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HYDROCARBON POTENTIAL OF OFFSHORE BRITISH COLUMBIA

N.E. Haimila and R.M. Proctor

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

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The estimates presented in this report are based on an evaluation carried out and prepared by a committee consisting of personnel from the Atlantic Geoscience Centre (Dartmouth, Nova Scotia), the Institute of Sedimentary and Petroleum Geology (Calgary, Alberta) and the Pacific Geoscience Centre (Pat Bay, British Columbia) of the Geological Survey of Canada; the Resource Management Branch of E.M.R. (Ottawa); and Petroleum Resources, Indian and Northern Affairs (Ottawa). This committee on geological potential consisting of some ten geologists and geophysicists was responsible for the finalization of estimates of undiscovered resources. The activities of this committee are co-ordinated by the Petroleum Resource Appraisal Secretariat located at the Institute of Sedimentary and Petroleum Geology, Geological Survey of Canada, Calgary, Alberta.

R. M. Procter, Executive Director
Petroleum Resource Appraisal Secretariat

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HYDROCARBON POTENTIAL OF OFFSHORE BRITISH COLUMBIA

Introduction

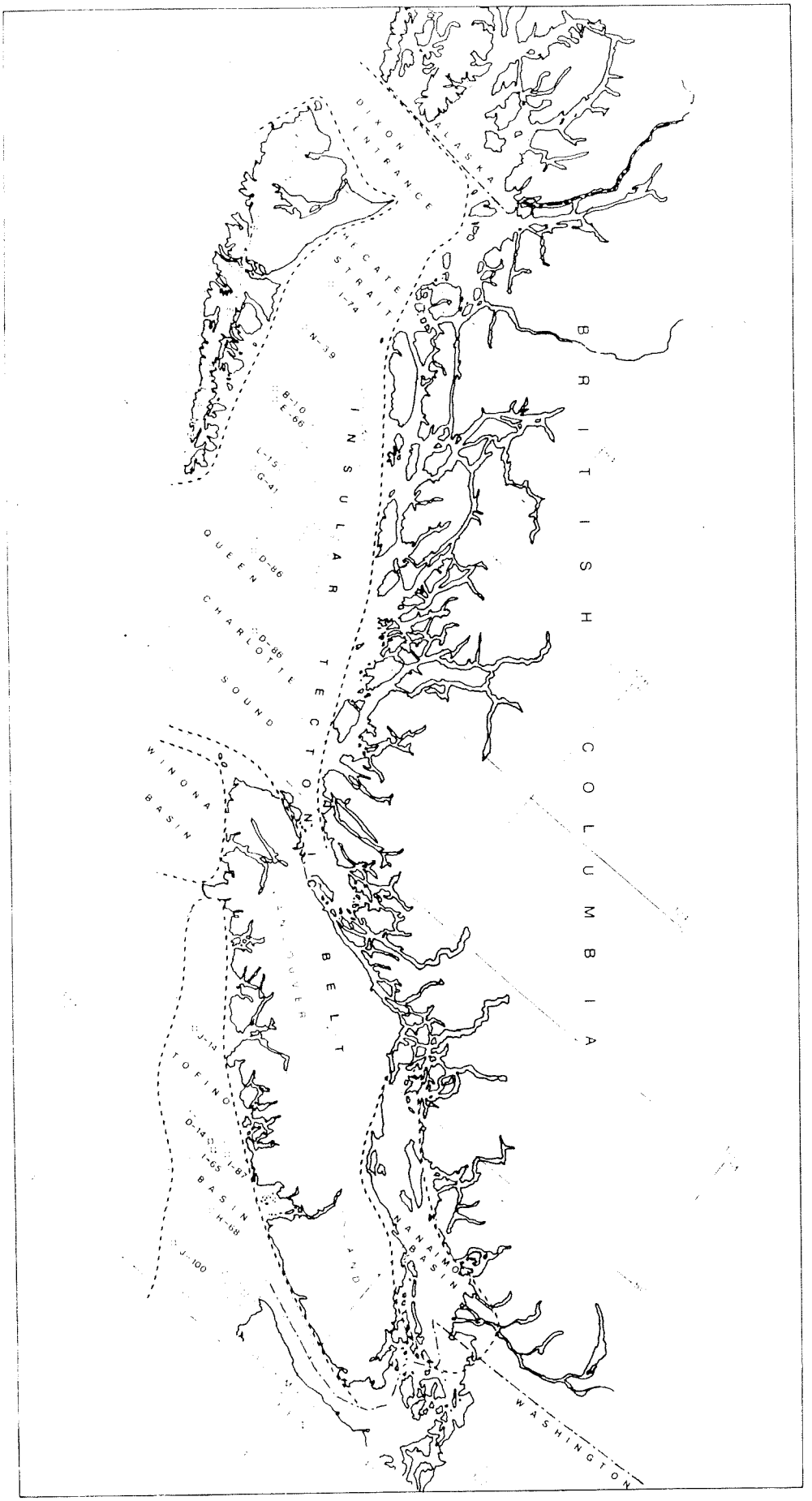
This report presents estimates of oil and gas potential of the offshore areas of British Columbia, the general geological setting, exploration history, and the method of estimation utilized.

The evaluation was done in the spring of 1978. In the winter of 1980 the evaluation was reviewed for consistency, checked for mathematical errors and aggregated to yield potential estimates for the whole area.

The evaluation was based on data published in the literature, data supplied to various government agencies under regulations, (i.e. well history reports including well logs, mud logs, paleontological reports, etc.; magnetic surveys; seismic interpretations and cross-sections; and geological and geophysical reports) and proprietary information supplied to the committee through the courtesy of industry.

History of Exploration

The first report of the hydrocarbons in a well in the Insular Tectonic Region of British Columbia (Figure 1) was a 1.6 metre gas flare from the 490 metre deep Tian No. 1 well. This well was drilled by the British Columbia Coal Company in the Queen Charlotte Islands during 1913-1915. Subsequently, Royalite Oil Company drilled the unsuccessful Queen Charlotte No. 1 well to a depth of 1006 metres in Mesozoic rocks near Skidegate in 1950. In 1958 Richfield Oil Corporation mounted an exploratory drilling program and drilled the Masset, Nadu River, Towhill, Gold Creek and Tlell wells on northwestern Graham Island to various depths (less than 2,500 m)



1. BRITISH COLUMBIA OFFSHORE AREAS

in the Tertiary section. The Cape Ball well was drilled in 1961 terminating the program without any significant signs of hydrocarbons.

During the 1960-1970 decade, Shell Oil Company initiated the exploration of the offshore areas. Following a 1963-65 seismic program, Shell drilled 14 exploration wells between May 1967 and May 1969. Six were drilled in the Tofino Basin area and eight in the Queen Charlotte Sound-Hecate Strait area.

In the Tofino Basin the wells were (from northwest to southeast): Apollo J-14, Zeus I-65, Zeus D-14, Pluto I-87, Prometheus H-68 and Cygnet J-100. In the Hecate Strait-Queen Charlotte Sound area the wells were (from northwest to southeast): South Coho I-74, Tyee N-39, Sockeye B-10, Sockeye E-66, Murrelett L-15, Auklet G-41, Harlequin D-86 and Osprey D-86.

Gas shows were encountered in shallow zones in the Pluto I-87 and Prometheus H-68 wells and an oil show was observed as staining in sidewall core in the Sockeye B-10 well.

In 1971 Union Oil Co. located the Port Louis well on the west coast of Graham Island. This well terminated at a total depth of 1569 metres, in igneous rocks, before it reached its prognosed depth.

Hydrocarbon Potential

The estimate of the hydrocarbon potential of Offshore British Columbia was derived from the consideration of "exploration plays" grouped as follows:

1. The stratigraphic and structural plays associated with the coarse clastic Eocene and Oligocene sedimentation in the arc-trench gap areas occupied by the Tofino and Winona Basins.
2. The Oligocene and Miocene structural and stratigraphic plays in the Tofino and Winona Basins. In some cases these plays are associated with shale diapirism.

3. The pre-volcanic Mesozoic plays of the Queen Charlotte Sound, Hecate Strait, and Dixon Entrance areas.
4. The structural and stratigraphic plays associated with the marine Tertiary sedimentation in the Queen Charlotte Sound, Hecate Strait, and Dixon Entrance areas.

The summations of the potential of the individual plays from all the offshore areas are presented as two cumulative frequency distribution curves; the natural gas potential of British Columbia offshore areas (Figure 2), and the oil potential of British Columbia offshore areas (Figure 3).

The shapes of the curves for both natural gas and oil are characteristic of regions in which there is very little exploration, sparse control and high levels of uncertainty regarding the presence of pooled hydrocarbons. Curves of this type are highly skewed with very little potential associated with the higher levels of probability, but larger potentials are suggested at lower levels of probability. In the case of the natural gas potential, for example, slightly more than $3.18 \times 10^6 m^3$ (0.112 billion cubic feet) are thought to exist at the 100% probability. The values of the potential increase gradually to an average expectation of $265 \times 10^9 m^3$ (9.4 trillion cubic feet) at the 34% level and increase rapidly in the lower probability ranges. The curve reflects the opinion of the committee that there is no likelihood of the potential exceeding $2.66 \times 10^{12} m^3$ (94.3 trillion cubic feet).

Similarly, the distribution of estimates for the recoverable oil indicates that at the 100% probability only a nominal quantity of oil may exist. There is an average expectation that more than $38.5 \times 10^6 m^3$ (241 million barrels) exist and there is no likelihood that more than $789 \times 10^6 m^3$ (4.97 billion barrels) of oil exist in the region.

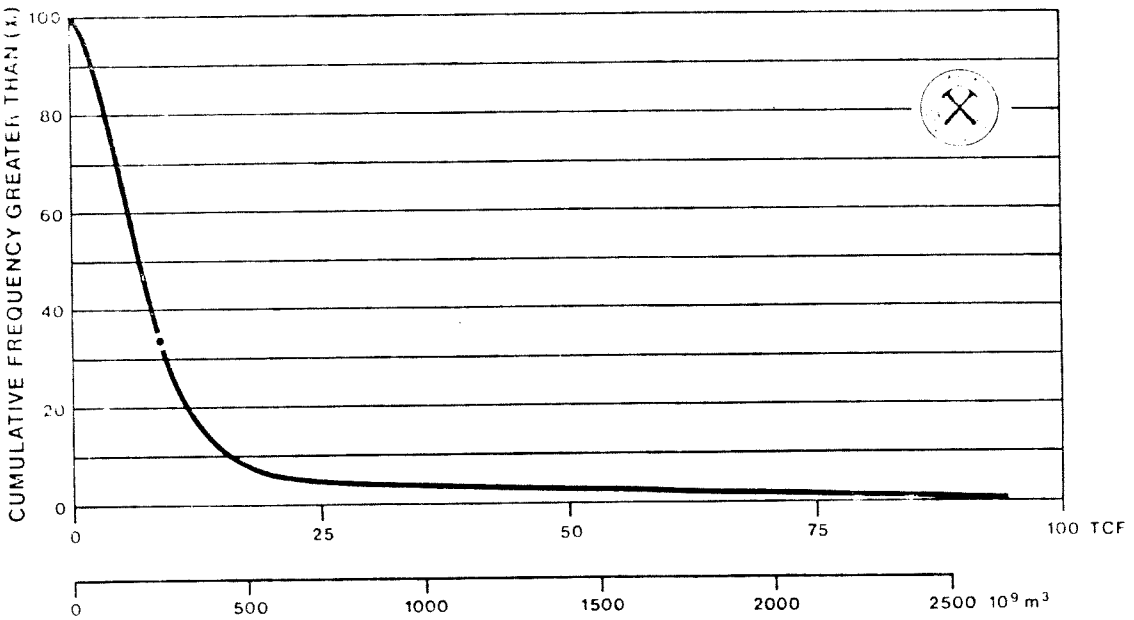


Fig. 2 Natural Gas potential of British Columbia offshore areas.

These estimates are based on the data available to the committee at the time the estimates were made. As exploration proceeds and additional data becomes available the estimates will likely change to reflect the new information.

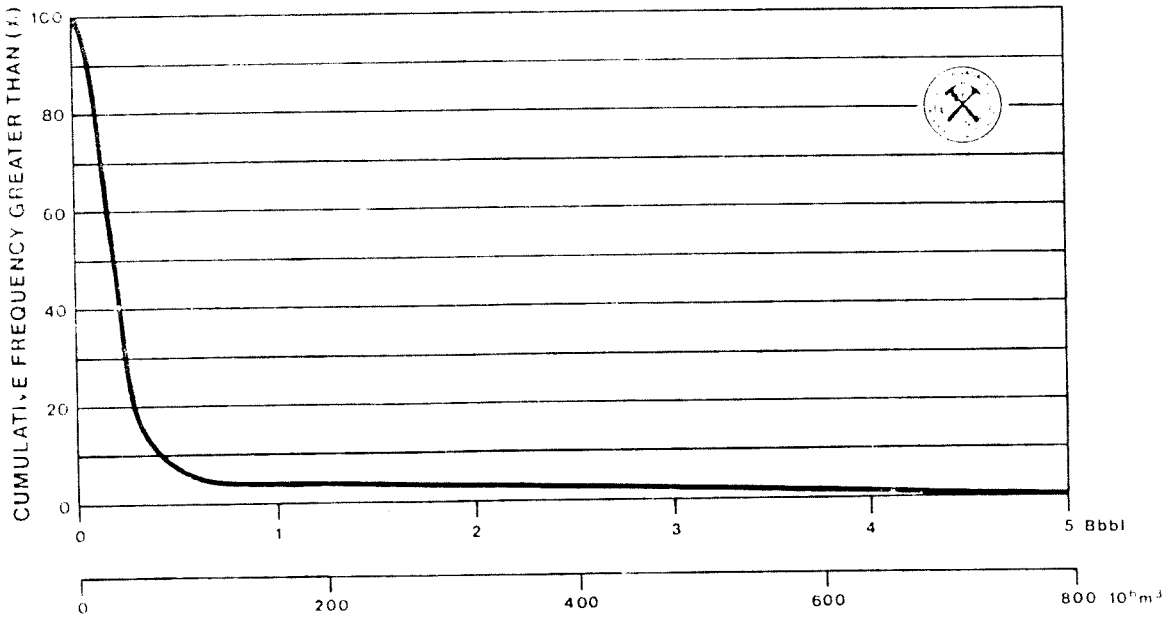


Fig.3 Oil potential of British Columbia offshore areas.

The ratio of gas to oil is based on the nature of organic material in the source rocks, the thermal maturation, and timing of the trap formation. Should these conditions prove to be different as the result of future drilling the ratio of gas to oil may change.[1]

[1] Since the preparation of this paper, C.J. Yorath (C.S.P.G. Luncheon talk: The Tectonics, History and Petroleum Potential of the Queen Charlotte Islands and Adjacent Areas, September 17, 1981, Calgary, Alberta) utilizing a model based on plate tectonics and heat flow, suggests a higher heat regime under the Queen Charlotte Sound than may have been conceived during the formulation of these plays. The validity of this hypothesis and the impact it may have on the gas-oil fraction cannot be evaluated without further drilling. During the assessment meetings this area was identified as having the best sedimentary types and thermal regime for the generation of hydrocarbons. It is possible that the impact of the anomalous heat flow or thermal regime has already been incorporated into the hydrocarbon estimates.

To compare the British Columbia offshore area one could look at similar basins along the West Coast of North America. The closest production is a new onshore discovery south of the Columbia River in Oregon. The Mist Field was discovered in 1979, seven miles south of the Columbia River, and thirty miles inland from the coast (Oil and Gas Journal, June 3, June 25, Aug. 27 and Sept. 17, 1979). This field may be similar to some of the prospects that occur in the Tofino Basin. To date, four wells in the field produce approximately 341,800 m^3/d (12 million cubic feet/day) of natural gas from Upper Eocene sands at a depth of 707 metres.

Further south the unusually prolific basins of California situated west of the San Andreas fault have had an estimated recovery of $2.276 \times 10^9 m^3$ (14.325 billion barrels) of oil (Taylor, 1976), or using a conversion factor of 1:10687 (1 barrel of oil equivalent to 6,000 cubic feet of gas) the oil would convert to $2.430 \times 10^{12} m^3$ (85.96 trillion cubic feet) of natural gas. The California basins produce from Eocene through Pliocene sediments in a tectonic setting similar to portions of the British Columbia offshore area. However, vulcanism in the California area is not as pervasive as in the British Columbia Insular Belt.

The geology of the Cook Inlet area in Alaska is quite similar to the Queen Charlotte Sound, Hecate Strait, and Dixon Entrance of offshore British Columbia while the Tofino and Winona Basins are similar to the undeveloped areas seaward (southeast) of the Kenai Peninsula. The Cook Inlet has an estimated recovery of $1.62 \times 10^9 m^3$ (1.02 billion barrels) of oil from the four largest of six producing fields (Oil and Gas Journal, January 28, 1980). In addition, seven producing fields containing gas have an estimated recoverable reserve of $142.6 \times 10^9 m^3$ (5.05 trillion cubic feet) of natural gas (C.G. Mull, personal communication, 1980).

Of the various regions on the West Coast of North America, Cook Inlet appears to be closest in terms of geology and total hydrocarbon potential to the British Columbia offshore areas. In British Columbia this hydrocarbon potential is mainly in the form of gas while in Cook Inlet the hydrocarbon resources are divided equally between gas and oil.

General Geology

The British Columbia offshore region evaluated in this report is located primarily in the Insular Tectonic Belt (Figure 1). The Insular Tectonic Belt, like most of British Columbia, is composed of allochthonous terranes that have collided with the western portion of the North American Plate. The area evaluated is located primarily in the Wrangellia terrane (Jones et al, 1977) with local overlap into the Alexander terrane (Berg et al, 1972) to the north and the Olympic terrane to the south.

Paleozoic and Early Mesozoic volcanic arc complexes and associated sedimentary basins form the Wrangellia terrane of Vancouver Island and the Queen Charlotte Islands. The terrane is exposed in two northwesterly plunging structural complexes which have been intruded by major batholiths.

The northeastern boundary of Wrangellia with the Alexander terrane is obscure but probably extends along the east side of Hecate Strait, through Dixon Entrance and northwestward towards the continental slope west of the islands of Southeastern Alaska. The Alexander terrane is a complex of Paleozoic and possibly Precambrian volcanic, clastic and carbonate rocks overlain and in fault contact with Mesozoic volcanic, carbonate and clastic rocks.

The southern boundary of Wrangellia with the Olympic terrane may extend through Southern Vancouver Island within the Leech River shear zone (Muller,

STRATIGRAPHIC AGE SYSTEM	STAGE	QUEEN CHARLOTTE ISLANDS AREA		NORTHWEST VANCOUVER ISLAND		CENTRAL WEST VANCOUVER ISLAND		SOUTHWEST VANCOUVER ISLAND		SOUTHEAST VANCOUVER ISLAND		OLYMPIC PENINSULA WASHINGTON	
QUATERNARY	PLEISTOCENE	CAPE BALL FM. Marine & Subaerial	150+ m claystone till, sand & gravel	GLACIAL BEDS	10+ m.	GLACIAL BEDS	10+ m.	GLACIAL BEDS	10+ m. sand, gravel	GLACIAL & ALLUVIAL DEPOSITS	360 m. till, sand, gravel & clay	GLACIAL BEDS	till, sand gravel & clay
1 m.y.													
	PLIOCENE	SKONUN FM. Near Shore Marine & Continental - Interfingering	1900+ m qtz. sand, silt, shale, lignite & conglomerate			UNNAMED SEDIMENTS Marine	1400 m. siltstone, shale & sandstone	UNNAMED SEDIMENTS	1400 m. siltstone, shale & sandstone			UNNAMED SEDIMENTS	1000+ m. siltstone, shale & sandstone
10 m.y.								UNNAMED SEDIMENTS	1300 m. shale, silt			UNNAMED SEDIMENTS	1000+ m. shale, siltstone & sandstone
	MIOCENE					DIVISION D	20 m. marine ss.	SOOKE FM. / DIV. D Marine	450 m. sandstone & conglomerate			UNNAMED SEDIMENTS	450 m. shale, siltstone & sandstone
25 m.y.		MASSET FM. Explosive Submarine & Passive Subaerial Eruptives	Basalt Mbr. 1500+ m. subaerial columnar basalt & andesite	HESQUIAT	75+ m. sand, silt & conglomerate	DIVISION B — DIV. C	1200 m. coquil & ss. 600 m. shale & silt	CARMANAH FM./DIV.B Marine	600 m. sandstone & conglomerate	KITSILANO FM. Continental & Marine	2500+ m shale, conglomerate, coal with sills & flows	WESTERN CORE LITHIC ASS. / WESTERN OLYMPIC LITHIC ASSEM.	phyllite, siltstone sandstone, slate, semi-schist & phyllite
OLIGOCENE				ESCALANTE Marine	35 m. bsl congl.	ESCALANTE / DIV. A	75 m. near shore ss.	METCHOSIN FM. Volcanic	2400 m. basaltic lava, pillows & tuff			CRESCENT FM. Volcanics / NEEDLES - GREY WOLF & ELWHA LITH. ASS. / GRAND VALLEY LITH. ASS.	sandstone, siltstone, phyllite, slate, semi-schist & basalts
40 m.y.													
EOCENE			Rhyolite Mbr. 1600-2100 m. ash rhyolite & basalt										
60 m.y.													
PALEOCENE			Mixed Mbr. 1900+ m. rhyolite tuff & basalt										
70 m.y.													
UPPER CRETACEOUS	MAESTRICHTIAN									NANAIMO GRP. Delta / BURRARD FM.	1500 m. sandstone, siltstone, shale, conglomerate & coal		
	CAMPANIAN												
	SANTONIAN												
	CONIACIAN	SKIDEGATE FM. Marine	900+ m. shale & fine sandstone										
	TURONIAN	HONNA FM. Near Shore Marine	150-1200 m. congl. & sandstone										
	CENOMANIAN	HAIDA FM. Near Shore Marine	Upper Shale Mbr. 200-325 m. shale & siltstone Lower Sandstone Mbr. 600 m. sandstone										
93 m.y.													
LOWER CRETACEOUS	ALBIAN												
	APTIAN												
	NEOCOMIAN	LONGARM FM. Marine	180-1200 m. siltstone, mudstone & ss	LONGARM FM. Marine	250 m. greywacke, conglomerate								
130 m.y.													
LATE JURASSIC	TITHONIAN			DIVISION B. Near Shore Marine	500+ m. shale, siltstone & sandstone								
	PORTLANDIAN												
	KIMMERIGIAN			DIVISION A. Near Shore Marine to Deep Marine & Trench Melange	400 + m. shale, sandstone, siltstone, bioclastic grit, conglomerate & exotic blocks								
	OXFORDIAN												
MIDDLE JURASSIC	CALLOVIAN	YAKOUN FM. Marine Sediments & Volcanic Ejecta (Highly Variable)	E Mbr. 135 m. vol. sandstone & shale D Mbr. 240 m. tuff C Mbr. 470 m. agglomerate & tuff										
	BATHONIAN												
	BAJOCIAN		B Mbr. 30+ m. shale & sandstone A Mbr. 200 m. tuff										
EARLY JURASSIC	TOARCIAN	MAUDE FM. Marine Sediments	180 m. shale, siltstone & minor sandstone	BONANZA GRP. Volcanic Flows & Ejecta	1500 m. basaltic to rhyolitic lava, breccia, tuff & minor argillite & greywacke	BONANZA GRP. Volcanic Flows & Ejecta	1500 m. basaltic to rhyolitic lava, breccia, tuff & agglomerate	BONANZA GRP. Volcanic Flows & Ejecta	1500 m. basaltic to rhyolitic lava, breccia, tuff & agglomerate	BONANZA GRP. Volcanics may be present at depth	1000+ m. basaltic to rhyolitic volcanics		
	PLIENSBACHIAN												
	SINEMURIAN	KUNGA FM. Offshore Marine Sediments	Argillite Mbr. 580 m. mudstone & gywkr	MARBLEDOWN FM. Marine Sediments to the northeast	argillite, greywacke & tuff								
	HETTANGIAN		Black Limestone Mbr 270 m. calcareous mudstone & argillaceous limestone										
190 m.y.													
UPPER TRIASSIC	RHAETIAN			PARSON BAY FM.	450 m. siltstone	QUATSINO FM. Marine	450 m. limestone	QUATSINO FM. Marine	450 m. limestone	QUATSINO FM. Marine	800 m. limestone		
	NORIAN		Massive Limestone Mbr. 180 m. limestone	QUATSINO FM. Marine	400 m. limestone grit, mudstone & [illegible]								
	KARNIAN	KARMUTSEN FM. volcanic flows & breccia	3000 m. basalt flows, breccia & minor sediment	KARMUTSEN FM. Volcanic flows & Pillows	2400+ m. basalt flows & pillows	KARMUTSEN FM. Volcanic flows & Pillows	2400+ m. basalt flows & pillows	KARMUTSEN FM. Flows & Pillow Lava	2000+ m. basalt flows & pillows	KARMUTSEN FM. Flows & Pillow Lava	2000+ m. basalt flows & pillows		
225 m.y.													
PERM. & PINN.		SICKER GRP. Marine Sediments & Volcanics	1000's m. andesitic tuff, flows & sediments	SICKER GRP. Mainly Volcanics	1000's m. andesitic flows & tuff	SICKER GRP./ BUTTLE LAKE FM. Marine Sediments & Volcanics	300 m. limestone, chert, argillite, volcanic flows, tuff & agglomerate	SICKER GRP./ BUTTLE LAKE FM. Marine Sediments & Vol.	300 m. limestone 2400 m. basalt, tuff cherts tuff & flows	SICKER GRP. Marine Sediments & Volcanics	2400 m. andesite to basalt flows, tuff, greywacke & siliceous tuffs		

TABLE I
TABLE OF FORMATIONS
FOR THE
INSULAR TECTONIC BELT
(BRITISH COLUMBIA & WASHINGTON)

Compiled by N.E. Haimila

1977 & 1980) or may occur within the Olympic Peninsula along the first thrust associated with the zone of subduction (i.e. from Cape Flattery extending along the Hurricane Fault zone). The Olympic terrane is composed of lower Cenozoic volcanics intercalated with, and overlain by deep and shallow water sediments. The basement for the Olympic terrane would be oceanic if the boundary is along Cape Flattery - Hurricane Fault. If the boundary is along the Leech River shear zone the basement is the Early Paleozoic Colquitz, Wark and Tyee complex with oceanic crust situated southwestward under the Olympic Peninsula.

Late Mesozoic and Cenozoic basins developed upon these coalesced exotic terranes both before and after their accretion to the North American Plate.

Stratigraphy

The oldest rocks in the region are found in the Victoria - San Juan Islands - Bellingham area where gneissic rocks of the Colquitz, Wark and Tyee complex form the "basement" for the Sicker Group of Pennsylvanian to Permian age (Muller, 1977) (Plate I, Schematic Stratigraphic-Structural Cross Section of the Insular Tectonic Belt; and Table 1, Table of Formations for the Insular Tectonic Belt).

The Sicker Group consists of a lower portion 1,000 metres to 3,000 metres thick of mainly volcanic rocks. In ascending order, this portion consists of siliceous tuffs, flows, sills, more tuffs, and breccias. A middle portion consisting of 10 to 600 metres of shale and greywacke may unconformably overlie the lower portion and is conformably overlain by the Buttle Lake Formation which makes up the upper portion of the group. The Buttle Lake Formation, in its type locality, is composed of 320 metres of Early Permian limestone. Locally, the top of the Buttle Lake Formation exhibits a karst surface which may be infilled with ash, breccia and conglomerates: a unit that has been referred to informally

as the "Henshaw Formation" (Jeffrey, 1967). The most northwesterly exposures of the Sicker Group are in Central Vancouver Island.

This central core of Paleozoic rocks is buried beneath several thousand metres of strata consisting of Late Triassic Vancouver Group. On Vancouver Island, the Vancouver Group, in ascending order, consists of Karmutsen, Quatsino, and Parson Bay Formations. The Karmutsen Formation consists of (in ascending order) siliceous shale, sills, flows, pillow lava, aquagene breccia, and additional flows of basaltic composition. The Karmutsen Formation may exceed 3,000 metres in thickness. To the north, northwest, west, and east the Karmutsen Formation is overlain by the Quatsino Formation which is composed primarily of limestone 25 to 800 metres thick. The Quatsino limestone is overlain by the Parson Bay Formation, a clastic carbonate sequence 300 to 600 metres thick.

To the west and northwest above the Vancouver Group is the Bonanza Group of Early Jurassic age. The Bonanza Group is mainly basaltic to rhyo-dacitic flows, breccia and tuff that become intercalated to the northwest with greater proportions of marine sedimentary rocks. At the north end of Vancouver Island the section is devoid of the volcanic rocks and the equivalent argillite, greywacke and tuff there are called the Harbledown Formation. The Bonanza Group may attain a thickness of over 2,500 metres. The volcanic rocks of the Bonanza Group are probably the extrusive equivalent of the Island Intrusions, batholiths and plutons emplaced within all the older successions. At the time of the emplacement of the Island Intrusions and the accumulation of the Bonanza Group, the Insular Belt is interpreted to have been an island arc system.

During Late Jurassic time (Callovian to Tithonian) unnamed island arc, arc-trench gap and trench melange sequences were deposited to the west of an emergent Vancouver Island volcanic-plutonic terrane. These rocks (Division A) consist of sandstone, clastic carbonates, shale, siltstone, greywacke

conglomerate and exotic blocks in a westward thickening wedge over 400 metres thick and are overlain by nearshore (Division B) shale, siltstone and sandstone over 500 metres thick.

Also on the Queen Charlotte Islands, the oldest rocks are in the southern portion of the area, with the Vancouver Group Karmutsen Formation cropping out on southern and western Moresby Island and adjacent smaller islands. Paleozoic rocks were encountered at total depth in the Tyee N-39 well (Shouldice, 1971 and 1973) and may represent the Sicker Group in the Queen Charlotte Islands. To the north, the Karmutsen Formation is overlain by Late Triassic to Early Jurassic marine sediments of the Kunga and Maude Formations. Sutherland-Brown (1968) included the Karmutsen, Kunga, Maude and the overlying Yakoun Formations within the Vancouver Group. The basal part of the Kunga Formation has two limestone members correlative with the Quatsino Formation. The black limestone member of the middle Kunga is correlative with the Parson Bay Formation and the upper argillite member of the Kunga Formation is approximately equivalent to the Harbledown Formation of the Bonanza Group. The Kunga Formation ranges in age from Late Triassic (Karnian) to Early Jurassic (Sinemurian) and may attain a thickness of nearly 1,000 metres. The organic content of the upper portion of the Kunga Formation is close to that of an oil shale (Sutherland-Brown, ibid.).

Argillites of the Kunga Formation are transitional into the overlying Maude Formation which is composed of shale and lithic sandstone. It ranges from Late Sinemurian through Middle Toarcian age and may attain a thickness of slightly over 100 metres. It is correlative with the upper portion of the Bonanza Group on Vancouver Island.

The Middle Jurassic (Bajocian through Callovian) Yakoun Formation, found mainly on Northern Moresby, Louise and Graham Islands, is probably the island arc equivalent of the lower portion of the unnamed Jurassic sequences deposited

in western Vancouver Island. The Yakoun Formation is composed of marine and near shore, calcareous lapilli tuff, sandstone, agglomerate and tuff, interbedded sandstone and shale, and local coal beds. The Yakoun Formation has been removed by pre-Cretaceous erosion from parts of the southern islands. The Yakoun Formation is transitional into finer volcanic material and more marine sequences in a southwestern direction. The Yakoun Formation may attain a thickness of 1,000 metres.

The Longarm Formation unconformably overlies the Yakoun Formation in the Queen Charlotte Islands and the Bonanza Group and the unnamed Upper Jurassic sequences on northern Vancouver Island. The Longarm Formation is a Lower Cretaceous (latest Valanginian through Barremian) marine trough and shoreline sequence composed of conglomerate, greywacke, siltstone and shale. It may attain a thickness of 250 metres in the nearshore environment and exceed 1,200 metres of the faulted trough environments.

Following a period of uplift and erosion isolated basins developed behind the island arc. Some of these basins were connected to marine environments by seaways. Many of these marine transgressions radiate outward from the Queen Charlotte Sound area which appears to have been an area of marine deposition throughout most of the interval spanning from Late Triassic to the Pleistocene and Recent.

The Queen Charlotte Group was deposited in one of these marine basins in the Queen Charlotte Islands area during Albian through Coniacian time. The Haida Formation, the lowermost sequence of this group, consists of a nearshore arkosic sandstone and siltstone member which is transitional upward into a highly carbonaceous marine shale and siltstone member. The Haida Formation may exceed 1,100 metres in thickness where it infills older topography. The Honna Formation composed of nearshore marine conglomerate and sandstone overlies

the Haida Formation with scoured but structurally conformable contacts. Locally the Honna Formation may interfinger with the Haida Formation. The Honna Formation varies from 200 to 1,200 metres in thickness. The Honna Formation is transitional with the overlying Skidegate Formation which is composed of marine shale, siltstone and fine to medium-grained sandstone. The Skidegate Formation is approximately 900 metres thick.

Another basin that developed behind an island arc was the Nanaimo Basin. Continental sandstone, conglomerate, shale and coal were deposited in the Nanaimo Basin during late Upper Cretaceous (Santonian and Maestrichtian). Marine tongues within the upper formations of the Nanaimo Group record southeastward transgression from the Queen Charlotte Sound area (McGugan, 1979), but for the most part the Nanaimo Group is composed of nonmarine and nearshore deltaic rocks.

An episode of vulcanism occurred during the Paleocene and Eocene and locally this vulcanism continued into the Oligocene and Miocene. In the Queen Charlotte Islands the volcanic rocks that accumulated during this episode are the Masset Formation whereas on southwest Vancouver Island and the Olympic Peninsula they are the Metchosin and Crescent Formations respectively. These volcanic rocks have yielded radiometric ages between 47 and 22 million years. Associated with this episode of vulcanism is a period of plutonism and metamorphism. The Sooke Intrusion is an example of the plutonic rocks, and the metamorphic rocks are represented by the fault bounded, metamorphic complex of the Leech River Formation. The metamorphism of the Leech River Formation is 40 million years old and the Sooke Intrusions have yielded radiometric ages between 32 and 59 million years (Muller, ibid.).

Along the shore and in the offshore areas of western Vancouver Island the Escalante Formation overlies and onlaps Eocene volcanic rocks. The Escalante

Formation (Division A of Jeletzky, 1954) is the basal conglomerate laid down on the Metchosin Formation and the Vancouver Group along the cost and may also onlap the volcanic ridge in the arc-trench gap offshore. The formation consists of pebble conglomerate, grit, and coarse to fine-grained sandstone in its lower part, and concretionary fine to very fine-grained sandstone in its upper part. Where exposed in its higher onlapping facies the Escalante Formation is of Eocene or lowermost Oligocene age and may attain a thickness of over 300 metres. Offshore it is probably thicker and at the base somewhat older.

Southeastward, along the coast and offshore, the Carmanah Formation overlies and onlaps the Escalante and Metchosin Formations and the Vancouver Group. The Carmanah Formation is composed mainly of marine siltstone and sandstone. Although some controversy exists relating to the age assigned to the various formations along the west coast of Vancouver Island (Jeletzky, 1954, 1973 and 1975, and Cameron, 1971, 1972, 1973 and 1975), for the purposes of this report, the Carmanah Formation is considered to be equivalent to Division B (of Jeletzky, 1973) and its deposition took place during most of the Oligocene. It is 600 metres thick.

Along the northwest coast of Vancouver Island, submarine channel deposits of the Hesquiat Formation cut into and overlie the Escalante Formation. The Hesquiat Formation is equivalent to Division C (of Jeletzky, 1975). The Hesquiat Formation is composed of alternating sequences of shale grading through siltstone to sandstone, coarse sandstone, pebble to boulder conglomerate and pebbly mudstone. The Hesquiat Formation may range from Late Eocene or Early Oligocene into Late Oligocene (Jeletzky, 1973 and 1975) and may attain a thickness of over 2,135 metres.

The Hesquiat or Carmanah Formations may be overlain with minor local unconformity by the Sooke Bay Formation (Muller, 1977) or its equivalent

Division D (Jeletzky, 1973). The Sooke Bay Formation represents a regressive near shore marine environment in which approximately 450 metres of sandstone and conglomerate were deposited. The age of this formation is Early Miocene (Upper Blakely or Upper Zemorrian).

A period of crustal deformation initiated during Early Miocene continued into the Middle Miocene. This period of deformation is represented by an unconformity followed by marine transgression in Late Miocene time. Late Miocene sediments are unnamed and are composed of marine siltstones and shale with local sandstone interbeds. This interval may be 1,100 metres thick in the offshore areas of the Tofino Basin.

Two additional regressive-transgressive phases occurred in Early Pliocene and in Late Pliocene-Pleistocene time. The regressive phases are represented by unconformities and transgressive phases are usually represented by marine sandstone units overlain by marine shale and siltstone. These last two regressive-transgressive cycles are represented by up to 1,350 metres of rock.

In the Queen Charlotte Islands, some authors have indicated that Tertiary sedimentation began in Miocene time over volcanic rocks of the Masset Formation (Shouldice, ibid., and Chase et al., 1975). However, from several lines of evidence it is possible to conclude that Upper Cretaceous and Lower Tertiary rocks may underlie the Queen Charlotte Sound area. In the Richfield Nadu River and Cape Ball wells both encountered marine sediments below and intercalated with the Paleocene to Eocene Masset Formation. Gravity modelling by Stacey (1975) indicates a much thicker layer of low density material in the Hecate Strait and Queen Charlotte Sound area than that shown by Shouldice (1973, Fig. 32). Stacey suggests that the Queen Charlotte Sound area was an earlier area of deposition underlain by Lower Tertiary, low density Mesozoic rocks or possibly even granite. The Masset Formation does not extend to Vancouver Island.

Facies and thickness changes in the Masset Formation demonstrate the change from continental to shallow marine deposition in the Southern Queen Charlotte Islands. Yorath (personal communication, 1978) indicated that magnetic data may also reflect a termination of the Masset volcanics in the Queen Charlotte Sound area. The Lower Tertiary sediments may even be intercalated with the distal facies of the Masset Formation as in the Nadu River well.

Above the inferred sediments in the Queen Charlotte Sound and Islands areas, the Miocene to Pliocene Skonun Formation overlies and is intercalated with the Masset Formation. The Skonun Formation is composed of non-marine and marine sandstone, siltstone, conglomerate and lignite. The Skonun Formation may be over 1,800 metres thick in some localities.

The Skonun Formation is overlain with local unconformity by the Cape Ball Formation. The Cape Ball Formation is of Pliocene to Pleistocene age and is composed of minor marine sandstone and claystone but for the most part consists of subaerially deposited clay, till, sand and gravel. It may attain a thickness of over 150 metres. The Skonun and Cape Ball Formations are mainly continental to the northwest but are transitional to marine in the southern Queen Charlotte Sound area (Shouldice, 1973) where marine conditions exist today.

The Tow Hill Sills composed of olivine basalt up to 100 metres thick intrude the Skonun Formation locally. Because of their position high in the Skonun section and because of possible sculpturing by glaciers the Tow Hill Sills are thought to be Late Pliocene or Earliest Pleistocene in age.

Tofino Basin

The Tofino Basin is located on the continental shelf west of Vancouver Island and extends into the Juan de Fuca Strait in the southeast. Shouldice (ibid.) gives a detailed account of the stratigraphy and structure of the area.

His stratigraphic, structural and seismic cross-sections illustrate the stratigraphic column, convergence of sedimentary units, local unconformities, faulting, diapirism and the position of the petroleum exploration "basement".

The basement in this basin is probably the upper surface of the Eocene Metchosin or Crescent Formations which, as mentioned earlier, are volcanic rocks composed of marine basalt and pillow lavas. Volcanics of the Crescent Formation occur in thrusted positions near the coast of the Olympic Peninsula (Tabor and Cady, 1978). This formation also crops out as overturned, to ocean-facing thrusts in a subduction zone within the Olympic Peninsula. The projection of the ocean-facing thrusted volcanics into the Tofino Basin forms the seaward sill of the isolated basins in the Lower Tertiary arc-trench gap. Eocene conglomerate and sand onlap the Vancouver Group (Jeletzky, 1973) on Vancouver Island and appear to onlap the volcanics offshore. Oligocene and Lower Miocene sandstone, siltstone and shale also appear to onlap the volcanic basin-sill, the Eocene sediments, or older formations locally. Submarine channel deposits cut through the Lower Tertiary sediments locally.

Upper Miocene marine siltstones and shale cover and seal the arc-trench-gap basins between the shore and the continental slope. Additional shale, siltstone and minor sandstone were deposited in the offshore areas. Within the arc-trench-gap basins and near thrust zones, shale diapirs have intruded and formed structures within younger sediments. Variable fluid over-pressuring is common within the areas of diapirism and within the sediments of the sealed basins.

The well history reports indicate that good porosities and permeabilities have been measured in sidewall cores from exploratory wells. The mud logs from these same wells detected gases in the muds. Some relatively high methane values were obtained and the C_2 through C_5+ values generally increased in the deeper and older Tertiary formations.

Winona Basin

The Winona Basin is a sedimentary basin situated at the foot of the continental slope and on the continental shelf off northern Vancouver Island. Lower and Upper Miocene and Pliocene rocks occur on the continental slope. Lower Cretaceous sediments found along the shore of Vancouver Island may extend into the Basin. The portion of the basin at the foot of the continental slope is composed of approximately 4,000 metres of Pleistocene, Pliocene and older Tertiary sediments below approximately 2,000 metres of water. These sediments are composed of mudstone, sandstone conglomerate and minor coal (Tiffin, 1973, as reported in Chase, 1975). The rocks are faulted and folded along northerly and northwesterly trends. The deformation increases with depth as the sediments respond to being oblique subduction beneath the North American plate.

Queen Charlotte Sound, Hecate Strait and Dixon Entrance Region

The Queen Charlotte Sound, Hecate Strait and Dixon Entrance are offshore of the Queen Charlotte Islands to the southeast, east and north respectively. The geology of the Queen Charlotte Islands is covered comprehensively by Sutherland-Brown (1968) and the offshore areas explored by Shell Canada are detailed by Shouldice (ibid.). Because the offshore well data, with few exceptions, are confined to the Upper Tertiary sediments, the lithology and stratigraphy below the Masset Formation must be projected from onshore outcrops.

The pre-Cretaceous sediments which have been intruded by plutons and plugs on the Queen Charlotte Islands may contain both source and reservoir rocks where they are unmetamorphosed. As mentioned earlier, the Kunga Formation may be a potential oil shale. The pre-Cretaceous sediments are unconformably overlain by the fine to coarse clastic sequences of the Longarm Formation which in turn are unconformably overlain by the sediments of the Queen Charlotte Group. Both

the Haida and the Skidegate Formations contain highly carbonaceous shale and siltstone units and the Honna Formation between them is a coarse clastic unit. Sutherland-Brown (ibid.) infers that the Haida Formation warrants consideration for its hydrocarbon potential. He observed tar-filled vesicles within the overlying Masset Formation and cites MacKenzie's (1916) earlier reports of the same phenomen~~a~~on. In addition, Sutherland-Brown also encountered one occurrence of tar-filled vesicles within the Middle Jurassic Yakoun Formation. He attributes the occurrence of tar within the volcanics to the distillation of hydrocarbons from woody material within the underlying formations.

Shouldice (ibid.) considered the Masset Formation, which is several thousand metres thick on the Queen Charlotte Islands, to be "basement" in the Hecate Strait and Queen Charlotte Sound areas. This may not be the case in all instances. The Masset volcanics trend from subaerial eruptives on Graham Island to shallow water fragmental accumulations on the southern islands. This argument and others presented previously would indicate that the Masset Formation terminates somewhere within the Queen Charlotte Sound area and possibly within the Hecate Strait also. The intercalation of the Masset volcanics with Skonun and older Tertiary sediments and the trend toward more marine conditions within the Tertiary sequence toward the southeast would make that area of the Queen Charlotte Sound and Hecate Strait highly prospective for hydrocarbon exploration.

The structural setting of the Queen Charlotte Island area is more complex than that of the Tofino Basin. The rift zone associated with the East Pacific Rise extension butts against the continental margin in the Queen Charlotte Sound area. The Fairweather-Queen Charlotte Sound Fault zone is the transform fault zone which separates the North American Continent from the North Pacific Plate. The northwest trending fault system associated with this zone appears to have predominantly right lateral offsets across the fault traces. Other

shear directions are also found within the area. They trend north, east and east-northeast. The north and east faults have left-lateral fault separation and the east-northeast faults have right-lateral separation. In addition to the lateral offsets, the southerly and easterly blocks are down-dropped relative to the adjacent blocks (Sutherland-Brown, ibid.). Overpressuring and shale diapirism are not in evidence in this area.

Good porosities have been measured in sidewall and conventional cores but the permeabilities are variable in the feldspar-rich sandstone of the Tertiary section, with most of the values being relatively low.

The methane values obtained from analyses of mud samples from the exploratory wells were relatively low except for the two Sockeye wells. All wells showed a general increase in the C_2 values through C_4 values in the deeper and older formations. In the Sockeye B-10 well, the highest gas values were found in the 3950-4300 metre interval.

The highly carbonaceous and petroliferous shales in the Mesozoic section and the occurrence of tar-filled vesicles in the volcanic rocks suggests that potential source rocks exist in the area. The area to the west and southwest of the Queen Charlotte Islands contributes marginally to the hydrocarbon potential of the area because the Fairweather-Queen Charlotte Fault system truncates the shelf within 8 kilometres of the coast and the limited areal extent of the shelf can accommodate few hydrocarbon traps.

Estimation Method

The estimates of the hydrocarbon potential of the offshore areas of British Columbia were made using the philosophy and methodology discussed in Appendix I "Resource Estimation (Part 1, Conventional Oil and Gas Resources)"

in Energy, Mines and Resources Canada Report EP77-1, Oil and Natural Resources of Canada, 1976. For purposes of this assessment, "exploration plays" were developed for the various regions within the offshore areas. These plays were based on past exploration in addition to the introduction of new play concepts which evolved from the synthesis of data accumulated from many sources.

Within each of the several exploration plays individual prospects were identified. Utilizing the data available, each parameter for the prospect was characterized by a cumulative frequency distribution curve and each aspect was "risked" in accordance with its perceived marginal probability. The cumulative frequency distribution curves and engineering conversion factors were sampled by a random number simulation technique (known in the discipline of statistics as a Monte Carlo technique) to give a conditional pool size distribution of the play.

The number of prospects which had been identified in each play plus any additional prospects which were thought likely to exist in the area were also expressed as a cumulative frequency distribution. The combination of the conditional pool size distribution with the distribution of the number of prospects appropriately risked generates a distribution of potential for each play.

The likelihood that any individual prospect contains hydrocarbons was derived from the product of all the marginal probabilities attached to the parameters of that play. This product is the risk factor of the whole play, approximating the perceived success ratio of finding hydrocarbons. In the British Columbia offshore areas the success ratios for the various prospects within the several plays were judged to be relatively low - in the order of 1:10 to 1:40.

During the evaluation process the committee estimated the ratio of gas to oil that should be present in each of the exploration plays. This estimate was based on geological and geochemical considerations such as: the source rock type, geochemical extraction determinations, mud log indications, coal ranks, hydrocarbon shows, tectonic and metamorphic setting, vulcanism, maturation levels, and historic recoveries. Mainly because of the source rock types and the levels of maturity which might be associated with an ancestral island-arc system the committee considered the offshore areas to be gas prone and the opinion of the committee is reflected in the gas/oil proportions of the final potentials.

Summary

Exploration for oil and natural gas has been carried out intermittently between 1949 and 1971 in the British Columbia Insular Tectonic Belt. A program initiated by Shell Oil Company of Canada resulted in 14 exploratory wells being drilled in the offshore areas between 1967 and 1969. Two of the wells in the Tofino Basin had very small gas shows and one well in the Hecate Strait had oil staining in sidewall core.

In 1978, assessments of the hydrocarbon potentials of several exploratory plays for the offshore areas of British Columbia were completed utilizing all the data available at that time. In 1980 these estimates were aggregated to produce the natural gas and oil potential curves for the British Columbia offshore areas. Considering the geology, the tectonic history, the vulcanism, the sedimentary types, the organic material, organic maturation and the thermal regimes in the region, the offshore area was considered to be gas-prone.

As is typical of a frontier area, only a nominal amount of gas or oil is expected with certainty. The average expectation is that $265 \times 10^9 m^3$ (approximately 9 trillion cubic feet) of natural gas and $38.5 \times 10^6 m^3$ (approximately 250 million barrels) of oil will exist within the area. At more speculative levels, incorporating greater uncertainty, the estimates increase by a factor of three or four times while the ultimate potential is approximately ten times the average expectation for natural gas and approximately twenty times the average expectation for oil.

The combined average expectation of the hydrocarbon potential of the British Columbia offshore area is similar to the combined hydrocarbon equivalents already found in the Cook Inlet area of Alaska. The geology of the British Columbia offshore area is also similar to that found in the Cook Inlet of Alaska.

The offshore basins of British Columbia contain a very thick and geologically complex sequence of sediments preserved in the Tofino, Queen Charlotte and adjacent smaller basins. Vancouver Island and the Queen Charlotte Islands are essentially two northward plunging complexes of Paleozoic through Mesozoic volcanic arc and sedimentary basin terranes intruded in Jurassic and Tertiary by major batholiths. Rocks as old as Devonian may be present in the area but ubiquitous Upper Triassic volcanics of the Karmutsen Formation and the intrusions and, in some cases the extrusions, of the Jurassic form the ultimate "basement" for hydrocarbon exploration in the region. In the Queen Charlotte Sound, Hecate Strait and Dixon Entrance areas the Middle and Upper Mesozoic and Upper Tertiary marine sequences may be the targets of hydrocarbon exploration, while in the Tofino and subsidiary Winona Basins the clastic sediments above the Eocene volcanic rocks are the targets for exploration.

The targets or prospects perceived by the assessment committee were evaluated and aggregated by a random number simulation technique called a Monte Carlo method to produce the natural gas and oil potential curves mentioned earlier.

Many of the play concepts that were examined will have to be tested by drilling before any stability can be expected in the resource estimates. Initially, exploration risks or the chance of failure must be considered extremely high. Until the major plays throughout the region have been tested with a minimum of 10 separate wells, it will be very difficult to assess the true gas-oil ratio that can be anticipated and other concerns related to the hydrocarbon potential that may have to be addressed.

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