Even at the initial stage of exploration, unique gas fields have been discovered in this region, such as the Stockman, the Leningrad and the Rusanovsky fields, and their consolidated reserves reaching over $10^{13}m^3$ of gas.

Greenland

The Melville Bay area covers the entire continental shelf between the Svartenhuk Peninsula at 71° 15′ N and Carey Island at 76° 13′ N (Fig. 7). In the Melville Bay area, offshore of the northwest Greenland, a very large sedimentary basin was confirmed by a recent seismic survey (Whittaker *et al.* 1997) (Fig. 8). Hood *et al.* (1967) on the basis of an aeromagnetic survey, first suggest that Melville Bay might be a potential petroleum province. Recently acquired seismic reflection profiles showed very large tilted fault blocks, draped by younger sediments, and anticlines, both of which could form large structural traps for hydrocarbons (Whittaker *et al.* 1997).

The eastern margin of Greenland, ultimately, may also stir exploratory interests. This Atlantic border was tectonically active during Proterozoic and much of Paleozoic time (Haller 1971). The geosynclinal

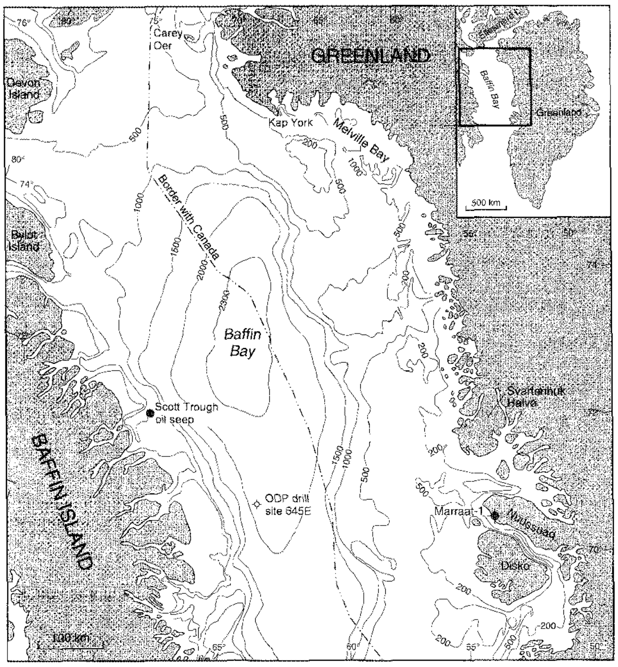

Fig. 7. Location map of the Melville Bay area with water depth contours in meters (modified from Whitakker *et al.* 1997).

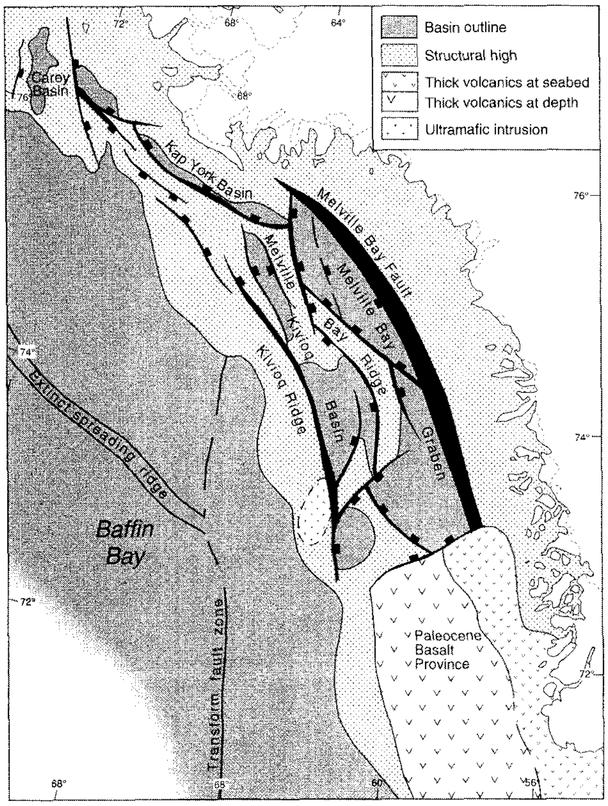

Fig. 8. Structural map of the Melville Bay area (Whittaker *et al.* 1997).

Proterozoic sedimentary section is as thick as 9,000 m. These rocks unconformably underlie an early Paleozoic sequence that was folded during the Caledonian disturbance. Devonian rifting produced grabens in which 6,000-7,500 m of continental sandstone accumulated. Mild Acadian deformation was followed by late Paleozoic marine transgression from north to south, and by the deposition of a sequence of Mesozoic rocks. Sedimentation was intermittent; deformation—mostly faulting—was spasmodic, however, marine deposition did not end until Campanian time. The post-Devonian sequence may have hydrocarbon potential. These rocks extend as much as 260 km offshore, where the exploratory environment leaves much to be desired, but where the possible rewards in Permian and Triassic terrigenous clastic, carbonate, and evaporite sections ultimately may counterbalance the physical and geological risks.

Gas Hydrates

Gas hydrates which have been identified from borehole samples, by acoustic characteristics (Bottom Simulating Reflection: BSR) in seismic reflection profiles (Grantz *et al.* 1976; Neave *et al.* 1978) and by well logging methods (Goodman 1980) are gas concentrators; the breakdown of a unit volume of methane hydrate at a pressure of one atmosphere produces about 160 unit volumes of gas (Dmitrievsky 1999). Because gas hydrates cement sediments, it can reduce permeability and create a gas trap. Such trapping of gas beneath hydrates may cause the formation of the most concentrated hydrate deposits, due to the presence of a reservoir of gas below the hydrate zone. The gas can continually migrate upwards to fill any open pore spaces. This process, in turn, causes the trap to become more effective, producing highly concentrated methane and methane hydrate reservoirs (Clennell *et al.* 1999). The worldwide amount of carbon bound in gas hydrates is conservatively estimated to total twice the amount of carbon to be found in all known fossil fuels on Earth (Dillon 1992). Such prospective resources of gas hydrates are apparently present in large areas of the Arctic Ocean region (Table 3).

Alaska

Most of gas hydrate wells are located in the vicinity of Prudhoe Bay and the Kuparuk oil fields (Fig. 9). Collett (1983) carried out wire-line logging from 125 wells in Prudhoe Bay region and possible gas hydrates were pointed to 33 of these wells were indicated. The depth intervals between which the occurrence of gas hydrates is inferred from well logs range from 128 to 1,090 m. The upper and lower depth limits for gas-hydrate stability are predicted to 177 m and 1,119 m. Gas hydrates were recovered at the Kuparuk oil field, and the Kuparuk field is likely to contain at least laterally continuous and gas hydrate saturated sedimentary units (Kvenvolden and Grantz 1990).

The most extensive offshore occurrence of gas hydrates lies north of Alaska beneath the Beaufort Sea (Grantz *et al.* 1976; Grantz and Dinter 1980). Seismic surveys of Grantz *et al.* (1982) indicated that the area of the Arctic continental slope across which the inferred gas hydrates occur may encompass a significant part of the Arctic Ocean Basin deeper than 400 to 600 m in water depth (Fig. 10).

Canada

Assessments of gas hydrate occurrences in the Mackenzie Delta-Beaufort Sea area have been made mainly on the basis of data obtained during the course of hydrocarbon exploration conducted over the past three decades. Smith and Judge (1993) summarized a series of unpublished consultant studies that investigated well log response of 146 onshore exploration wells in the Mackenzie Delta area. In total, 25 wells were identified as containing possible or probable gas hydrates. All of these inferred gas hydrates are found within unconsolidated to weakly cemented sediments of Kugmallit and Mackenzie Bay (Fig. 11). Gas hydrates typically occur in coarse-grained sandy intervals interbedded with fine-grained layers (Dallimore and Collett 1999). Two of the occurrences were associated with permafrost while the remainder were beneath the permafrost interval. The frequency of gas hydrate occurrences in offshore wells (Beaufort Sea area) was higher with possible or probable gas hydrates being identified in 35 out of 55 wells.

3. Minerals

Alaska

According to the U.S. Geological Survey, metallic minerals of Alaska accounted for more than 90% of the State' s total non-fuel mineral production value in 1998. Major producing area is concentrated in the southeast-

Table 3. Known and inferred gas hydrate occurrences in the Arctic region (from Kvenvolden *et al.* 1993).

Location	Evidence	Reference
Alaska (Beaufort Sea)	SRP	Grantz and Dinter (1980)
Canada (Beaufort Sea)	Log	Weaver and Stewart (1982)
Canada (Sverdrup Basin)	Log	Judge (1982)
Norway (Barents Sea)	SRP	Andreassen *et al.* (1990)
Svalvard (Fram Strait)	SRP	Eiken and Hinz (1989)

SRP : Seismic Reflection Profile, Log: well-log response

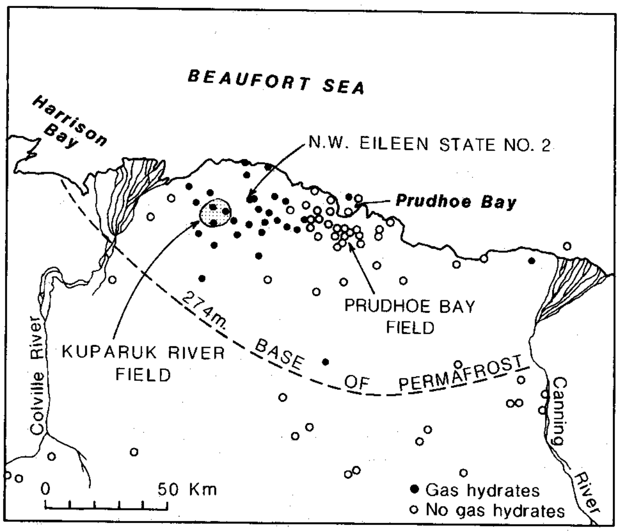

Fig. 9. Map of wells examined for gas hydrate occurrences in the Prudhoe Bay region of Alaska (Kvenvolden and Grantz 1990).

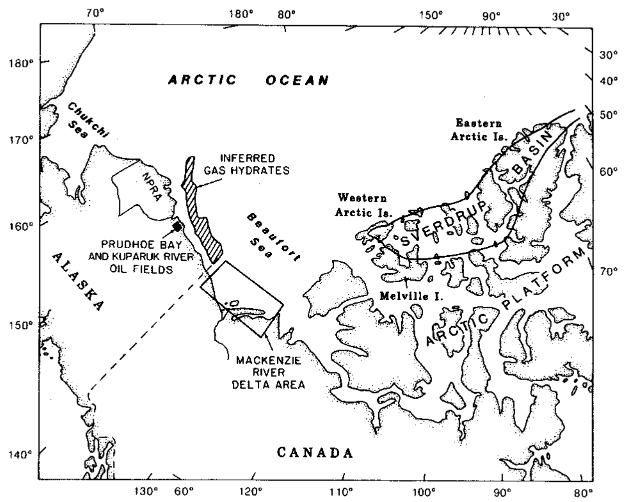

Fig. 10. Map of the North American Arctic showing regions of probable gas hydrate occurrence (Kvenvolden and Grantz 1990).

ern part of Alaska. In the northwestern Brooks Range, silver-lead-zinc massive sulfide deposits, consisting of layers rich in sulfide minerals, were found (Fig. 12). The dominant minerals are sphalerite, silver-rich galena, pyrite, and marcasite (Gray and Sanzolone 1996). At Red Dog, one of the largest zinc deposits in the world, mining of lead, zinc and silver began in 1990 and continues today. Lik and Drenchwater deposits near Red Dog were not mined until 1996.

Sand and gravel are the only commodities that appear to offer development potential off the Alaskan coast of the Chukchi and Beaufort Sea shelves from Point Lay to Demarkation Point (Hale 1990). Potential sites for mining of sand and gravel on the shelf include mid and outer shelf lag gravels, hydraulic bedforms, and buried gravels on the inner shelf, beaches, and barrier islands. The distribution of sand and gravel along the northern shore of Alaska is highly variable. Gravel is abundant in many regions, with the best sources being glacial outwash, alluvial deposits, or lag-type gravel deposits in the offshore. However, future mining of marine aggregates will depend on the nature and extent of offshore oil and gas development which demands for sand and gravel.

Canada

During the past 40 years, gold, silver, copper, lead, zinc, nickel, asbestos, tungsten, uranium, coal and some byproducts such as cadmium and cobalt which mainly come from the Precambrian shield (Lang 1970), have been produced from more than 30 mines in the NWT.

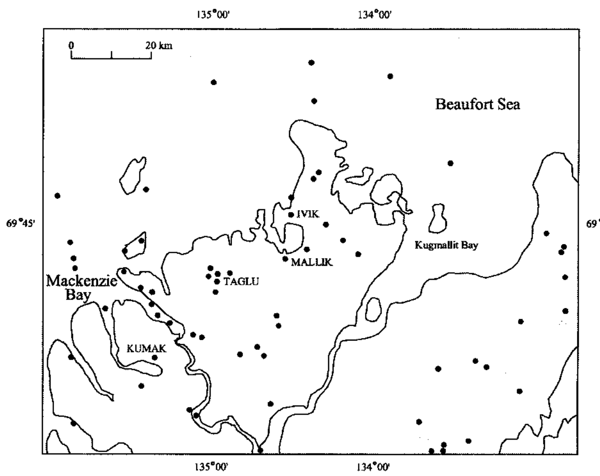

Fig. 11. Exploration wells with well log interpreted gas hydrate occurrences in the Mackenzie Delta region (modified from Dallimore and Collett 1999).

Presently only six mines, however, are producing gold, silver, lead and zinc in the NWT: Con, Giant Yellowknife, Echo Bay, Mount Skukum, United Keno Hill and Faro mines (Hicks 1997). All mines are metal producers, and the assortment is large. Lead and zinc are being produced at the world' s most northernly mine, Polaris, on Little Cornwallis Island, and lead, zinc and silver are mined at Nanisivik on Baffin Island. Base metal exploration has taken place in the Arctic Islands, in the greenstone belts north of Yellowknife and southwest of Rankin Inlet resulting in the discovery of the massive deposit at Voisey' s Bay (Hicks 1997). Recently, the search for diamonds has resulted in the staking of vast tracts of land on the mainland of the NWT as well as in the Arctic Islands. Location of major mines in the Canadian Arctic is shown in Fig. 13.

The major mineral province is also located in the Western Cordillera of the Yukon (Little 1970), which has 10 mining camps. One produces asbestos and the others metals—primarily gold, but some silver, and one mine produces lead-zinc with the byproduct cadmium. The linear pattern of the paired gold belts, the unique occurrence of the Sudbury Ni-Cu-Ag complex, the hematite ores in parts of the Proterozoic sequence—these and other types of mineralization in the southern part of this area indicate a variety of geologic situations.

In contrast to onshore mining, the absence of commercial exploration for placer deposits in the Canadian Arctic offshore makes it difficult to assess placer potential. Nevertheless, coastal areas possessing suitable host rocks to yield detrital heavy minerals such as chromite, tungsten, platinum-group metals, gold and diamond were identified (Hale and McLaren 1984).

Although large quantities of sand and gravel for petroleum related construction projects may be required in the Canadian Beaufort Sea, aggregate is in relatively short supply (O' Connor and Associates Ltd. 1983). However, approximately 95 million m^3 of gravel had already been discovered near Herschel Island, the Issungnak and Isserk well sites, and the west side of Banks Island (Hale 1990).

Russia

In the Western Siberia Which is a vast lowland extending northward to the Karaganda, eastward to the Urals, southward to the Arctic Ocean, and westward to the Rena River, the development of mineral resources for heavy industry until the early 1960s was centered almost entirely in the Kuznetsk basin, one of Russia' s principal coking coal producers (Meyerhoff and Meyerhoff 1973).

Like the Western Siberia, the Eastern Siberia also contains large amounts of energy resources, especially brown coal. One of the largest and oldest is the Noril' sk district, just east of the Yenisey River at 68° N (Fig. 14). It is a major supplier of nickel, copper, titanium, vanadium, platinum metals, and a variety of minor metals. The Eastern Siberia is essentially a highland of complex mountains and plateaus, flanked on the west and east by the Yenisey and Lena Rivers, respectively. A broad lowland just north of 70° N extends across the entire east-west width of the region, however, its central or Taymyr section is separated from the Arctic Ocean by a mountain range that also forms the Severnaya Zemlya archipelago, which ends at 82° N. The geology of the

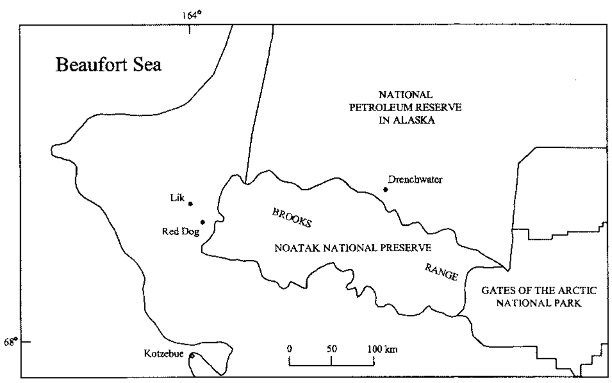

Fig. 12. Location of silver-lead-zinc massive sulfide deposits in the northwestern Brooks Range, Alaska.

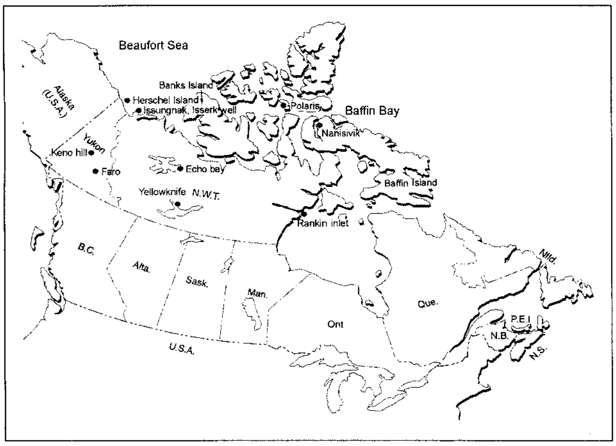

Fig. 13. Location of major mines (dots) in the Canadian Arctic.

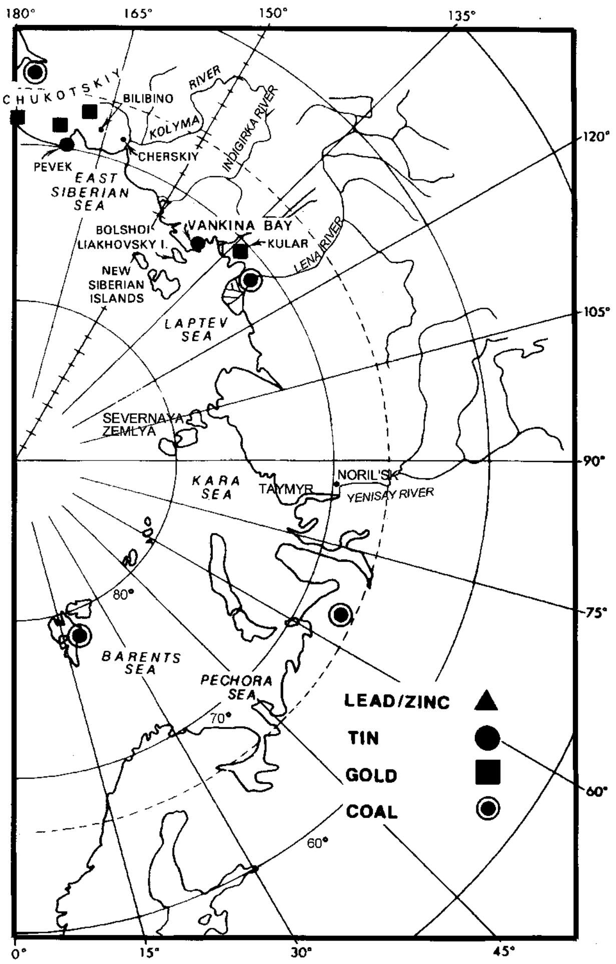

Fig. 14. Lead-zinc, tin, gold and coal mines in the Russian Arctic (modified from Hale 1990).

region south of the Taymyr lowland, unlike that of Western Siberia, is that of a shield rather than a basin area, and favors mineralization rather than hydrocarbon accumulation (Meyerhoff and Meyerhoff 1973).

The Chukotskiy region in the Eastern Siberia (Fig. 14) accounts for more than 57% of Russian gold production (Meyerhoff 1983). Most of the gold produced from this region is derived from placer deposits that have been under development since the 1930s (Conquest 1979). Many of these are situated along the Kolyma River, but some occur along the coast of the Chukchi Sea. Gold is also mined from deposits close to the coast in the central Arctic at Kular.

Published reports on the distribution and characteristics of placer deposits in the Russian offshore are sparse. However, offshore cassiterite deposit was discovered in the early 1970s in Vankina Bay (Eastern Laptev Sea) (Fig. 14). The cassiterite appears to lie directly on the bottom of Vankina Bay, only several tens of meters from the shoreline and extends over a large area (Hale 1990). There also appears to be good potential for other placer minerals including ilmenite-magnetite, rutile, zircon, and gold.

4. Summary

1. The Arctic region contains a gigantic oil and gas bearing superbasin (Gramberg *et al.* 1983). The highest oil and gas potential are at the Alaskan North Slope and the adjacent Beaufort Sea off both the Alaskan and the Canadian coasts, Canada's Arctic Islands, the northern Russia, and the Kara, Barents, and Norwegian Seas. Although Russia has found large onshore petroleum reserves, offshore exploration and production remain low in the Arctic region. On the other hand, offshore activities of the Western countries for petroleum development are in full swing in the Arctic (Weeks and Weller 1984).
2. Gas hydrates are widespread in permafrost regions and beneath the sea within sediments of outer continental margins. Most of the hydrate gas is probably methane (National Research Council 1991). The amount of gas-hydrates in Alaska has been estimated to range from 10^{11} to 10^{14} m^3 (Potential Gas Committee 1981). Kvenvolden and Grantz (1990) estimated that more than $10^{15}m^3$ of methane may be present in gas hydrates in sediments of the margin of the Arctic Basin.

   Although gas hydrates are known to occur in numerous Arctic sedimentary basins, little is known about the geologic parameters controlling their distribution. Recently, various researches are being carried out to provide the engineering evaluation of in situ gas hydrates and refine geological, geophysical and geochemical methods for gas hydrate detection (Dallimore and Collett 1999).
3. Numerous regions in the Arctic Ocean Basin possess favorable geology for placer deposits. However, no deep-sea mineral deposits have as yet been identified in the Arctic Ocean Basin (Hale 1990). At least one offshore tin placer has been brought into production in the Russia, and other tin and gold placers may also be mined (Miles and Wright 1978). However, marine mining in the Arctic Ocean Basin is not yet active compared with land mining which is well developed,

especially in Russia, due to the absence of appropriate mining technologies.

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