OIL&GAS JOURNAL

HOPEDALE BASIN—1

Favorable geology, advanced technology may unlock Labrador's substantial resource

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Several large gas discoveries were made along the Canadian Labrador shelf during an early exploration cycle that extended through the 1970s into the early 1980s. With the focus at the time being strictly on oil exploration, no development and no further drilling have occurred in the area since 1983.

That early drilling, which included only 27 wells (21 located in the Hopedale basin) proved the presence of 4.2 tcf of recoverable natural gas in the five discoveries made and demonstrated the presence of a rich petroleum system over a vast area.

With recent trends in commodity prices and the need for new supply regions it is understandable that industry is now revisiting this highly prospective frontier located on the northeast corner of North America. To date this renewed activity has been in the form of modern 2D seismic data across the shelf and into the unexplored slope and deepwater area.

Although there are two major basins in the Labrador Sea, the focus in the new exploration cycle is the Hopedale basin which contains the significant discoveries from the earlier cycle. The Hopedale basin is a large Mesozoic rifted area that covers 175,000 sq km and extends from the modern day shelf to the lower slope (200 to 3,000 m of water).

Based on the characteristics of the prerift basement and of the sedimentary infill, the Hopedale basin can be subdivided into a series of subbasins and ridges probably offset on strike by transfer faults. Several larger depocenters are recognized on the shelf and slope that contain thick Mesozoic sequences including mature Cretaceous source rocks and possibly Late Jurassic aged sediments at deeper locations.

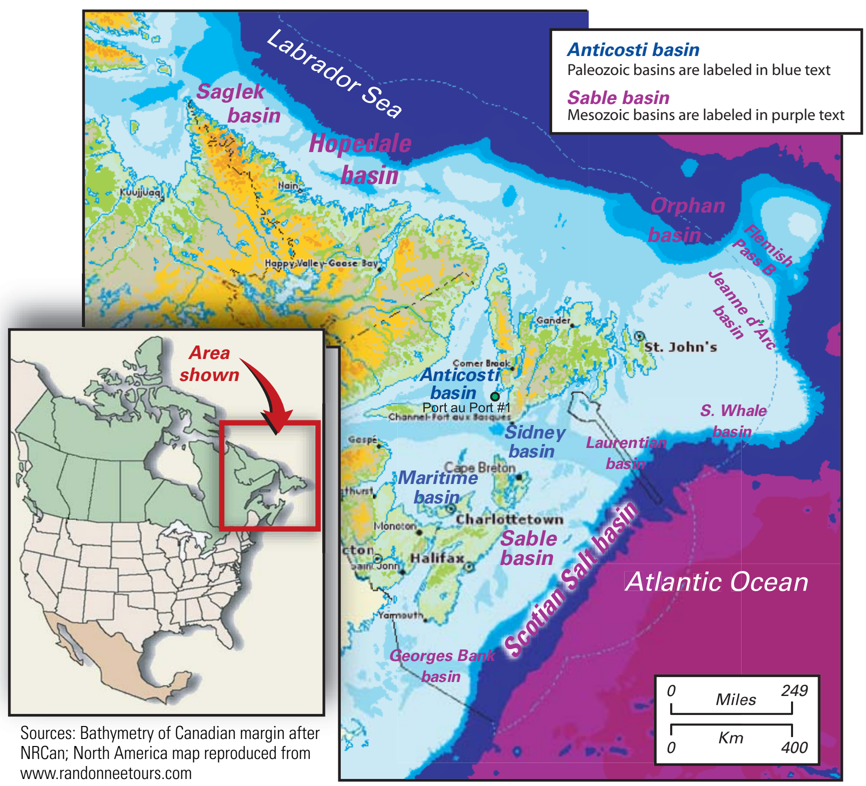
The improved resolution of seismic data shows a number of large, previously unknown structural and stratigraphic leads on the distal continental shelf and on the slope.

As attested by the existing discoveries, the Hopedale basin has considerable potential for natural gas development and presents a wide variety of large, undrilled structural and stratigraphic features. However, oil shows in two of the Labrador wells, as well as on the conjugate margin off west Greenland, also indicate that there is a good possibility of oil finds.

The increasing demand for clean energy in the Eastern US and Canada is being supplemented by the emergence of new cold-ocean production and transportation technologies (CNG, LNG, GTL tankers, for example) and is setting the stage for a new cycle of exploration drilling and monetizing the stranded gas resources off Labrador.

HOPEDALE, OTHER EAST CANADA BASINS

Fig. 1

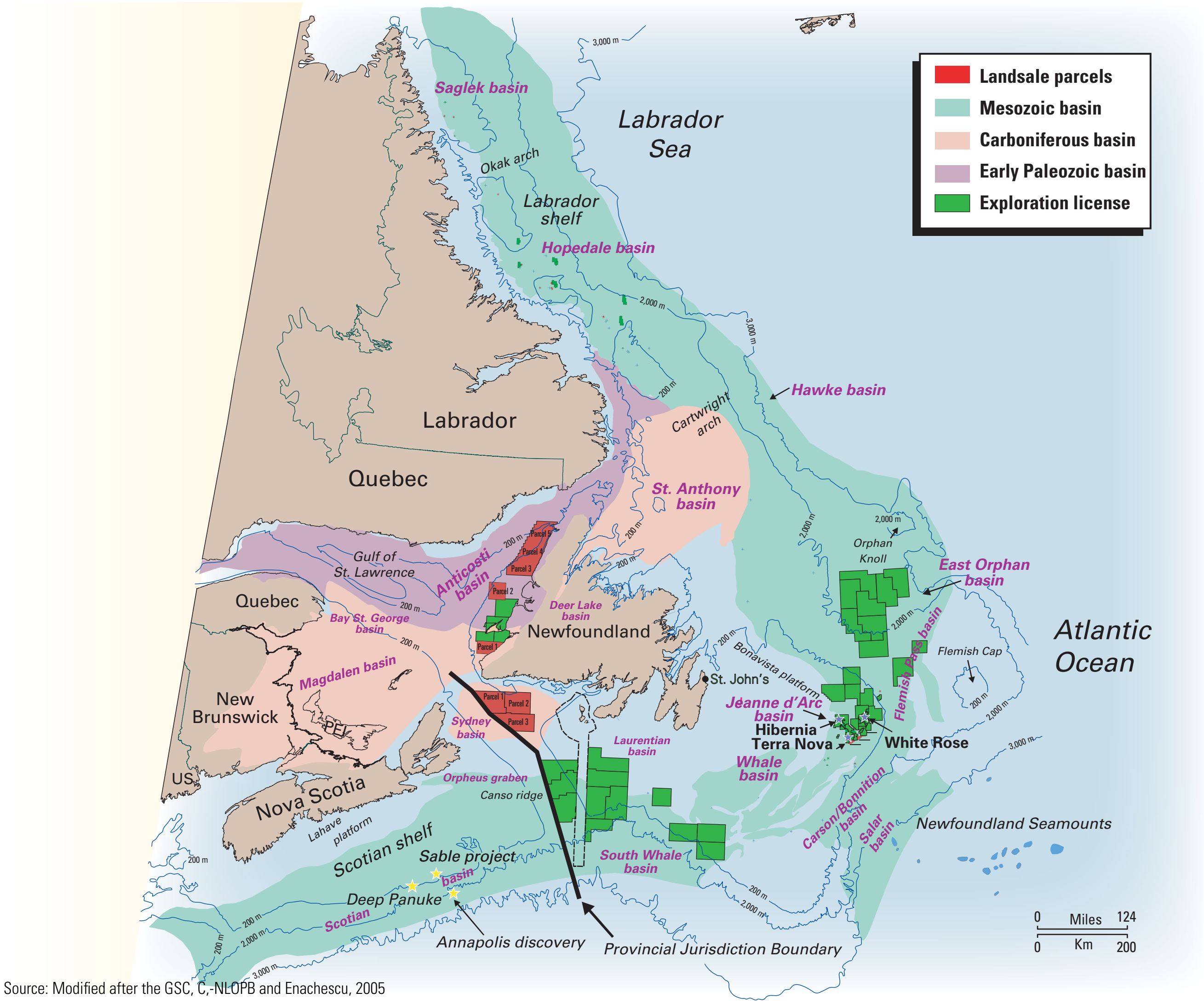


Sources: Bathymetry of Canadian margin after NRCan; North America map reproduced from www.randonneetours.com

Reprinted from the June 19, 2006 and June 26, 2006 edition of **OIL & GAS JOURNAL**

ATLANTIC CANADA BASINS AND NL LAND TENURE MID-2006

Fig. 2



Source: Modified after the GSC, C,-NLOPB and Enachescu, 2005

Introduction

Although almost 10 tcf of recoverable natural gas has been discovered offshore Newfoundland and Labrador, (4.2 tcf offshore Labrador and 5.99 tcf on the Grand Banks), commercial production of gas has yet to proceed.[1-4]

The solution gas being produced with the oil on the Grand Banks is presently being re-injected to maintain reservoir pressure and for eventual commercialization. Work is under way in government agencies, at Memorial University, and among the industry players on the best means to bring this gas to market.

A new exploration program off Labrador may bring the large future gas discoveries that provide the critical mass and will launch offshore Newfoundland and Labrador as a new gas supply area for North America. Alternatively it may bring new oil discoveries to a province that it will soon produce 400,000 b/d of oil.[5]

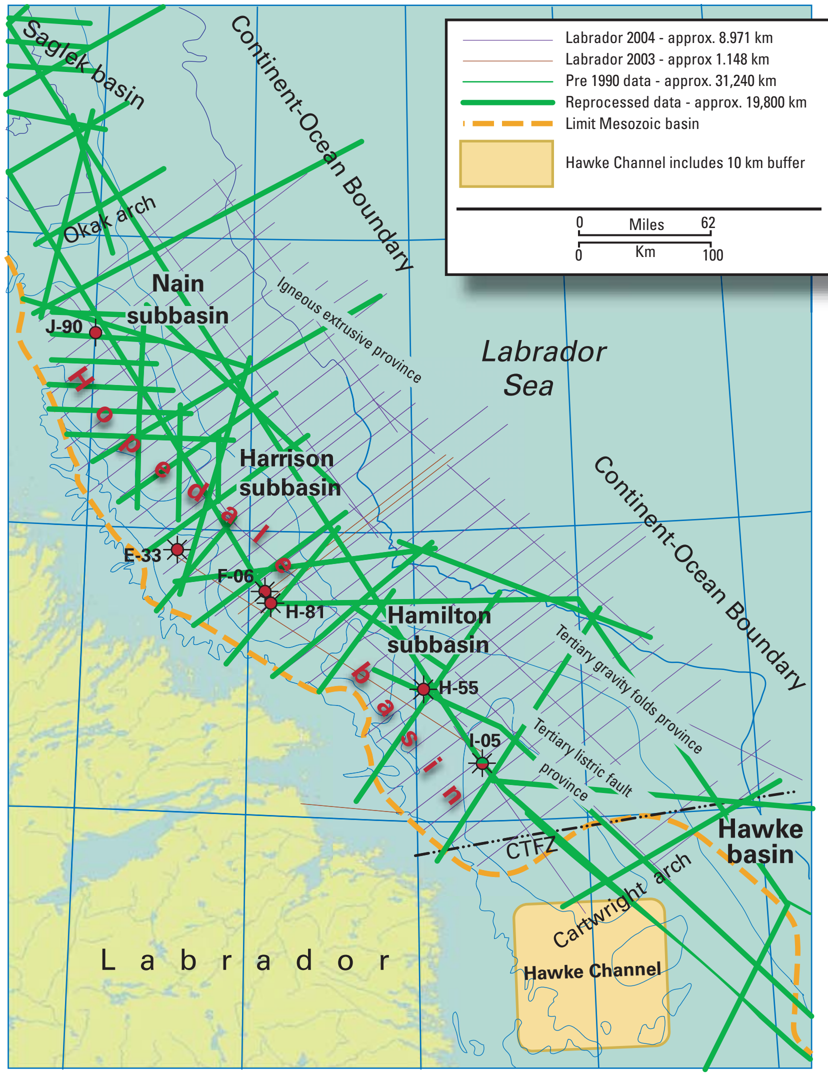
The passive continental margin of Atlantic Canada stretches on for more than 3,000 km from Georges Bank, at the Canada-US border to the northern tip of Labrador (Figs. 1 and 2) and off Baffin Island.[1 2 6-8]

With production of more than 338,000 b/d, representing around 10 million bbl/month, the province of Newfoundland and Labrador is producing at the level of a world class producer from one giant, Hibernia, and two large fields, Terra Nova and White Rose. This production represents about 40% of Canada's light oil output and it is equivalent to about 40% of the present deepwater Gulf of Mexico production.

White Rose field began production in late 2005 and is expected to ramp up this summer to about 100,000 b/d, while the other two fields have reached their production peaks. These fields are in the increasingly productive Jeanne

HOPEDALE BASIN STRUCTURAL SUBDIVISIONS, DISCOVERIES, SEISMIC DATA

Fig. 3



d'Arc basin, which is only one of the many Mesozoic basins located in Atlantic Canada.

Based on latest geologic, petrophysical, and reservoir simulation studies and drilling results, the C-NLOPB has revised upward its estimates of recoverable reserves-resources. It put Hibernia field oil reserves at 1.244 billion bbl, an increase of 379 million bbl, and the Hebron complex at 731 million bbl of proven and probable oil resources, an increase of 317 million bbl.

These amounts bring the total of oil reserves-resources in the Newfoundland and Labrador offshore area to 2.75 billion bbl, an increase of 696 million bbl from previous estimates. This combined reserve boost generously counterbalances the already produced oil from Hibernia and Terra Nova fields.

Newfoundland and Labrador's area of petroleum potential extends far beyond the boundaries of the producing Jeanne d'Arc basin.[6-8] Mesozoic sedimentary basins are found from the Laurentian basin, across the Grand Banks basins, through the deeper waters of the Flemish Pass basin, and into the Orphan basin, where activity is now focused, and continuing northward into several basins along the Labrador shelf and slope (Figs. 1 and 2).[7 9-11]

Also present are Paleozoic basins that occupy several large areas on land and the entire Gulf of St. Lawrence, off Newfoundland's west coast.[12] Recent petroleum land sales including the present 2006 Call for Bids (closing November 2006) have targeted both Mesozoic and Paleozoic basins, with major exploration programs ongoing in the East Orphan and Laurentian basins.[6 7]

The Labrador Mesozoic area (Fig. 2) is the most northerly of the Atlantic Canada basins, and it appears that the large 2D programs in the area are part of a reconnaissance phase that is likely to lead to a licensing round in the near future.

Regional geology

Favorable geology with proven large gas discovery but relatively remote location and harsh environment characterize the Labrador Sea.

The Hopedale basin is the southernmost rift basin within the Labrador Sea and is positioned just north of the Orphan basin, which is an area of current exploration drilling by Chevron, ExxonMobil, Imperial Oil, and Shell (Figs. 1 and 2). The basin has an elongated area of 175,000 sq km situated between 55° and 59° N. Lat. (same latitude as North Sea) and in 100 to 3,000 m of water.

The shelf part of the basin has water as deep as 400 m, was recently glaciated, and contains several banks, plateaus, and troughs. The slope is relatively gentle and less sculptured by canyons as compared to the Scotian shelf or Southern Grand Banks margins.

The Labrador Sea is an Atlantic-type extensional margin, initially part of the intracontinental network of basins formed during the Mesozoic between North America and North Africa and Europe.[2 7 13-19]

The region was subjected to rifting, continental mantle exhumation, drifting, seafloor spreading between Labrador and Greenland, oceanic rift cessation, ridge abandonment, and significant thermal subsidence.[2 5 17 20-24]

The prerift basement consists of Precambrian metamorphic and magmatic rocks and Paleozoic clastics and carbonates.[12 25-28] The Mesozoic sedimentary fill contains faulted and slightly folded mostly Early Cretaceous synrift sedimentary rocks, all covered by a thick wedge of Tertiary and recent glacial deposits.

Geologically, the Hopedale rift basin is bounded:

- To the west by the onlap of Mesozoic beds into a prerift basement hinge zone or in places by a down-to-the-sea basin-bounding fault;
- To the south by the Cartwright Transfer Fault Zone (CTFZ) that separates it from the Cartwright arch and Hawke basin;
- To the east by the lineament marking the Continent-Ocean Boundary (COB) that is placed beyond the end of the seismic survey; and
- To the north by Okak arch and an implied transfer zone separating it from the Saglek basin (Fig. 3).

Recent seismic exploration in the basin began in 2002 and includes more than 30,000 line km of speculative 2D seismic, predominantly acquired by Geophysical Services Inc. (GSI), Calgary. The original programs were more of a regional grid to define the major structural and stratigraphic elements of the basin, but each year GSI has returned to acquire denser coverage that is more suitable for identified leads and prospects. GSI has donated the data to Memorial University for regional geology studies and made the data available for illustrations in this article.

Exploration history

Over 40 years of petroleum exploration has unlocked the regional geology and unveiled some of the petroleum wealth of the sedimentary basins.

The shelf of the Hopedale basin was intensively explored in the 1970s-early 1980s when over 120,000 km of 2D seismic data was collected and all existing 21 industry wells within the basin were drilled.[7 14 29-32] Several wells did not reach their petroleum targets and only 16 wells provide significant data in terms of basin analysis.

This earlier seismic and drilling information helped to identify the main stratigraphic units and structurally map the shelfal Late Mesozoic-Cenozoic basinal area that contains proven reservoirs and source rocks.[29 30 33]

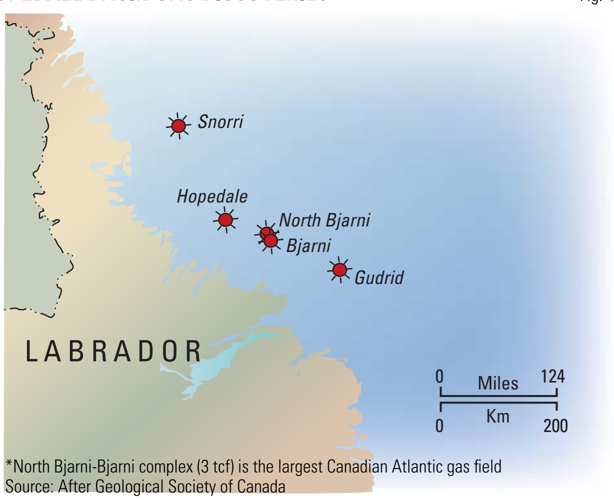
The Geological Survey of Canada (GSC) provided a thorough portrayal of Labrador Sea basins based on interpretation of earlier seismic data in its monumental Labrador Atlas.[14] The present study extends the Hopedale basin description into the deeper parts of the basin and to the outer shelf and slope area (up to 3,000 m of water) and helps evaluate its further petroleum potential

All five Labrador shelf gas discoveries have come from shallow targets in the Hopedale basin (Figs. 1 through 4). The first discovery, Bjarni H-81 in 1973, was followed by Gudrid H-55 (1974), Snorri J-90 (1975), Hopedale E-33 (1978), and North Bjarni F-06 (1980) (Figs. 3 and 4).[2 4 13 29 30 32] These wells tested between 8 and 20 MMcfd.

The computed recoverable resources (P50) are for North Bjarni 2.2 tcf, Bjarni 0.9 tcf, Hopedale 0.1 tcf, Gudrid (0.9 tcf), and Snorri 0.1 tcf.[3 7 31 34] No drilling has occurred in the basin since 1983.

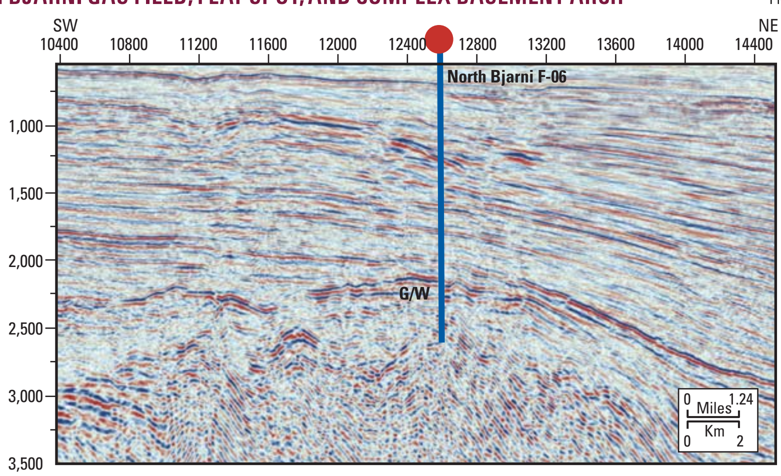
The excellent quality reservoirs encountered at depths of 2 km to 3.5 km are Late Cretaceous sandstones of the synrift sequence and Paleozoic prerift limestone and dolomites.[5 14 29 33] The discoveries have estimated total reserves of 4.2 tcf of gas and 123 million bbl of NGL of 50-60° API. The undiscovered gas potential in the Labrador shelf is estimated at

HOPEDALE BASIN GAS DISCOVERIES* Fig. 4



*North Bjarni-Bjarni complex (3 tcf) is the largest Canadian Atlantic gas field
Source: After Geological Society of Canada

NORTH BJARNI GAS FIELD, FLAT SPOT, AND COMPLEX BASEMENT ARCH Fig. 5



Source: Seismic line courtesy of GSI.

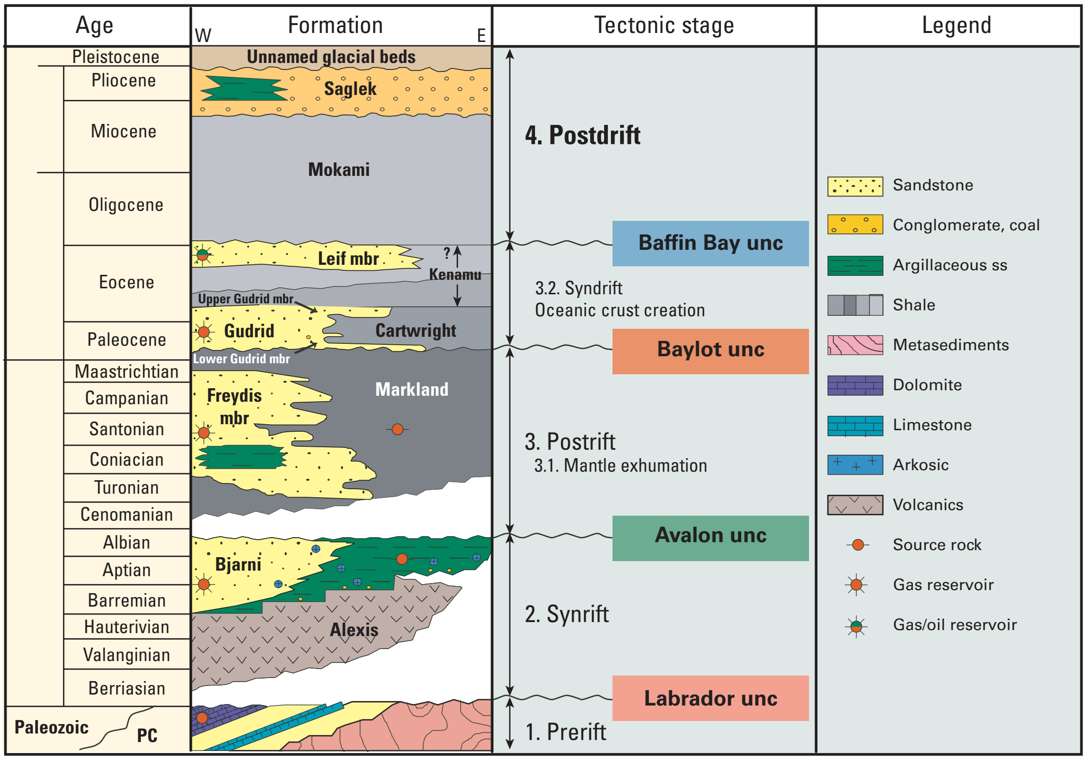
22 tcf.[34]

One complex formed by adjacent Bjarni and North Bjarni fields contains more gas than the currently producing Sable Project (Sable is composed of five medium size fields off Nova Scotia) or the large (2.7 tcf) White Rose gas cap in the Jeanne d'Arc basin (Figs. 3 to 5).

Umpleby defined the stratigraphic nomenclature of the Labrador shelf sequence.[33] McWhae et al.[29] redefined the basin stratigraphy using several new seismic stratigraphic units; GSC adapted his published chart, which was largely accepted by the exploration community.

Labrador shelf lithostratigraphy and tectonic stages

Fig. 6



Source: Modified after Umpleby, 1979; McWhea et al., 1980; GSC, 1987; and Enachescu et al., 2006.

A lithostratigraphic chart modified from these authors and including tectonic evolution, source, and reservoir intervals and main unconformities marked by regional seismic markers is presented in Fig. 6. During the early exploration cycle, drilling targeted basement highs, drape anticlines, sand pinchouts, and several listric fault blocks. One well, North Leif I-05, has recovered small quantities of 33° API waxy oil from the Bjarni sandstone (Fig. 3).

It is worth mentioning that gas discoveries were recorded accidentally during the search for oil reservoirs. No systematic gas drilling, using DHI or AVO analysis of the seismic data, was ever performed in this area.

Geoscience data base

A large variety of industry and research reflection, refraction, gravity, magnetic, bathymetric, engineering, economic, environmental and well data has accumulated in the Labrador Sea and are available for consultation from the GSC, C-NLOPB, Government of Newfoundland and Labrador, Memorial University, and other sources.

Only the geoscience database is discussed here, and the reader can find more detailed information in the attached references.

Seismic data. The early seismic data base is extensive, comprising well over 100,000 km of data spanning over 15 years of seismic exploration and research in the Labrador Sea area. Most of the older data were collected only on the continental shelf and upper slope and are not migrated.

Several multichannel deep seismic lines were also acquired by research institutes in Canada and abroad.[18 19 24] GSI and TGS recently recorded high quality long lines and made them available to the industry.

The GSI 2003-2004 Hopedale basin 2D seismic grid was donated to Memorial University for regional structural studies and investigation of its petroleum systems (Fig. 3). This data set was used in this study. The GSI dip lines cover the entire continental margin extending into the deep and ultradeep water.

A dozen basin-crossing strike lines were collected to tie most of the significant exploration wells and correlate regional markers. Evidently, this data grid contains better quality imaging than data collected 30-35 years ago, and it extends from the near shore to the lower slope of the basin, which is a very important factor in allowing the deciphering of the basins evolution, and in the identification of new play concepts.

Additionally, 20,000 km of older GSI lines have been reprocessed and added to the current grid.

Seismic data parameters. The 2003-04 GSI 2D seismic grid contains 10,121 line km. Acquisition was done with 6 to 8 km long streamers and recorded to a minimum of 12 sec. Processing to 10 sec includes modern multiple elimination routines and Kirchoff prestack time migration resulting in ninety-sixfold data with excellent to fair quality data (depending on geological complexity).

Data quality suffers on the shelf break and upper slope whenever a rough and-or hard water bottom is present. The regional dip grid is generally 30 km spaced and in places it gets denser to 20 and 10 km spacing. Dip lines are tied by very long strike lines that are denser on the shelf and 80 km apart on the slope.

A denser grid was recorded over North Bjarni and several other discoveries. During 2005, GSI more than doubled its Labrador Sea coverage and extended the work north into the Saglek basin using the same acquisition parameters and data processing sequence. The company plans more data acquisition (15,000 km) in the 2006 season.

Well data. A total of 21 wells were drilled in the Hopedale basin during the late 1970s-early 1980s; only 19 are classified as exploration and two are delineation wells (Bjarni O-82 and Herjolf M-92). Only 16 exploration wells reached the planned exploration target. Good electric and radioactive logs exist for most wells as well as good velocity information for seismic data correlation and depth conversion.

While several wells have encountered gas in Cretaceous and Tertiary reservoir sandstones as well as in Paleozoic carbonates, no Kimmeridgian source rock (the prolific source of Grand Banks) was penetrated, but source rocks with high TOC were drilled in Cretaceous and Lower Tertiary formations. Excellent cores through reservoir and source rock intervals are available from the C-NLOPB Core Repository.

Well history reports and various information (logs, check-shot surveys, tops, drillstem tests, etc.) are publicly available from Canada-Newfoundland Labrador Offshore Petroleum Board (C-NLOPB) and from the Geological Survey of Canada (GSC) Basin web site (www.gsca.nrcan.gc.ca/BASIN)

Potential field data. A compilation of marine magnetic and gravity data is available from GSC in both map and digital form.[35] This dataset was used to correlate the tectonic and structural elements observed on the reflection data and estimate sediment thickness on the margin.[24 25 36] Satellite gravity is also available in the public domain.

Potential field data provided by the GSC help to better estimate the composition of the numerous large rotated fault blocks and ridges that form the prerift basement and are covered by Early Cretaceous clastics and volcanics and draped by later sediments.[5]

Several authors[20 21 23 37] discussed the magnetic data when trying to establish the seaward extension of continental and transitional crust and discuss the geodynamic evolution of the Labrador Sea.

Based on analysis of the potential field data integrated with reflection lines we can extend the area viable for oil and gas exploration farther into the deep water where we can interpret a thick, mainly Tertiary, sedimentary cover over large swaths of transitional crust, containing peridotite ridges disposed parallel to the Labrador coast.[5 22 23]

Next: A look at the Hopedale basin's structural and tectonic evolution, petroleum system, and exploration potential. ✦

The author

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HOPEDALE BASIN—2

Atlantic off Labrador poised for modern exploration round

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This is the second of two parts on the geology and potential of the Hopedale basin off Labrador, site of several gas-condensate discoveries in the 1970s-80s on the shelf.

Seismic data interpretation

Interpretation of GSI seismic data in conjunction with marine potential field data provided by GSC and information from the 19 industry wells has allowed the identification of a number of subsurface structural-physiographic subdivisions including several deeper sedimentary areas that contain attractive exploration targets (Figs. 3 and 5-10).

Tertiary beds onlap the prerift basement at a structural lineament (orange interrupted line on Fig. 3) situated between 40 and 75 km from the shoreline, while the Mesozoic sediments onlap against a hinge zone or are fault bounded 80-100 km away from the shoreline. More than 10 km of Mesozoic and Tertiary sediments are present in the deeper parts of the basins, with the entire Mesozoic basinal area located within C-NLOPB jurisdiction.

Most of the wells have been drilled in a narrow strip of about 50 km, with locations selected on the shallower emerging basement ridges with Cretaceous cover (Fig. 3).

Basinwide seismic interpretation can be done using the following markers: a) prerift basement (Labrador unconformity)—excellent on the shelf and poor under deeper half-grabens and on the slope; b) Mid-Cretaceous (Avalon unconformity)—fair to excellent, and in places highly interpretive reflector due to faulting; and c) Base Tertiary (Baylot unconformity)—most continuous and correlatable horizon. A few intra-Tertiary markers are well expressed and in places show significant amplitude anomalies (Fig. 6).

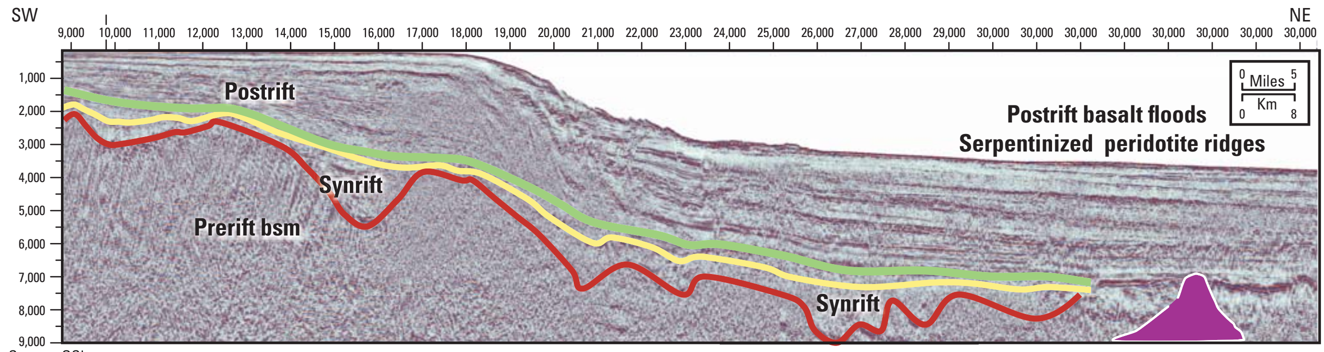
Based on the interpretation of the prerift, synrift, and syndrift seismic sequences, the area covered by the new seismic survey can be subdivided from south to north into several physiographic and structural sectors (Fig. 3):

1. *Hawke basin.* This is a deepwater Mesozoic rift basin located east of the Cartwright arch and in communication with deepwater Hopedale basin. The Cartwright Transfer Fault Zone (CTFZ) that separates the two basins is evident in the potential field data but is more elusive on the seismic lines crossing this tectonic zone. An abrupt change in the direction of main structural lineaments (ridges, elongated fault blocks, and half grabens) marks this transfer zone.

2. *Cartwright arch.* This is a prerift basement high area that is comprised of a) a shelfal sector with thin Tertiary sequences overlying strongly reflective top prerift basement and b) an upper slope sector marked by a down-to-sea bounding fault, where numerous rotated basement blocks containing a stratified Paleozoic section can be interpreted. Another down-to-sea fault zone

HOPEDALE BASIN SEISMIC STRATIGRAPHIC SEQUENCES AND STRUCTURAL ELEMENTS

Fig. 7



Source: GSI

marks the contact between Cartwright arch and Hawke basin.

3. *Hopedale basin shelfal sector*. This includes three in-communication depocenters named here: a) Hamilton subbasin, b) Harrison subbasin, and c) Nain subbasin. They contain several almost parallel lineaments of ridges, elongated fault blocks, and half grabens separated on strike by transfer faults and accommodation zones. The offset on these transfer zones is 10-15 km. Only about a dozen of the identified highs have been drilled; just a few of them are situated on the most prospective side of the shelf where deeper source rock depocenters are located.

4. *Hopedale outer shelf sector*. The basement plunges deep under the shelf; a large basinal trend exists followed by several high trending ridges. In certain parts of the basin a large anticlinal lineament is placed before the shelf break. The shelf break is generally marked by down-to-sea large faults affecting the basement and its sedimentary cover.

5. *Hopedale upper slope*. The upper slope of the Hamilton subbasin dips gentler and is occupied by a large Mesozoic depocenter. Specific for this area is a detached Tertiary sedimentary cover forming numerous fault-bounded rotated blocks and named here the Tertiary listric fault sector.

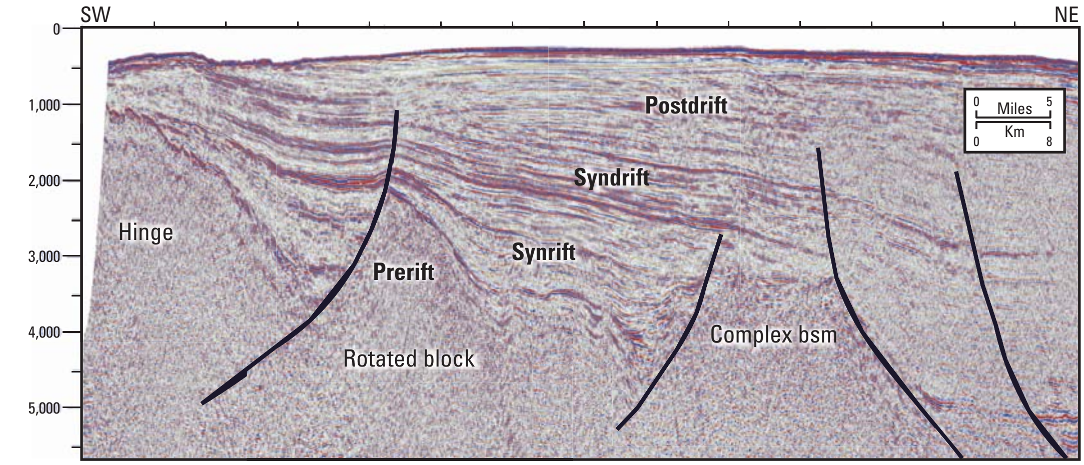
6. *Hopedale lower slope*. The lower slope of this subbasin is occupied by a large Mesozoic depocenter that contains numerous structural features. In places, due to reduced resolution these features are hard to correlate. Structurally intriguing is a cluster of Tertiary gravity detachment folds that exists between the Hamilton and Harrison subbasins in this region. Transtension or shale diapirism may also play a role in the formation of these large folds.

7. *Igneous extrusive province*. The easternmost part of the Nain and Harrison subbasins is occupied by an igneous province formed by lava flows covering thinned continental crust. The flows have been faulted and intruded by igneous bodies. The succession is probably of Late Cretaceous age and contains interbedded sedimentary successions. Flows and emerging mantle derived serpentinite ridges are overlain by parallel layers of Tertiary sediments (Fig. 5).

No salt was observed on the seismic data from the Canadian Labrador Sea. Amplitude anomalies and other various direct hydrocarbon indicators are observed throughout the Cretaceous-Tertiary sequence.[5,7]

HOPEDALE BASIN DEPOCENTERS AND FAULTED BASEMENT RIDGES

Fig. 8



Source: GSI

Structural-tectonic evolution

New regional seismic grids are essential for geological description and investigation of petroleum potential of such a large offshore area.

The Labrador Sea is an Atlantic-type rifted margin and consists of Precambrian metamorphic basement, Paleozoic platform deposits, and faulted and slightly folded mostly Early Cretaceous synrift sedimentary rocks, all covered by Late Cretaceous and Tertiary postrift and recent glacial deposits (Fig. 5).

The geologic evolution of southern Labrador included a Lower Paleozoic period of basin formation and limestone platform deposition, followed by a long period of peneplanization.[12,25,27] Several episodes of Precambrian shield/Paleozoic platform crustal stretching took place first as part a Mesozoic intracontinental network of basins and then during slow emplacement of transitional and oceanic crust in the southern Labrador Sea.

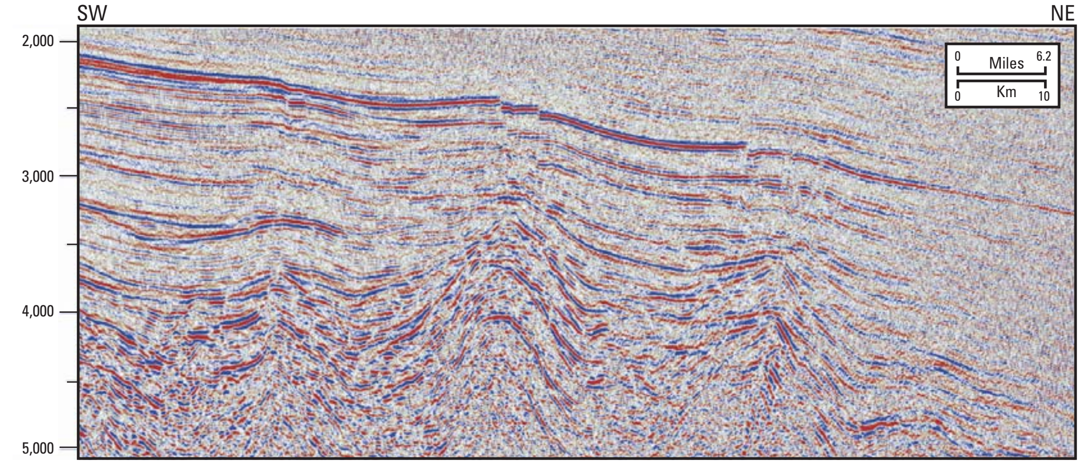
It is possible that during the North Atlantic rifting stage (Late Jurassic-Early Cretaceous), when basins in the south underwent extension and when excellent source and reservoir rocks were deposited, parts of the Labrador/Greenland area had already started to be subjected to sag or intracontinental rifting with alluvial and lacustrine stage deposition and even sea incursions from the south.

Several arguments for the existence of an incipient Jurassic marine seaway in the area have been presented by Danish geoscientists for the Greenland side;[38] however no Jurassic rocks have been recovered up to now from the Labrador Sea wells. The older synrift age identified in the Hopedale basin Herjolf M-92 well is Berriasian.[14,29]

Significant faulting and tectonic subsidence took place during most of the Cretaceous and lasted in some areas, up to Paleocene time, interrupted by

Hopedale basin structural highs with Bjarni and younger sandstones reservoir potential

Fig. 9



Source: GSI

several episodes of thermal subsidence. The initial Early Cretaceous rifts formed in several parallel strips, now located close to the basin western margin, on the middle of the shelf and in the downthrown side of a major fault that approximately marks the shelf break.

The amplitude of tectonic subsidence varies across the basin, with the deepest troughs existing east of the earlier well locations. Some fault activity continues during the continent break-up, mantle exhumation, and drifting.

Petroleum system

A proven petroleum system exists in the Hopedale basin, and expectations are high for further gas discoveries.

During the initial intracontinental extension, elongated rift valleys and the intervening ridges have received a major pulse of coarse clastics that formed the Bjarni formation. The most widespread reservoir, Bjarni sandstone (12% porosity and 100 md permeability) is thick in the grabens and thins on the ridges, showing syntectonic deposition.

Until recently, Cenomanian to Maastrichtian Markland shales were considered the main source rock.[3 6 14 31 32] Recent Rock-Eval analysis of cuttings, geochemical analysis of organic-rich interval, and organic petrology show that the best source rocks occur in the Early Cretaceous Bjarni formation and contain mostly type III terrestrial organic content.[39] The source interval is quite thick—more than 500 m at the Herjolf well with TOC of 5%—and thickens in the numerous half grabens.

After the Labrador/Greenland break-up, basin subsidence followed with deposition of a thick, fine-grained Markland formation that according to several authors includes high TOC shales. The thick Markland shale also forms an excellent regional seal. Other regional seals are in Eocene (Kenamu shales) and Oligocene (Mokami shales).

The Labrador rift system spreads from northern Orphan basin to the Baffin Island area. Continuous extension and minor transtension during the North Atlantic and Labrador rift phases resulted in a landscape of alternating ridges and deep half grabens, mostly oriented NW-SE. Fault activity may have lasted up to Early Tertiary in some areas.

To give an indication of the scale of these structural elements, the ridges and troughs have lengths of more than 100 km while individual subbasins extend for more than 400 km (Figs. 3 and 4).

There are several structural and stratigraphic trapping mechanisms for the Bjarni sandstone, which was derived from both rift shoulders and from intrabasinal ridges (Figs. 5 and 7-10).

Three coarse clastic pulsations originating mostly from the western rift shoulder formed the younger Freydis, Cartwright, and Leif sandstones (Figs. 5 and 7-10) that have increasingly better reservoir properties (up to 25% porosity). It is accepted that the Hopedale basin had a high thermal gradient (2.7° C.) and that source rocks started expelling wet gas after reaching depths of approximately 2,500 m probably in Late Oligocene-Early Miocene time.[14 31] According to Fowler et al.,[39] the oil window is deeper at 3,000-3,500 m.

Numerous horst and fault blocks are seen on the seismic data, some forming impressive exploration leads. Paleozoic limestones and dolomites found on the tops or sides of higher basement blocks often have reservoir properties. Drape over these high blocks and lateral pinchouts of Bjarni and younger sandstones are other possible hydrocarbon plays. On the outer shelf and slope, listric faults and their associated rollover are exploration targets (Fig. 10).

Exploration potential

With a long intracontinental rift evolution, terrestrial and probably marine interludes of source rock deposition and numerous synrift and postrift structural and stratigraphic trapping possibilities, the Hopedale basin has significant undrilled petroleum potential.

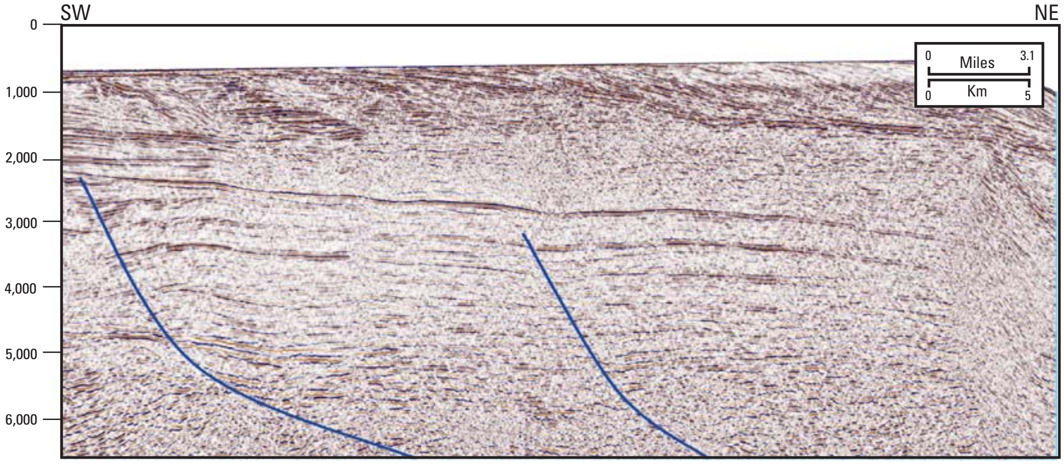
Only 16 wells have reached planned targets at significant depths resulting in five gas discoveries, with one, North Bjarni F-06 (Fig. 5), proving a giant gas discovery. An excellent success ratio for a frontier basin of over 30% was recorded.

Improved seismic imaging and recording of data into deepwater areas is key to understanding the tectonic evolution and the exploration potential of the Labrador basins. As proven by this study the continental crust extends more than 300 km from the Mesozoic onlap on basement and this entire area is prospective for hydrocarbon exploration (Figs. 5 and 7).

The most important reservoir in the basin is the Bjarni sandstone, and this has been the most successful play in the basin. The unbiodegraded oil encountered at North Leif I-05 shows immaturity,[39] but more mature source rock and reservoired oil may exist in deeper parts of the basin.

HOPEDALE BASIN LARGE ROLLOVER ANTICLINES TRIGGERED BY LISTRIC FAULTS

Fig. 10



Source: GSI

The Top Bjarni formation (Avalon unconformity) is a good quality marker that can be mapped now with relative confidence east of the Bjarni field and North Leif lineament into deep water. Younger sandstone with reservoir properties has been deposited in the basin during the Neogene uplift of the basin flank (Labrador Peninsula), and probably turbidites have been accumulated on the slope and in deepwater, a play that is yet undrilled in the Hopedale basin or anywhere on the Grand Banks and Labrador slope.

The Paleozoic "basement" sediments cannot be written off as exploration targets, as two large gas discoveries have been made in the carbonates. The Gudrid discovery (924 bcf recoverable) tested 20 MMcfd, and the Hopedale discovery (105 bcf recoverable) tested 20 MMcfd from a Paleozoic dolomite. This play should be particularly found in the southern part of the basin.

The Bjarni and Markland shales deep hydrocarbon kitchen existing on the outer shelf seems to be the source of the gas filling the five discovered accumulations. Another, probably Markland shale filled depocenter, exists in front of the slope. The Markland is also a terrestrial dominated source rock with some marine influence.

Several large anticlinal features are located under the shelf break area. These can be hydrocarbon sourced from both the western and eastern depocenters. Whether oil prone Jurassic source rocks exist in these deeper undrilled depocenters remains to be proven. Increased exploration activity has taken place across the sea on Greenland's continental margin where indications of older sequences, including Late Jurassic source rocks, have been observed in outcrop and on seismic data.

While exploration for offshore oil in Newfoundland and Labrador has been ongoing for over 40 years, no systematic effort has yet been undertaken to find natural gas. As it stands the almost 10 tcf of recoverable gas that has been discovered is a byproduct of oil exploration.

With the recent increases in North American natural gas prices and the obvious need to develop new supply areas, serious discussions have begun on ways and means to bring the Newfoundland and Labrador natural gas to market. Possible modes of transportation under consideration include pipeline, compressed natural gas, LNG, and gas to liquid tankers. Oil is currently being transported from the Grand Banks fields by shuttle tankers.

It is encouraging that gas prospects are now in the drilling inventory of some of the operators, and research into ways to monetize the stranded gas resource of the Jeanne d'Arc and Hopedale basins is ongoing. Advancements in seismic acquisition and techniques coupled with regional geological studies are key to successful drilling of high-risk, high-reward frontier areas such as the Hopedale basin.

Important improvements in the offshore regulation regime of the Newfoundland and Labrador E&P were recently taken by the federal and provincial governments. One excellent initiative that will considerably reduce the overall cost of drilling is to introduce discretionary requirements related to flow testing of the first well drilled on a new hydrocarbon prospect.[40]

The earlier Hopedale basin gas finds and eventual new large discoveries may be utilized in the future for:

- Smelting and providing electricity to Labrador's emerging nickel industry.
- Supplementing Labrador hydroelectricity exported to North America.
- Supplying gas to the Canadian Atlantic provinces and US using any of the CNG, GTL, or LNG technology.

In spite of harsh environment the Labrador fields are significantly closer to the East US or central Canadian markets than many of the alternatives. Operations on the Grand Banks have shown that iceberg management using towing by standby vessels is effective and economic, particularly as such vessels must be onsite in support of drilling operations in any case. And it can be also said that much greater transport distances (such as Siberia to Western Europe) and comparable logistical challenges are being met in other areas of the world.

The big picture

The Hopedale basin had a complex geological evolution, starting with intracontinental rifting in the Early Cretaceous (possible Jurassic?) and followed by significant subsidence and accumulation of passive margin sediments.

Large gas discoveries were made during the 1970s exploration cycle in the shallow Labrador Sea, proving the presence of a rich petroleum system. No follow-up drilling has taken place, and only during the past few years has exploration returned with the acquisition of modern, high quality 2D seismic data.

While numerous drillable structures have been identified in the past, all located in the inner shelf area, new seismic data allow the extension of the geophysical study into outer-shelf and deepwater, and show several previously unknown large depocenters and anticlinal features, some of which are accompanied by amplitude anomalies.

The Bjarni sandstone is recognized as the main reservoir target, but quality reservoirs have been encountered in prerift, synrift, and syndrift sequences. The Bjarni formation also contains interbedded shales with terrestrial organic content that constitute an excellent type III source rock. Source rocks are also present in Late Cretaceous and Early Tertiary, while the occurrence of a Late Jurassic marine source is still unproven on the Canadian side of the rift but has been documented on the conjugate margin off west Greenland.

The discovered gas has remained stranded due to its more remote location and some logistical challenges (such as iceberg management) that made it less attractive when cheap gas was widely available elsewhere. Higher prices, new technologies, and political considerations of the alternatives (LNG for example) are changing the equation. The area's proven resource is substantial and the potential resource is enormous.

No doubt challenges to exploration and production of the hydrocarbons from Labrador Sea remain great and many, but the demand for cleaner energy, increased commodity prices, improved government regulations, large size of the prize, technological advancements, and relative proximity to the largest world markets will place the Hopedale basin and the rest of the Labrador shelf clearly on the industry radar screen in the coming years.

Acknowledgments

Davey and Paul Einarsson at GSI for seismic data donation to Memorial University and permission to show the Hopedale basin lines. John Hogg at ConocoPhillips, Phonse Fagan at A.J. Fagan Consulting/MUN; Sam Nader, consultant, and Steve Kearsey at MUN/Husky Energy for collaboration on the Labrador Sea project. J. Wright, H. Miller, I. Atkinson, M. Martin, V. Hardy, S. Schwartz, and A. Dearin at Memorial University; D. Hawkins, T. Bennett at C-NLOPB; M. Fowler, S. Dehler at GSC Atlantic; W. Foote, L. Hicks, and L. Stead at the Government of Newfoundland, and D. Chafe at ABM. ✦

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