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GEOLOGY OF THE LABRADOR SHELF

D.C. UMPLEBY

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GEOLOGY OF THE LABRADOR SHELF

Abstract

The Cretaceous-Tertiary sequences penetrated by drilling operations on the Labrador Shelf have been divided into four formations for which formal names are proposed in this paper. The Berriasian-Valanginian Alexis Formation, up to 260 m thick, consists of subaerially extruded basalt flows and associated sediments which overlie Precambrian basement containing outliers of Paleozoic rocks. The Alexis Formation is overlain by the Bjarni Formation, a series of predominantly continental coarse clastic rocks up to 1130 m thick of Hauterivian to Early Neocomian age. The unconformably overlying Cartwright Formation, up to 1200 m thick, consists of shallow water marine turbiditic shales of Turonian to Early Eocene age. Locally, paralic to shallow water marine sand members occur in the Cartwright Formation. The conformably overlying Early Eocene and younger Saglek Formation, over 1700 m thick, comprises a series of deeper water marine turbiditic mudstones overstepping the older formations. Within the Saglek Formation, shallower water and locally developed paralic sediments were deposited during the Late Eocene and Oligocene, a period of reduced basin subsidence.

Structural sections across the Labrador margin show that two superimposed basins are present. The earlier, forming in the Berriasian, is bound by en echelon faults, trends approximately parallel to the present day Labrador coast and terminates on the northern flank of the Cartwright Arch. This inshore basin is overstepped by Early Eocene and younger sediments which form a simple clastic wedge on the margin of the present day Labrador Sea, a basin apparently formed in the Late Cretaceous or Paleocene.

While the Labrador Sea is presumed by others to have resulted from seafloor spreading, this theory does not satisfactorily explain some important geological features. An alternative origin for the Labrador Sea proposed by the author is the collapse of a minor undation in lowermost Cretaceous times followed by the collapse of a major undation in late Cretaceous times.

Three gas and condensate discoveries on the Labrador Shelf show similarities in structure and source though the reservoirs are different. In each discovery, closure is associated with upthrown faulted basement blocks within the inshore basin and the hydrocarbons appear to originate from the Cartwright Formation. Insufficient data exist to assess the hydrocarbon potential of the Labrador Shelf but there are indications the area could prove to be an important hydrocarbon province.

Résumé

Les séquences du Crétacé et du Tertiaire qui ont été étudiées lors d'opérations de forage dans le plateau continental du Labrador ont été divisées en quatre formations; leurs noms officiels sont proposés dans cet article. La formation Alexis datant du Berriasien et du Valanginien inférieur, dont l'épaisseur peut atteindre 260 m, est composée de coulées de basalte extrusives et des sédiments connexes qui recouvrent un socle datant du Précambrien, contenant des buttes témoins de roches paléozoïques. La formation Alexis est recouverte par la formation Bjarni, une série principalement constituée de roches clastiques continentales grossières, dont l'épaisseur atteint jusqu'à 1 200 m et l'âge s'échelonne du Hauterivien au Néocomien inférieur. La couche sus-jacente est discordante; il s'agit de la formation Cartwright d'une épaisseur atteignant jusqu'à 1 200 m. Elle est constituée par des schistes argileux, formés par des courants de turbidité en eaux peu profondes, qui s'échelonnent du Turonien à l'Eocène inférieur. En certains endroits de la formation Cartwright, il y a des termes de sable marin formés dans la zone littorale ou en eaux peu profondes. La couche sus-jacente formée en superposition date de l'Eocène inférieur. Il s'agit d'une formation plus récente, la formation Baglek, de plus de 1 700 m d'épaisseur, constituée d'une série de pélites formées par un courant de turbidité en eaux profondes, recouvrant les formations plus anciennes. Dans cette formation, des sédiments ont été déposés en eaux peu profondes et dans la zone littorale, en certains endroits, à l'Eocène supérieur et à l'Oligocène, péroide où le rythme d'affaissement des bassins était assez lent.

Les coupes structurales traversant la marge du Labrador montrent qu'il s'y trouve deux bassins superposés. Le plus ancien, formé au début du Berriasien, bordé par des failles en gradins, s'étend à peu près parallèle avec la cote actuelle du Labrador et se termine sur le flanc nord de l'arche Cartwright. Sur ce bassin littoral chevauchent des sédiments de l'Eocène inférieur et d'époques ultérieures qui forment un coin clastique simple dans la marge de la mer du Labrador actuelle, située dans un bassin apparemment formé au Crétacé supérieur ou au Paléocène.

Bien que certains estiment que la mer du Labrador a été formé par l'expansion du fond marin, cette théorie n'explique pas de façon satisfaisante certaines particularités géologiques importantes. L'auteur propose une théorie différente de l'origine de la mer du Labrador; il s'agirait de l'affaissement d'une ondulation mineure au tout début du Crétacé, suivi de l'affaissement d'une ondulation majeure au Crétacé supérieur.

Quoique les réservoirs soient différents, trois gisements de gaz et de condensats découverts dans le plateau continental du Labrador présentent des similitudes de structure et d'origine. Dans chacun d'eux, la fermeture est associée à des blocs de socles faillés soulevés dans le bassin littoral et les hydrocarbures semblent provenir de la formation de Cartwright. Il n'y a pas assez de données sur le plateau continental du Labrador pour évaluer sons potentiel en hydrocarbures, mais des indications portent à croire que cette région pourrait être une importante province riche en hydrocarbures.

INTRODUCTION

Knowledge of the geology of the Labrador Shelf between 53° and 61°N has been enhanced in the last few years by the drilling of several exploratory wells. These have penetrated a series of Cretaceous and Tertiary rocks which can be correlated over long distances. Formal lithological units proposed provide the basis for a stratigraphic framework and this permits an interpretation of the geological history and the hydrocarbon potential to be made.

The first information concerning the geology of the Labrador Shelf came in the early 1960s from geophysical surveys which showed the area to be underlain by a seawards-thickening wedge of sediments. Refraction lines shot over the shelf and rise of southern Labrador showed these sediments to be up to 7 km thick (Mayhew, 1970). High resolution seismic reflection data collected between 1965 and 1969 confirmed these sedimentary thicknesses and permitted the overall morphology of the Labrador Shelf to be outlined (Grant, 1972). The approximate thickness of sediments underlying the shelf are shown on maps prepared by Wade et al. (see Fig. 1).

REGIONAL GEOLOGICAL SETTING

Morphology of the Labrador Shelf

Grant (1972, 1974) described the Labrador Shelf as a typical glaciated shelf mostly less than 200 m deep and locally as shallow as 80 m. Areas less than 500 m in depth cover approximately 120 000 km^2. The shelf is dissected by northwest and northeast trending troughs and channels, with relief between banks and adjacent channels of up to 800 m. Thus the shelf can be divided south to north into Hamilton, Harrison, Makkovik, Nain and Saglek banks (Fig. 2). An important feature is the Labrador Marginal Trough which parallels the present coastline and separates an area underlain by Precambrian crystalline rocks on the west from an area underlain by sediments to the east. The trough probably represents an area of deepened glacial scour of pre-existing, late Tertiary subsequent valleys as continental ice sheets debouched from the more resistant Precambrian terrane onto areas underlain by softer sediments. The pre-Pleistocene erosion by river action is supported by geomorphological analyses of mainland Labrador and adjacent Quebec. These show the area to have warped probably in Pliocene times

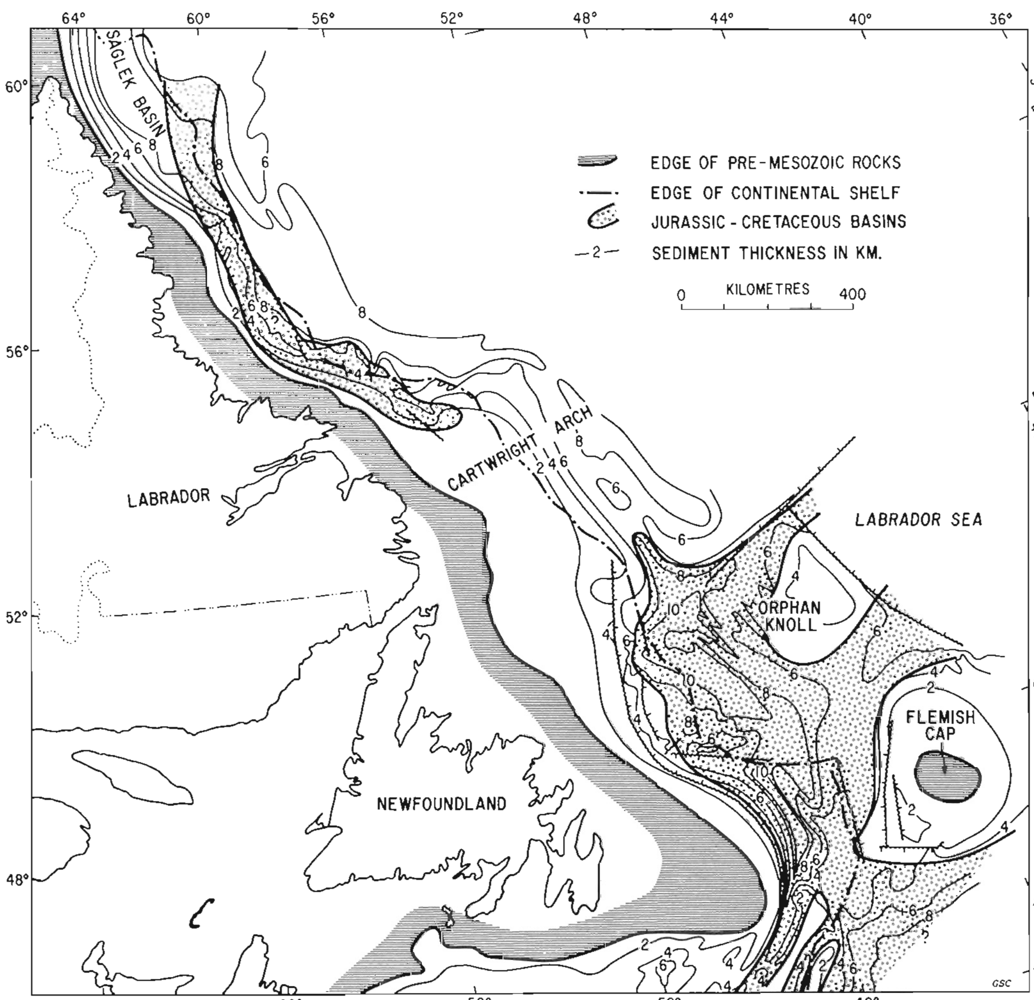


Figure 1. Thickness of sediments, Labrador Shelf and Grand Banks. Area underlain by epicontinental shallow marine to continental basins of Jurassic and Cretaceous age are also shown.

(Henderson, 1959) which resulted in the differential uplift of low lying Late Tertiary peneplanes so that, consequent streams now flow for long distances against the general slope of the terrain and are often deeply incised in preglacial valleys. On Labrador, interfluves are concordant over wide areas.

Grant (1972) showed line drawings prepared from reflection seismic profiles across the Labrador Marginal Trough, including the sediment-basement contact. Projecting dip segments on these profiles suggests that the depositional edge of the Cretaceous and Tertiary sediments occurs within a narrow zone (Fig. 3). Erosion of the proximal part of the sediments took place in the late Tertiary with subsequent redeposition in a more distal part. Reworked palynomorphs and foraminifers in Upper Tertiary rocks of the Labrador Shelf supports this hypothesis. The trough corresponds to the removal of a prism of sediments up to 50 km wide and averaging 500 m thick. A total of at least 4500 km^3 of sediments has been removed and redeposited in a more distal position.

Regional Geology

With minor exceptions, lands adjacent to the Labrador Sea are underlain by Precambrian rocks. To the south is the northeast-southwest trending Appalachian Orogen composed of Lower Paleozoic geosynclinal rocks with included Carboniferous sediments filling postorogenic successor basins.

Pre-Mesozoic Rocks

The Precambrian rocks of Labrador are part of the once-continuous North Atlantic Craton. This craton is made up of several provinces corresponding to two fundamental rock types. Older terranes, regionally metamorphosed to granulite and amphibolite facies, are Archean; greenstone- and low-grade metasedimentary terranes with extensive granite and anorthosite plutons are Proterozoic.

The Nutak Province (Fig. 5) occurs along a coastal strip between 57°N and 63°N and contains Archean rocks which have been dated radiometrically as 3200-2880 Ma (Taylor, 1972). Scattered infolded and metamorphosed supracrustals of Aphebian (Lower Proterozoic) age include the Aillik, Mugford and Ramah groups. Both the infolded supracrustal rocks and the Archean cores were presumably reworked during the Hudsonian Orogeny (1800 Ma). In addition the southern part of Nutak Province was reworked during the Grenvillian Orogeny (1000 Ma).

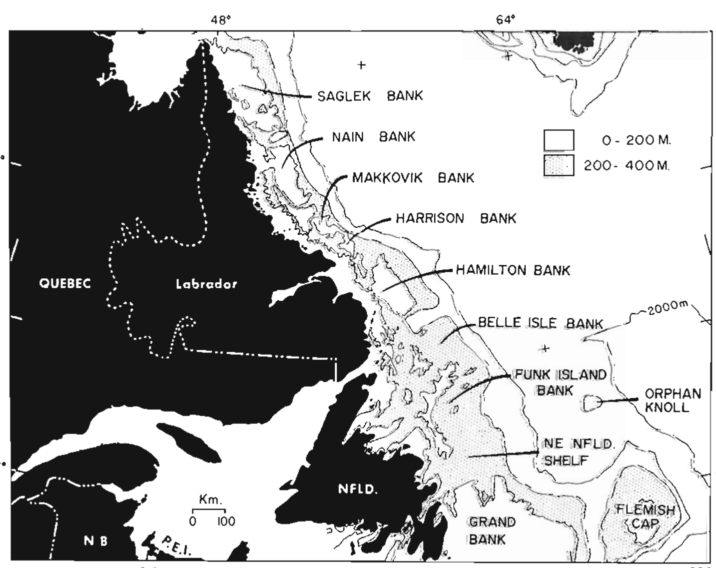


Figure 2. Morphological features, Labrador and east Newfoundland shelves.

The western boundary of the Nutak Province is a near-vertical belt of mylonitized rocks which appear to have formed in response to transcurrent motions during the Hudsonian Orogeny. However, this boundary is frequently hard to define because of Paleohelikian (i.e. post-Hudsonian) massive granite and anorthosite plutons emplaced along it.

West of the Nutak Province is the Churchill Province, consisting of geosynclinal sediments and associated volcanics (Davidson, 1972). These rocks are Aphebian and were folded and metamorphosed during the Hudsonian Orogeny. The foreland of the sedimentary-volcanic sequence is another Archean block, the Superior Province.

When traced southwards, the three Precambrian provinces have been complicated by younger events. Running obliquely through southern Labrador between 53°N and 54°N is the Grenville Front. This feature separates the structurally higher Nutak Province to the north from an overthrust belt of younger supracrustals and plutonic rocks (the Grenville Province) to the south (Wynne-Edwards, 1972).

South of the Grenville Province is the Appalachian Orogen, containing very thick upper Proterozoic to Lower Devonian rocks deformed in a complex manner by a late Caledonian orogeny. Postorogenic successor basins are filled with upper Devonian to Lower Permian rocks.

The original southern limit of the Nutak Province is not known, as it is included in Grenville rocks south of the Grenville Front. The northern limit is concealed beneath the present Labrador Sea, an area where an extensive area of Archean terrane was destroyed by assimilation with mantle products in the Late Cretaceous.

Despite these uncertainties, Bridgewater et al. (1973) made a generalized reassembly of the North Atlantic craton. This reassembly is possible because Precambrian terranes in both Labrador and Greenland contain similar provinces. Thus the Archean core of south Greenland is overridden by the Ketilidian Belt from the south and the Nagssugtoqidian Belt from the north. The southern overthrust may equate to the Grenville Front as the Grenville and Ketilidian provinces have features in common. Similarly the Nagssugtoqidian Province consists of older Proterozoic sediments folded and metamorphosed during the Hudsonian Orogeny and may correlate with the Churchill Province.

Bridgewater et al.'s reconstruction of features on either side of the Labrador Sea can be modified (Fig. 4). On this diagram, which assumes seafloor spreading to have occurred, the boundary between the Nutak and Churchill provinces is shown as right-lateral shear zone. Also shown is a left-lateral shear zone between the Nutak Province and its Greenland counterpart. Offsets on either side of the shear zone between younger Precambrian metamorphics to the north and to the south and the Archean core are similar. This shear zone may have at least partially controlled taphrogenesis on the Labrador Shelf in earliest Cretaceous times. Basins of this age are bound by deep-seated faults that cut through stabilized, cratonic areas which are underlain by thick crust, rather than being peripheral to such areas.

Cretaceous and Paleocene rocks outcropping in Labrador

In the general area of the Labrador Sea are four different Mesozoic and Cenozoic sequences that are pertinent to the geology of the Labrador Shelf. The locations of these sequences are shown on Figures 5 and 6 and include:

1. Late Cretaceous and Paleocene rocks outcropping on Labrador,
2. Igneous rocks in northwest Newfoundland,

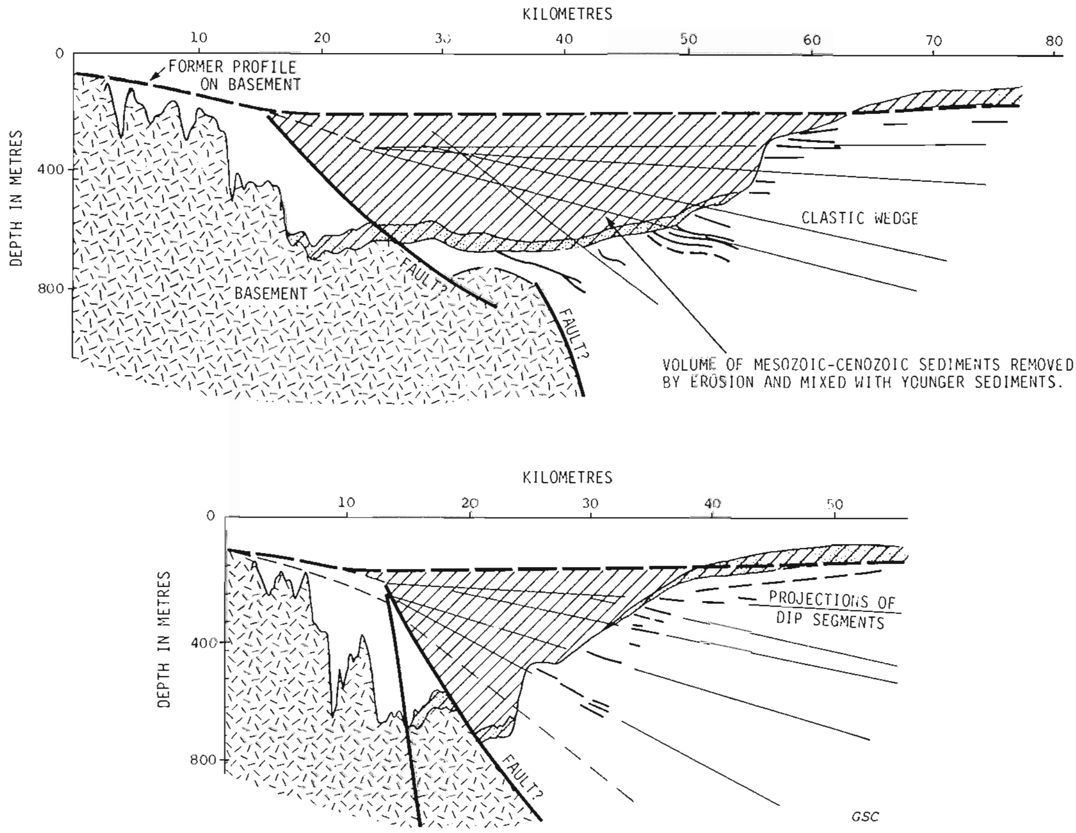


Figure 3. Details of Labrador Marginal Trough showing amounts of Mesozoic and Cenozoic sediment removed. (After Grant, 1972).

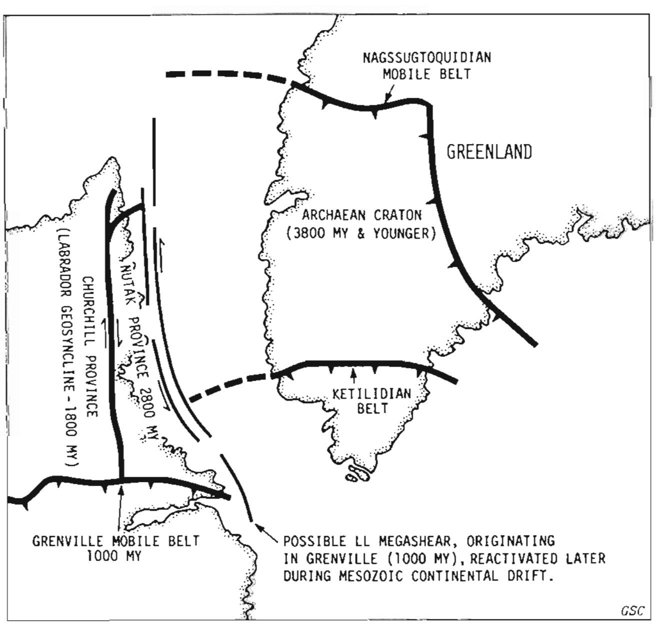


Figure 4. Precambrian provinces and tectonic features on the North Atlantic craton adjacent to the Labrador Sea.

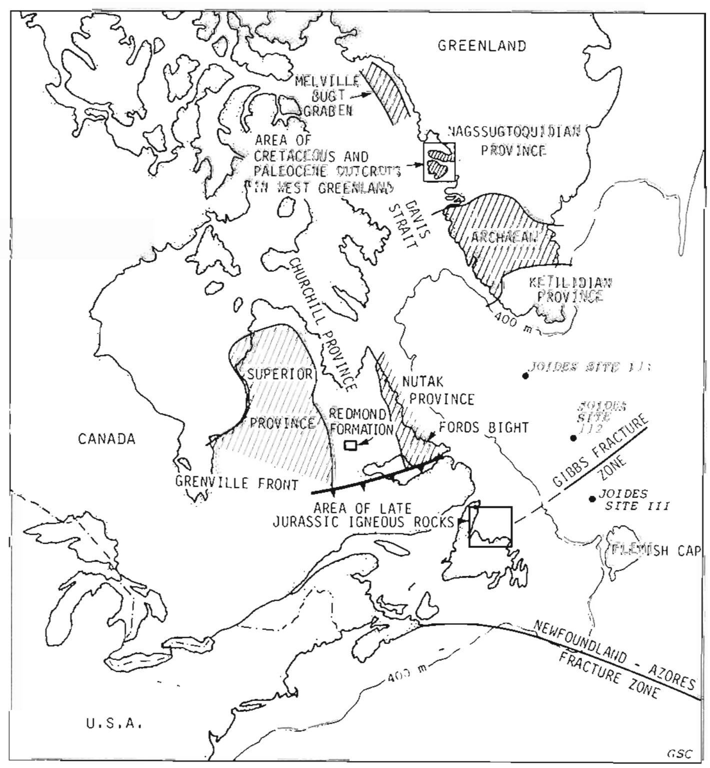


Figure 5. Index map showing pertinent geological features round the Labrador Sea mentioned in the text.

3. Sedimentary sequences of the Grand Banks and northeast Newfoundland basins,
4. Cretaceous and Tertiary sequences of the Nugssuaq Embayment of West Greenland.

Lower Cretaceous inliers at Ford's Bight

Brecciated Lower Cretaceous sediments associated with a lamprophyre dyke occur on the southwest side of Ford's Bight on the coast of Labrador at 55°05'N, 59°05'W. The outcrops consist of three, small and discontinuous patches covering only 7 m^2 near the present shoreline in an area otherwise underlain by high-grade metamorphics of Proterozoic age. The breccias lie on a peneplaned surface.

They were first discovered by King in 1973 and described in 1975 (King and McMillan, 1975) when they were also sampled and examined by Aquitaine Co. paleontologists of Pau, France. Poorly preserved palynomorphs occurring within the breccia indicate an Early Cretaceous age.

Lithologically, the breccias are difficult to interpret and consist of clasts of various metamorphic and igneous rocks in a matrix of quartz, feldspar and mafic minerals. Both clasts and matrix have been brecciated and carbonatized, possibly during the emplacement of the lamprophyre dykes seen cutting one of the outcrops. Radiometric age determinations of these dykes give possible ages of 145 ± 6 Ma and 129 ± 6 Ma or Late Kimmeridgian to Valanginian.

The association of a lowermost Cretaceous sedimentary sequence associated with a coeval basic intrusive phase is also encountered in adjacent offshore wells.

Redmond Formation of the Ruth Lake – Knob Lake areas, Labrador

The Richmond iron deposits contain lacustrine beds of early Late Cretaceous age in the Knob Lake area. Similar beds in the Ruth Lake area are slightly younger (Rice, 1969), being of latest Cretaceous and Paleocene age.

The lacustrine beds at Knob Lake constitute the Redmond Formation and have been described in detail by Blais (1959). Significantly, they contain beds of ferriferous gravels containing wood fragments, including **Cupressoxylon,** a late Cretaceous and early Tertiary gymnosperm. Red clay horizons within the gravels locally contain abundant fossil leaves and insect wings. The leaves are mainly angiosperms and have been examined by Dorf (1959) who assigned to them an early Late Cretaceous age and compared the flora to that from the Raritan Formation of New Jersey, the Dakota Formation of the midwest and the Tuscaloosa Formation of Alabama. According to Dorf, the Knob Lake flora grew in a warm, humid climate.

The Redmond Formation is also important because its unusual lithologies enable conditions on the continent during the Late Cretaceous to be reconstructed. Terrain surrounding the exposures of Redmond Formation consists of shallow water sediments of the Kaniapiskau Group of Proterozoic age (Frarey and Duffell, 1964; Gross, 1968). Notable among these sediments because of the economic importance is the Sokoman Formation which is composed of chert and several iron-bearing minerals (Zajac, 1974).

All exposed Proterozoic sediments were intensively, chemically weathered throughout most of Paleozoic and lower Mesozoic times, up to and including the Early Cretaceous. The thick regolith thus formed was locally partly redistributed during the Late Cretaceous to form the lacustrine Redmond Formation which may contain up to 62 per cent Fe_2O_3 and is currently being mined as ore. The Redmond Formation appears to be restricted to depressions in the Proterozoic terrane.

Processes forming the so-called rubble ores or ferriferous gravels at Knob Lake have been compared to weathering processes presently occurring in parts of Venezuela and tropical Africa (Blais, 1959; Gross, 1968). Both areas are characterized by humid tropical climates with a marked dry season. Under such conditions, chemical weathering is intense and cations from silicate minerals are solubilized. Iron, having a low mobility, is readily precipitated on nuclei in the ferric state during dry periods. In this way, a relatively lean parent rock, such as the Sokoman Formation, which averages only 16 per cent Fe_2O_3, is naturally enriched to ore grade.

Red clay horizons within the Redmond Formation appear to be reworked ferriferous laterites deposited in lakes. This and other lithological evidence suggests that in the Late Mesozoic, Labrador was a relatively low lying area with a humid, subtropical to warm temperate climate. A thick regolith developed which appears to have been stabilized, possibly by forest cover.

There is evidence that the Labrador Sea formed in latest Cretaceous times (for example, Le Pichon et al., 1971) and this event no doubt caused regional climatic changes. The stratigraphy in offshore sequences also shows marked changes at this time as Paleocene and older sediments belong to a biostatic phase during which the regolith was still largely preserved; Eocene and younger sediments appear to belong to a rhexistatic phase during which the clay-mineral rich regolith was rapidly denuded from land surfaces and redeposited in adjacent marine areas as thick turbiditic mudstones.

Igneous rocks of Mesozoic age of northeast Newfoundland

In the Notre Dame Bay area of northeast Newfoundland, several igneous intrusions of Mesozoic age have recently been identified. Some have been described by Currie (1976). Most are carbonatite lamprophyre dykes though basic extrusive and basic to ultrabasic intrusive rocks are also present. These rocks range in age from Late Jurassic to Early Cretaceous and appear to have a deep-seated origin.

The intrusions were emplaced just prior to or during an early stage in the formation of sedimentary basins on the western margins of the Labrador Sea. They are thus associated with an earlier taphrogenic phase and not with the main phase of Labrador Sea development.

McWhae and Michel (1975) stressed two aspects of this igneous activity – the intrusions are emplaced during periods of some tectonic activity represented by regional unconformities and they precede the main phase of basin development.

Sedimentary sequences on the Grand Banks and northeast Newfoundland Basin

Drilling operations on the Grand Banks show two sedimentary sequences separated by an unconformity which has been correlated with the Late Kimmerian event of northwest Europe (Amoco-Imperial staffs, 1973 and 1974).

A brief description of the two sequences is as follows:

1. An older sequence of basal redbeds of later Triassic to Sinemurian age overlain by Sinemurian to Pliensbachian evaporitic carbonates, with shallow marine interbedded shale and carbonate of late Early Jurassic to late Early Cretaceous age. Locally paralic sequences including coarse sand and coals are developed in the top part of the older sequence.
2. An upper wedge of sediments consisting of thin, condensed basal beds of Albian to Cenomanian age. These are overlain by locally developed Late Cretaceous chalks and marls, which are overstepped by Tertiary silty mudstones grading upwards into shallow water sandy mudstones.

In the southwest part of the Jeanne d'Arc Basin (Fig. 6), the late Kimmerian Event is well developed (Fig. 7). Thus at Amoco-Imperial et al., Spoonbill D-30, Upper Cretaceous and Tertiary rocks overlie an unconformity-bound, thin Albian sequence which overlies Lower Jurassic (Hettangian to Pliensbachian) carbonates and evaporites (Amoco-Imperial staffs, 1975). However, in the general part of the basin, in the vicinity of Mobil-Gulf Adolphus 2K-41, seismic reflection profiles show at least 15 000 m total sediments are present and the Kimmerian event is probably scarcely developed. North of this location, still within the axis of the basin, the unconformity is again present but the thickness of pre-Kimmerian sediments is reduced. At 52°N, on the south flank of the Cartwright Arch, the Jurassic basin trends east so that on the Arch, Tertiary rocks overlie pre-Mesozoic basement.

Figure 6. Index map showing distribution of lower Jurassic rocks and key wells drilled in the East Newfoundland Basin.

Jansa and Wade (1975) showed the distribution of gross stratigraphic units on the Grand Banks; McWhae and Michel (1975) stressed the "stepwise" evolution of the eastern Canadian offshore margin. Thus between the Newfoundland-Azores Fracture Zone and the Gibbs Fracture Zone (see Fig. 5), ocean development was a mid-Cretaceous feature; south of the Newfoundland-Azores Fracture Zone, the ocean floor formed in mid-Jurassic times and north of the Gibbs Fracture Zone, in late Cretaceous times. Offshore areas are thus divisible into sectors delineated by fracture zones, each sector having a typical stratigraphy that is related if not controlled by seafloor development phases within that sector. This concept is shown on Figure 7 which emphasizes that an "oceanic" basin was not established in the Labrador sector until the Late Cretaceous although an epicontinental basin dates from the earliest Cretaceous.

In 1972, Joides Leg 12 cored three sites in the Labrador Sea (Fig. 5). These sites have been comprehensively described (Laughton, 1972) but pertinent details will be presented here and correlated to stratigraphic sequences encountered in exploratory wells on adjacent shelf areas.

Sites 112 and 113 are located in deeper waters in the central part of the Labrador Sea. Site 113 penetrated thick turbidites of late Miocene and Pliocene age; Site 112 penetrated varicoloured clays of early Eocene to Pleistocene age overlying altered porphyritic basalt. Faunal evidence from this site suggests that a stabilized bathyal regime has been in existence since the early Eocene.

Site 111 on Orphan Knoll, penetrated a stratigraphically longer interval, terminating in a nonmarine Middle Jurassic (Bajocian) sequence which seismic reflection profiles show to be up to 1500 m thick and preserved as a synclinal inlier. The cored part consists of coarse lithic sand overlain by grey laminated shale. An Albian to Lower Cenomanian sparry calcarenite unconformably overlies the Jurassic. Similar, coeval limestones are present in Mobil-Gulf Dominion 0-23, 360 km southwest of Site 111, and at Amoco et al., Egret N-46, 510 km southwest of Site 111. At Dominion, an unconformity-bound limestone of Albian age occurs between 3192 and 3133 m (Mobil Oil Co., 1976). The limestone is buff to white, finely crystalline with vuggy porosity and overlain by light grey Late Paleocene shales. At Egret, the Albian consists of medium crystalline limestone between 1365 and 1320 m (Amoco, 1976).

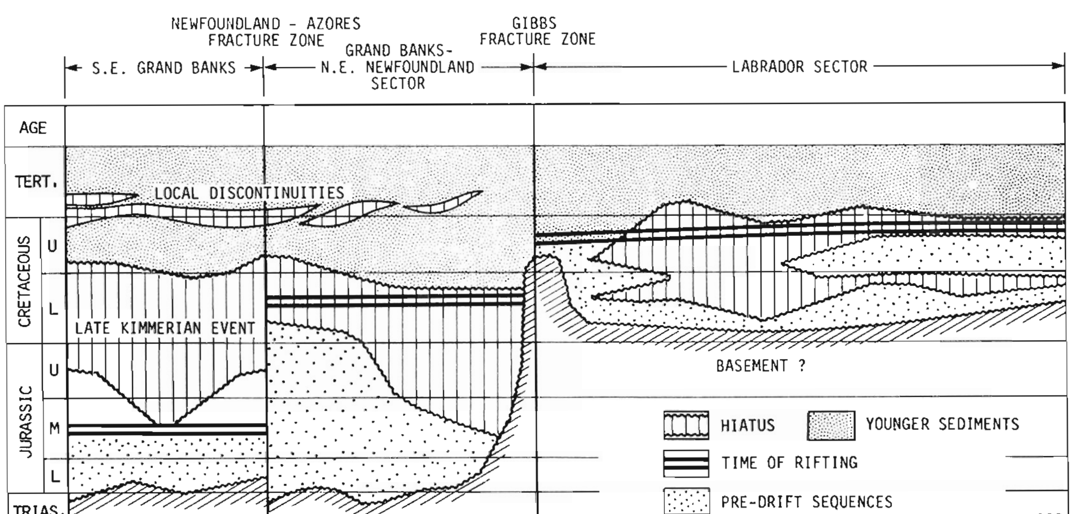


Figure 7. Major stratigraphic sequences, Grand Banks, East Newfoundland Basin, and the Labrador Shelf.

Figure 7 shows Albian and Cenomanian rocks are absent from large areas of the Grand Banks because of erosion during the Late Kimmerian Event. However, the local preservation of rocks of this age indicates that an epicontinental shallow marine basin existed in the area. By contrast, the coeval basin off Labrador was separated from these carbonate basins by the Cartwright Arch and received clastic sediments.

In Joides Site 111 cores, light-coloured soft chalk oozes of Maestrichtian age have correlatives in the adjacent Jeanne d'Arc Basin. Chalk of this age was encountered at both Mobil-Gulf Adolphus 2K-41 (Mobil Oil Co. Ltd., 1975) and BP et al. Bonavista C-99 (B.P. Canada, 1977), 390 and 360 km respectively southwest of the Joides site. Deposition in a relatively shallow, epicontinental basin is indicated. Coeval sediments off Labrador are siliclastic shales.

Eocene and younger turbiditic green-grey laminated silty muds in Site 111 contain bathyal foraminifera suggesting Orphan Knoll lay near its present depth of 1800 m by Lower Eocene times. Thus regional sinking appears to have occurred rather suddenly during the early Eocene. Sequences penetrated on the Labrador Shelf show that similar rapid foundering occurred at this time. A regional bathyal regime was thus established to within a short distance of the basin margin over the entire area in the early Eocene.

Pertinent features of the stratigraphy and sampled intervals of Site 111, the subsidence history of Orphan Knoll are shown on Figure 8.

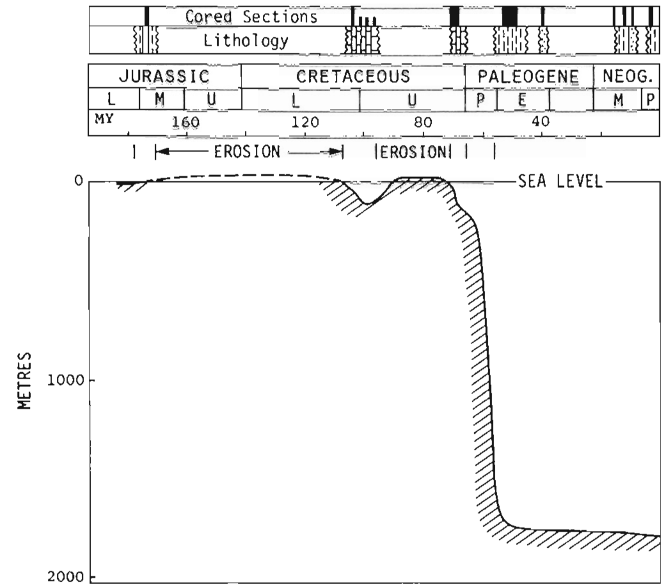


Figure 8. Sequences cored, stratigraphy and subsidence history of JOIDES Site 111, Orphan Knoll. Redrawn from Ruffman and van Hinte, 1973.

Cretaceous and Paleocene sequences of the Nugssuaq Embayment, West Greenland

The Nugssuaq Embayment includes Disko Island and most of the adjacent Nugssuaq Peninsula, in West Greenland (Fig. 5). The area is about 1200 km north of the Labrador Shelf. Sedimentary sequences in the embayment have been extensively studied and consist of a basal clastic sequence of Lower Cretaceous age overlain by sand-shale sequences of Cenomanian to Danian age (Henderson et al., 1976). The sequence is largely nonmarine, complicated by normal faulting, poorly fossiliferous and consists of rather monotonous lithologies making accurate correlation between exposures difficult. The sedimentary sequence is overlain by a thick wedge of basaltic rocks extruded in late Danian times.

Recently, an excellent facies analysis of the Nugssuaq Embayment has been made (Schiener, 1975). Facies belts in the basin run obliquely east-west. The increasing proportions of sand and a decreasing marine influence in southerly direction within the embayment indicate a south and east provenance for the sediments. The role of the north-trending basement ridge under the western part of the embayment has been recognized as controlling the facies but contributing little, if any, detritus. The entire sequence is composed of delta complex deposits filling a north-trending, fault-controlled basin, seemingly rather isolated from the more normal marine regime which probably existed to the west under what is now Baffin Bay.

Only pre-Tertiary sequences in the Nugssuaq Embayment are similar to Labrador Shelf sequences. During Cretaceous and Paleocene times both areas received basal coarse clastics overlain by organic rich dark shales deposited in linear, partly fault-controlled basins. The basins may be genetically related; certainly they are structurally similar.

However post-Paleocene developments in the two basins are very different. The Labrador Basin foundered about a hingeline near the present coast; the Nugssuaq Embayment was covered by thick basaltic lavas extruded throughout the Paleocene, during and after a brief but severe period of tectonism and remained structurally high. The adjacent basin under Baffin Bay formed by hinging west of the western limits of the Nugssuaq Embayment.

MESOZOIC AND CENOZOIC STRATIGRAPHY OF THE LABRADOR SHELF

Introduction

To date, nine deep wells have been drilled on the Labrador Shelf (Fig. 9), all of which have been released from confidential status. Data from these wells, consisting of cuttings, side-wall and conventional cores and mechanical logs, have been analyzed and the sedimentary sequences penetrated have been divided into formations. Paleontological zonations interpreted by Gradstein and Williams (1976 and pers. comm.) are included and their permission to incorporate some of their results is gratefully acknowledged. Figure 10 shows the generalized lithology and stratigraphic sequences penetrated in these wells.

These paleontological zonations facilitate correlation between wells and provide dates for key reflectors of seismic profiles. Because of their unconsolidated nature, extensive reworking of fossils and incomplete sampling, sequences younger than Miocene have not been examined in detail. The stratigraphic classification chart of van Eysinga, 3rd edition, 1975, has been used throughout.

The nomenclature, dominant lithology and maximum thicknesses of the proposed formations are summarized in Table 1 and are described below. The basal Mesozoic includes subaerial basalt flows and intercalated sediments of Neocomian age. The overlying clastic sequence can be divided into two parts:

a. Cretaceous and Paleocene to earliest Eocene sequences of limited distribution. Berriasian to lower Albian rocks are mainly continental; sequences younger than early Albian are predominantly marine.

b. Lowermost Eocene and younger sequences consisting of marine sandy turbiditic mudstone.

Names of formations have been changed as little as possible from those names introduced by Eastcan geologists (McWhae and Michel, 1975, and Eastcan, 1975-78). New names, derived from prominent morphological features, have been introduced only when necessary.

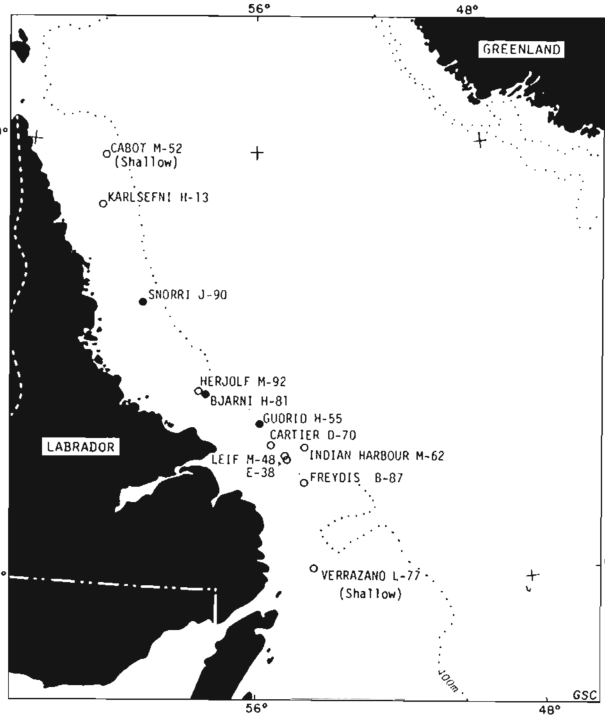
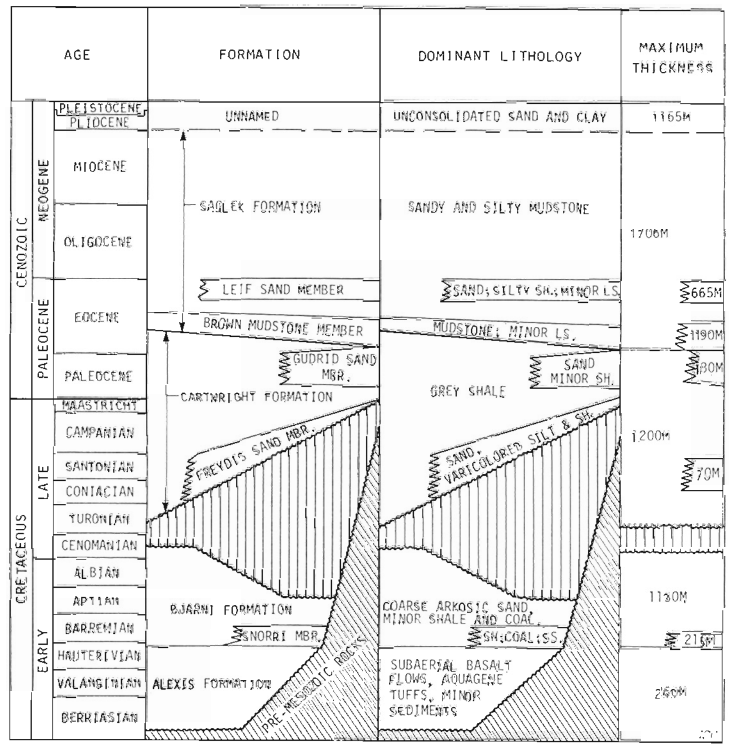


Figure 9. Location of wells drilled on the Labrador Shelf.

Table 1

Stratigraphic nomenclature, Labrador Shelf



Lower Cretaceous

Alexis Formation

The type section of the Alexis Formation is 2515-2255 m in Bjarni H-81. Seismic reflection profiles suggest that the volcanics of the Alexis Formation overlie Precambrian basement and they occur immediately below a thick sand unit with which they have sharp contact. The formation is 260 m thick and is named after the prominent point on the Labrador coast at 53°30'N.

Examination of cuttings show that the Alexis Formation consists of repeated sequences of red and green weathered basalts alternating with fresher amygdaloidal basalt. This alternation is apparent on sonic logs and is interpreted as a series of relatively thin basalt flows with severely altered and weathered upper parts. The flows appear to have been extruded intermittently at an early stage in the development of the Labrador Basin.

The lithology and appropriate logs for the formation in the Bjarni well are shown in Figure 11. Fresh to slightly altered amygdaloidal basalts are shown by cross-hatching and are interpreted as the base of discrete flows. The upper, weathered part of each flow includes reddened sections which in part are "boles" or laterites, known to be the extreme weathering product of basalt in warm, humid climates. However, the weathering of most flows was arrested at the less-severe "green" stage prior to burial by another flow.

The lower part of the formation contains purple and red rocks which do not seem to fit into the above categories. These rocks are inferred to be aquagene tuffs – moderately weathered basalt flows locally eroded and redeposited under water. Pyroclastic rocks have not been recognized. Occasional thin horizons within the Alexis Formation consist of interbasaltic sediments – quartzose sands and red silty clays which have a nonbasaltic source.

Superimposed on the entire formation is a second type of alteration. A general colour change to red-brown and purple hues is evident deeper in the section. This change is interpreted as a pervasive hydrothermal alteration affecting the volcanic pile as a whole. As fresh flows were extruded over the weathered, water-laden parts of earlier flows, the steam generated interacted with newly extruded flows forming zeolite-filled amygdales and hydrolysing the basalt. This hydrolysis, probably including mild oxidation, has a cumulative effect the deeper, older flows being the most severely affected.

Two conventional cores were cut in the formation. The lower one at 2510 m, gave a radiometric age determination of 139 ± 7 Ma (early Berriasian) (Eastcan, well completion report, 1975). The upper core at 2260 m was in relatively fresh amygdaloidal basalt and gave a radiometric age of 122 ± 6 Ma (Hauterivian). Both age determinations were on whole rock samples; the lower one was on altered rock and was deemed less reliable.

To build up a pile of flows to the thickness encountered in Bjarni H-81 would probably take more time than is represented by a single geological stage. However, the time interval (17 Ma or early Berriasian to late Hauterivian) implied from radiometric age determinations is probably too long for the same geological process to have occurred, especially when it is known that this time interval is one of appreciable tectonic activity and changing geological processes. The lower age limit of 139 ± 7 Ma of the Alexis Formation is thought to be too old and a revision of a younger one is suggested. A late Berriasian to early Valanginian age for the base of the Alexis Formation is more likely.

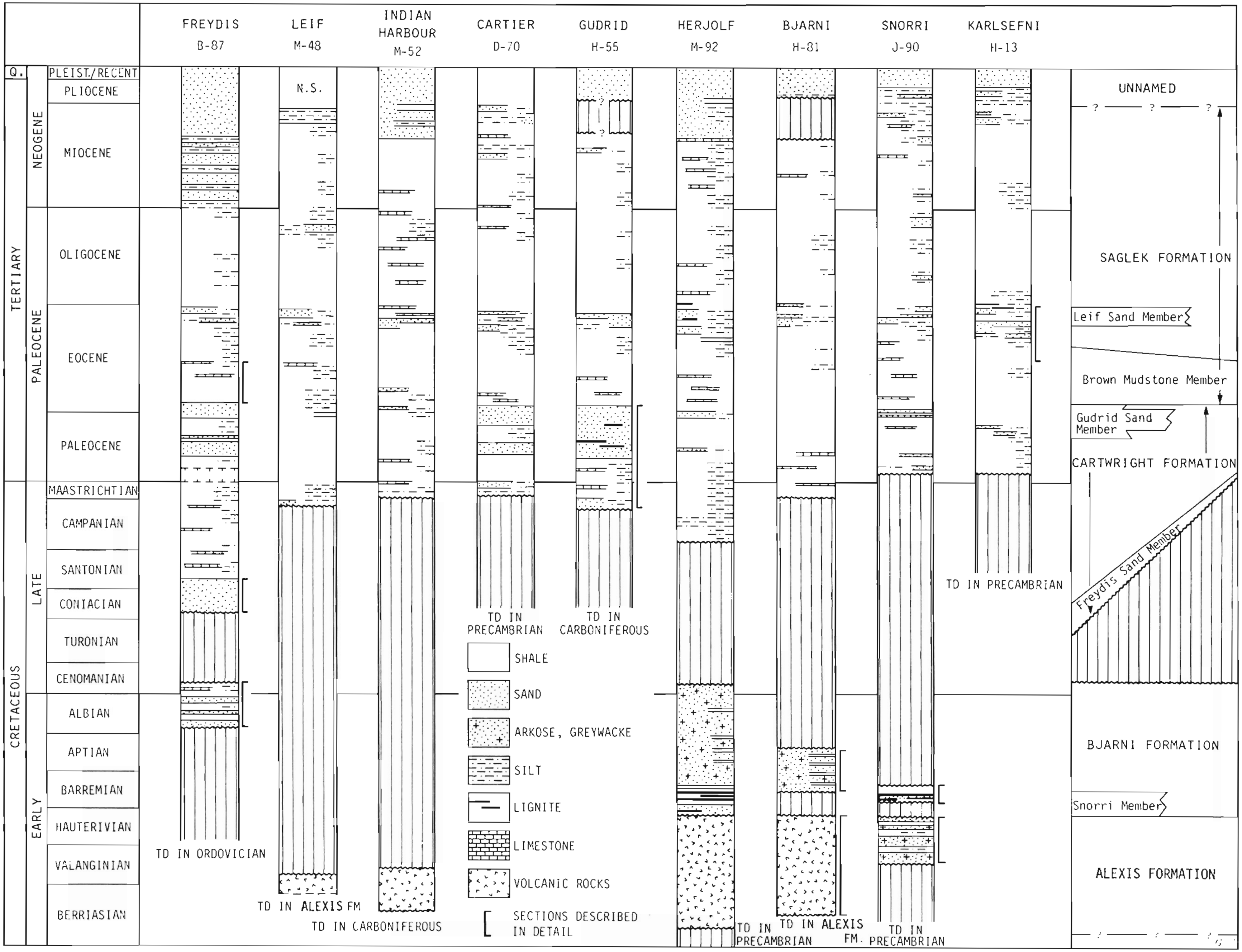


Figure 10. Stratigraphic sequences, Labrador Shelf wells.

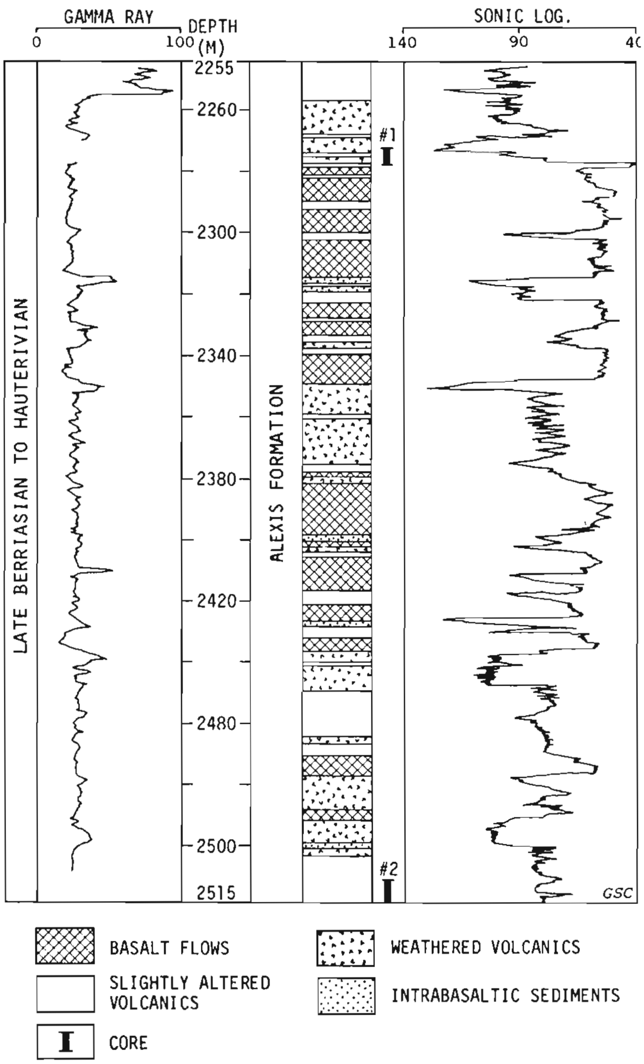


Figure 11. Lithologic details and mechanical logs, Alexis Formation, 2255-2515 m, Bjarni H-81.

The total thickness and areal extent of the lavas are not known. Maps compiled by van der Linden and Srivastava (1975) show high amplitude magnetic anomalies occur off southern Labrador, including the area round Bjarni. Other anomalies occur round Leif M-48 and just west of Snorri J-90, areas where basalts are also known to occur (Fig. 12). If these magnetic anomalies reflect the occurrence of extruded basalts, their distribution is erratic. Le Pichon et al. (1971) had previously claimed that the wide quiet magnetic zone found on the margin of the Labrador Sea was due to extensive subaerially extruded basalt.

At Herjolf M-92, 3.7 km northwest of Bjarni H-81, 258 m subaerial weathered basalt flows were encountered overlying Precambrian basement (Eastcan, 1976a). The volcanics at Herjolf were cored and are lithologically comparable to those from Bjarni. A radiometric age determination from the top of the volcanics at Herjolf gave 122 ± 2 Ma or Hauterivian but an age determination on some more severely altered volcanic rocks near the base of the volcanic sequence gave a Carboniferous age (314 ± 12 Ma) (Eastcan, 1978c).

At Leif M-48, altered basalts are present below 1840 m. Radiometric age determination on cored samples range from 104 ± 5 Ma (late Aptian) to 131 ± 6 Ma (late Berriasian) (Eastcan, 1975). The Leif basalts appear to be coeval to those from Bjarni; they are petrologically similar.

At Snorri J-90, a series of light grey to grey-green greywackes, interbedded arkosic sands and silts with coal beds are present between 3150 m and 3061 m (Eastcan, 1978b). The lithology and appropriate logs over this interval are shown on Figure 13. Palynology indicates the sequence to have a Valanginian to Barremian age, thus it is coeval with the Alexis Formation.

The greywackes overlie Precambrian basement and are interpreted to be sediments derived from volcanic rocks. This sequence consists of aquagene tuffs of basaltic composition and volcanic-clastic rocks of a more acidic nature.

A fifth occurrence of volcanic rocks occurs at Indian Harbour M-53, the easternmost well on the Labrador Shelf. At this location, volcanic rocks occur between 3228 m and 3485 m, unconformably overlying silicified carbonates of undetermined Paleozoic age. They are overlain by marine Maestrichtian rocks.

Fragments of rock recovered during drilling operations and whose exact stratigraphic position is not known, yielded radiometric ages of 90 ± 4 Ma or Turonian (BP Canada Ltd., 1978).

These rocks are lapilli tuff deposits (Fisher, 1966) of intermediate to basic composition. Variably sized light grey lapilli to 10 mm diameter occur in a medium grey, very fine grained matrix. The tuffs are variably weathered and altered, quite unlike the basalt flows of the Alexis Formation. The dissimilarity and the younger age determination suggest that the tuffs at Indian Harbour cannot be assigned to the Alexis Formation.

Bjarni Formation

This formation was named by McWhae and Michel (1975) after Bjarni H-85, the well in which it was first encountered. The type section occurs at Herjolf M-92 between 3767 m and 2614 m where 1153 m coarse arkosic sands of Barremian to

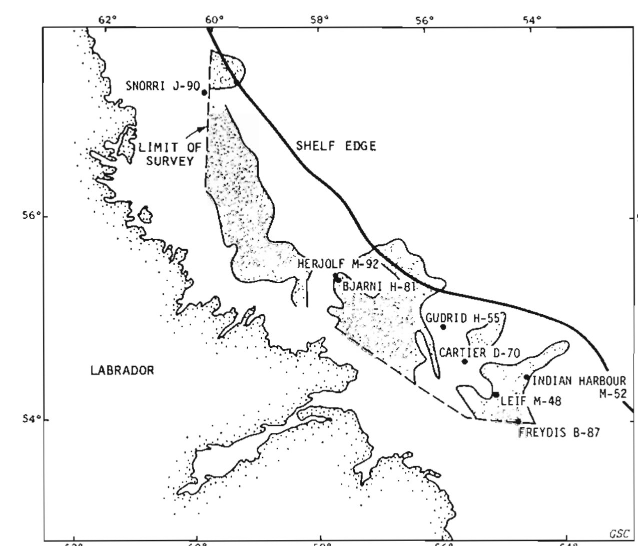


Figure 12. Distribution of high amplitude magnetic anomalies Labrador Shelf. (Redrawn from van der Linden and Srivistava, 1975).

early Cenomanian age are present. The generalized lithology of the Bjarni Formation at Herjolf is given in Figure 14, which shows approximately 80 per cent of the interval consists of light brown-grey to dark grey, coarse arkosic sand. The remaining 20 per cent consists of dark grey silty shale in beds 2 to 20 m thick and thin coal seams. Shale and coal dominate the lowermost 217 m interval which has been distinguished as the Snorri Member. Future work may show this interval can be reclassified as a formation.

In Herjolf M-92, a 7.3 m core cut at 2532 m shows two types of sand. A massive, very coarse arkose containing ovoid granules of pink feldspars up to 20 m diameter is interbedded with a massive, crossbedded to thinly bedded, quartz-rich, medium to very coarse sand. The contacts between these rock types are sometimes sharp and erosional, at other times gradational. Occasionally, the base of the quartz-rich sand beds contains numerous very dark grey shale laminations, mostly 1 mm or so thick, though occasionally they may be up to 20 mm thick. The shale laminations often show penecontemporaneous deformation-slumping, small-scale faulting and dewatering phenomena.

The Bjarni Formation in thin section consists of detrital quartz and feldspar grains in equal proportions. The feldspars are frequently corroded and are of varied composition. Rare detrital mica grains are present and are sometimes altered to kaolinite. The sands are variably cemented; some beds are hard and well-cemented while others remain quite friable. The calcitic silty clay matrix contains abundant neoformed kaolinite which, together with diagenetic calcite, locally occludes the intergranular porosity. The porosity is irregularly distributed and appears to be mainly secondary after the dissolution of calcite. Measured porosities average 12 per cent, values consistent with those obtained from log analysis and visual estimation.

Contacts of the Bjarni Formation with underlying and overlying units are sharp. Pollen and spores extracted from it indicate a Hauterivian to Aptian age. No marine fossils have been found.

The formation was deposited as a series of delta plain sands during a period of mild tectonism. The clastics originated from varied, western sources which include kaolin-rich, regolith-covered areas. During late Hauterivian and early Barremian times when the shale-dominated, coal-bearing Snorri Member was being deposited, relief within the basin was probably low and the area was tectonically relatively stable. Later in the interval of sand deposition, in Aptian and Albian times, differential movements between faulted blocks and adjacent basin areas occurred. By late Albian-early Cenomanian times, the area appears to have been tectonically less active with regional, epeirogenic uplift and warping.

Sequences correlatable with the Bjarni Formation are present in three other wells. The stratigraphic intervals of these sequences are shown on Figures 10 and 14. Figure 10 suggests that Lower Cretaceous rocks are of local occurrence. However seismic data show them to have wider distribution. Most wells have been drilled on basement highs and penetrated "abnormal" sequences which were modified by the emergence of these features until Late Cretaceous or Early Tertiary times. Between the highs, considerable thicknesses of Lower Cretaceous rocks are present. Thus Herjolf M-92, a well drilled on the flank of a structure, encountered 1153 m sediments but Bjarni H-81, drilled near the crest of a basement block, penetrated only 106 m of Bjarni Formation.

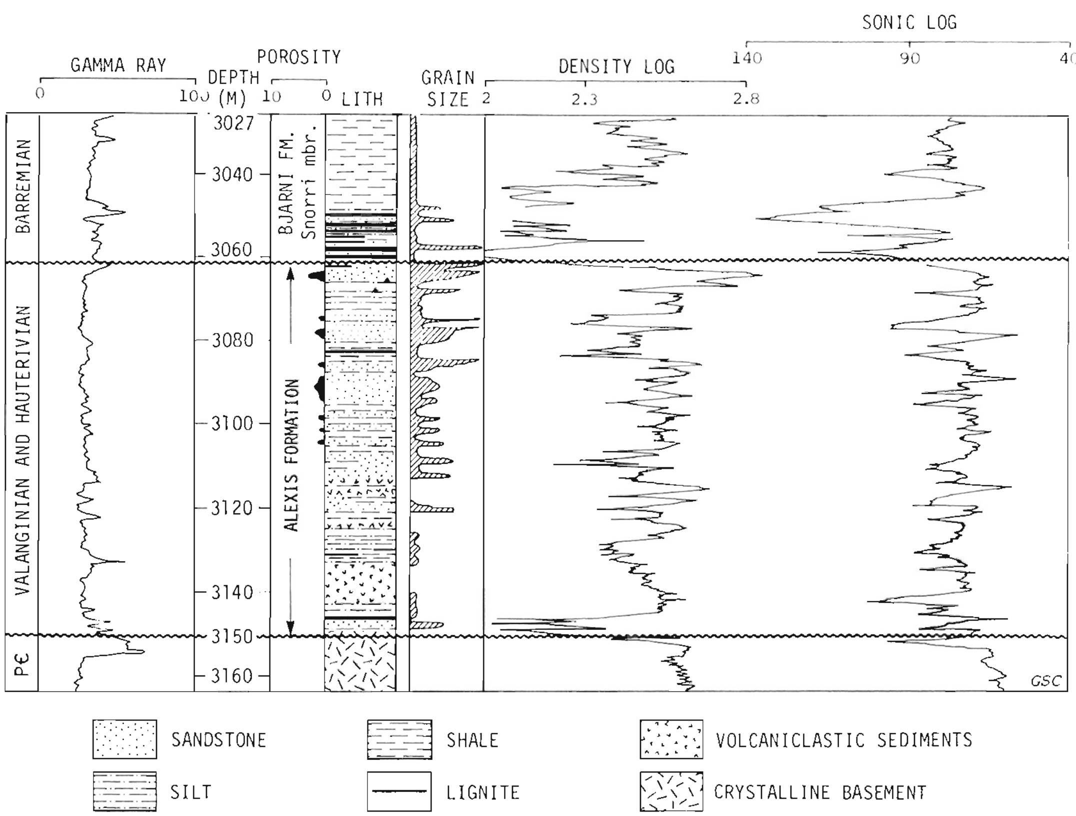


Figure 13. Lithology and mechanical logs of the Alexis Formation and Snorri Members of the Bjarni Formation, 3151-3061 m and 3051 to 3027 m, Snorri J-90.

In Bjarni H-81 coarse arkosic sands occur between 2255 m and 2149 m. The generalized lithology and mechanical logs over this interval are shown in Figure 15, which shows contacts with underlying and overlying formations to be sharp. These sands are lithologically comparable to those of Herjolf M-92 and contain thin, dark grey silty shale laminations, thin lignite beds and carbonized wood fragments scattered throughout.

The Bjarni Formation at both Herjolf M-92 and Bjarni M-81 has a fairly high radioactivity compared to the overlying Late Cretaceous marine shales. This comparison is apparent on gamma ray logs (Fig. 15). Although no chemical analyses are available a possible source of this radioactivity is uranium, an element often concentrated in lignitic continental sands.

At Bjarni, the sands are Barremian to Aptian in age and correlate with the middle part of the Bjarni Formation at Herjolf M-92 (Fig. 14).

Freydis B-87 encountered a sequence dated as Albian and early Cenomanian between 1902 m and 1795 m (Fig. 16). The basal 47 m consists of variably silty shaly sand. Cleaner horizons to 6 m thick are medium grained white quartzose sands. Interbedded silty horizons have dull red purplish and greenish hues. Thin shale beds are also varicoloured and include buff kaolinitic claystones. Lignitic streaks and carbonized wood fragments occur throughout this interval which unconformably overlies calcareous sand of Middle Ordovician age (W.A. Jenkins, pers. comm.).

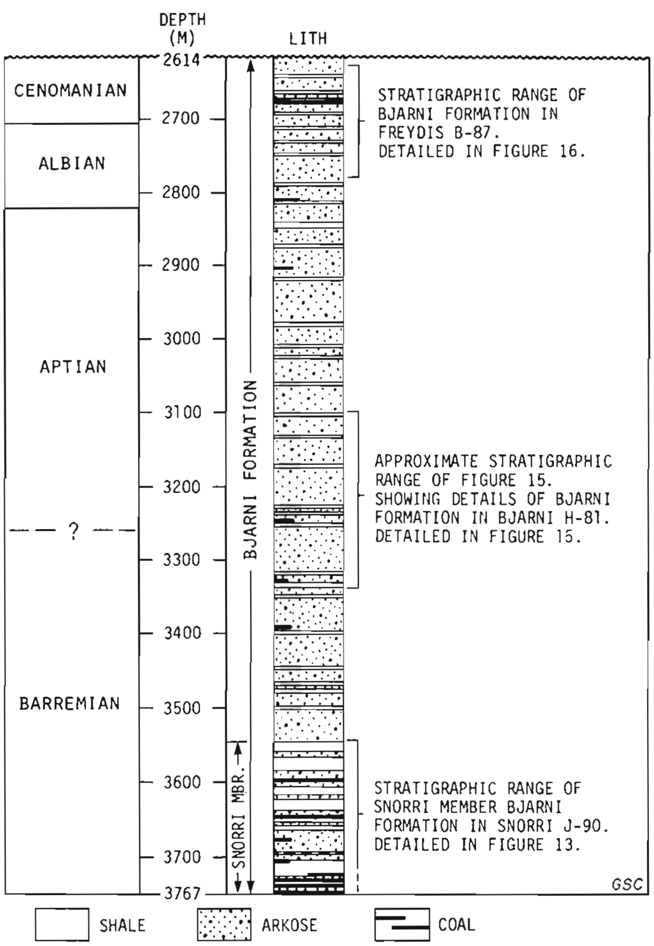


Figure 14. Generalized lithology, Bjarni Formation, 3767-2614 m, Herjolf M-92. The stratigraphic positions of correlatives of the Bjarni Formation encountered in other Labrador wells are also shown.

Palynomorphs give an Albian age for this sequence which contains the oldest marine fossils (foraminifers) seen to date on the Labrador Shelf. Unfortunately, these foraminifers are long-ranging arenaceous taxa of possible northern or boreal affinity. They indicate that at least temporary marine incursions occurred in an area dominated by continental deposition. Thus during Albian times the spectrum of depositional environments widened to include shallow marine deposits.

The uppermost 50 m of Bjarni Formation in Freydis consists of light grey silty shale with thin interbeds of white, glauconitic sand and occasional layers of white chert pebbles. This part of the Bjarni Formation is predominantly marine; long-ranging arenaceous foraminifers are present and palynomorphs indicate an Albian and early Cenomanian age. The contact with the disconformably overlying Upper Cretaceous marine shale is sharp.

In Snorri J-90 radioactive grey to dull dark brown-maroon silty shale with abundant plant remains and thin coal seams occur between 3045 m and 3027 m (Fig. 13). Immediately below this is a 16 m-thick interval containing coal seams to 2 m thick, interbedded with dark grey silty shale and argillaceous, medium grained sandstone. The unit conformably overlies greywackes of Valanginian age (equivalent to the Alexis Formation) at 3061 m.

The radioactive shales overlying the coal-bearing clastic sequence have been dated by palynology as Valanginian to Barremian. This sequence is therefore equivalent to the lower part of the Bjarni Formation at Herjolf M-92 and constitutes the Snorri Member.

Upper Cretaceous and Paleocene

Cartwright Formation

The type section of this formation is between 2650 m and 2393 m in Gudrid H-55. The unit consists of medium to dark grey mudstone grading to light grey splintery, siliceous shale. On drying, cuttings acquire a characteristic blue-grey tinge. The lower part of the formation includes thin intervals of light grey silt, very fine sand and grey-brown to dark brown micrite. The contact with the underlying Carboniferous dolomite; and the overlying Gudrid Sand Member is sharp. Characteristics of the Cartwright Formation are shown in Figure 17.

Foraminifera and palynomorphs indicate a late Campanian to early Paleocene age at Gudrid H-55. In other wells, the age of the base of the formation varies from late Coniacian to Maastrichtian. Off structure, the base of the formation may be older. This variation shown in Figure 10 and Table 1.

The depositional environment of the Cartwright Formation varies. In part it is marine, yielding a good foraminiferal fauna, has glauconite-rich beds and contains thin shelly micrite horizons. In part it is marginally marine with thin lignitic streaks and thin, fine to granule-sized sands occurring in intervals apparently devoid of foraminifera. The proportion of marine and nonmarine facies is difficult to estimate and deposition in a shallow water regime oscillating between normal marine and nonmarine conditions is visualized.

Locally developed with the Cartwright Formation are two sand members. At the base is the Freydis Sand Member; at or near the top of the Cartwright Formation is the Gudrid Sand Member.

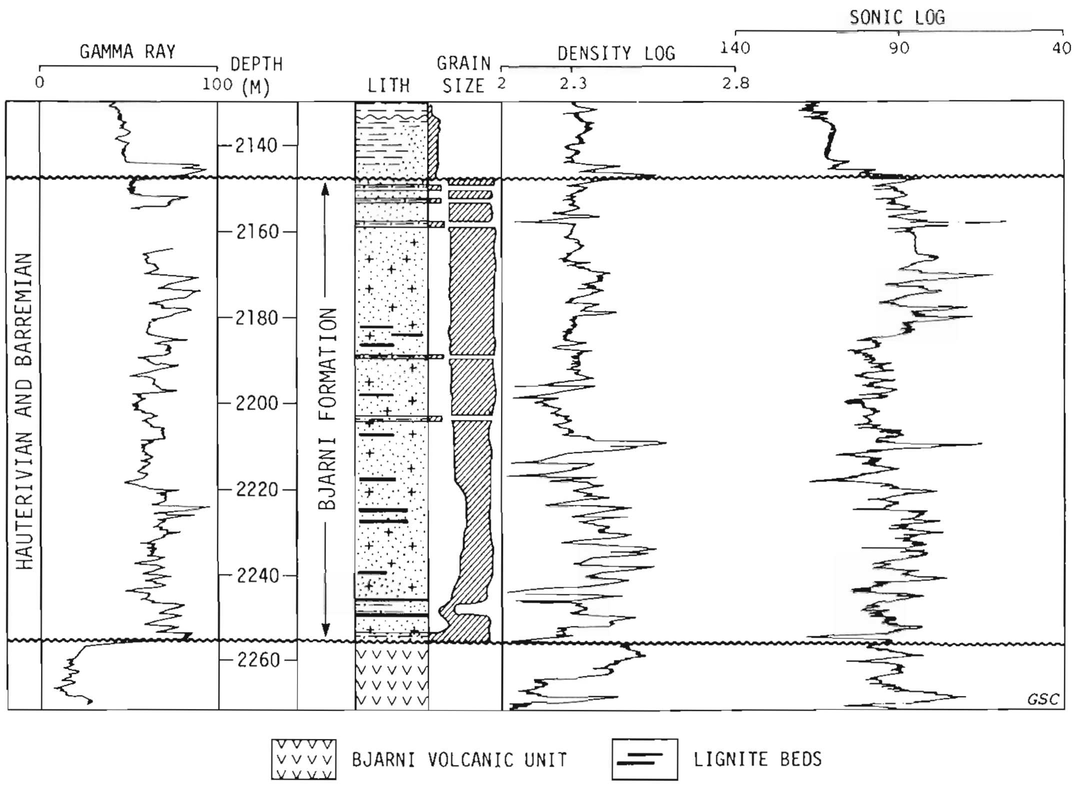


Figure 15. Lithological details and mechanical logs Bjarni Formation, 2255-2149 m, Bjarni H-81.

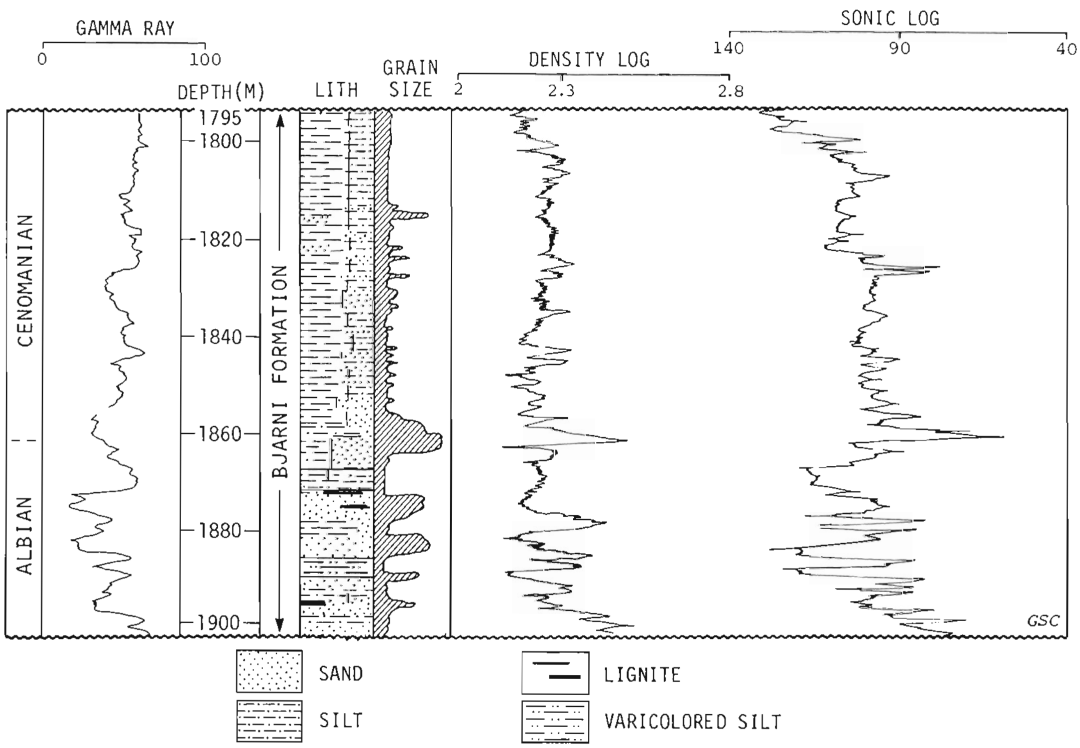


Figure 16. Lithological details and mechanical logs, upper part of the Bjarni Formation, 1902-1797 m, Freydis B-57.

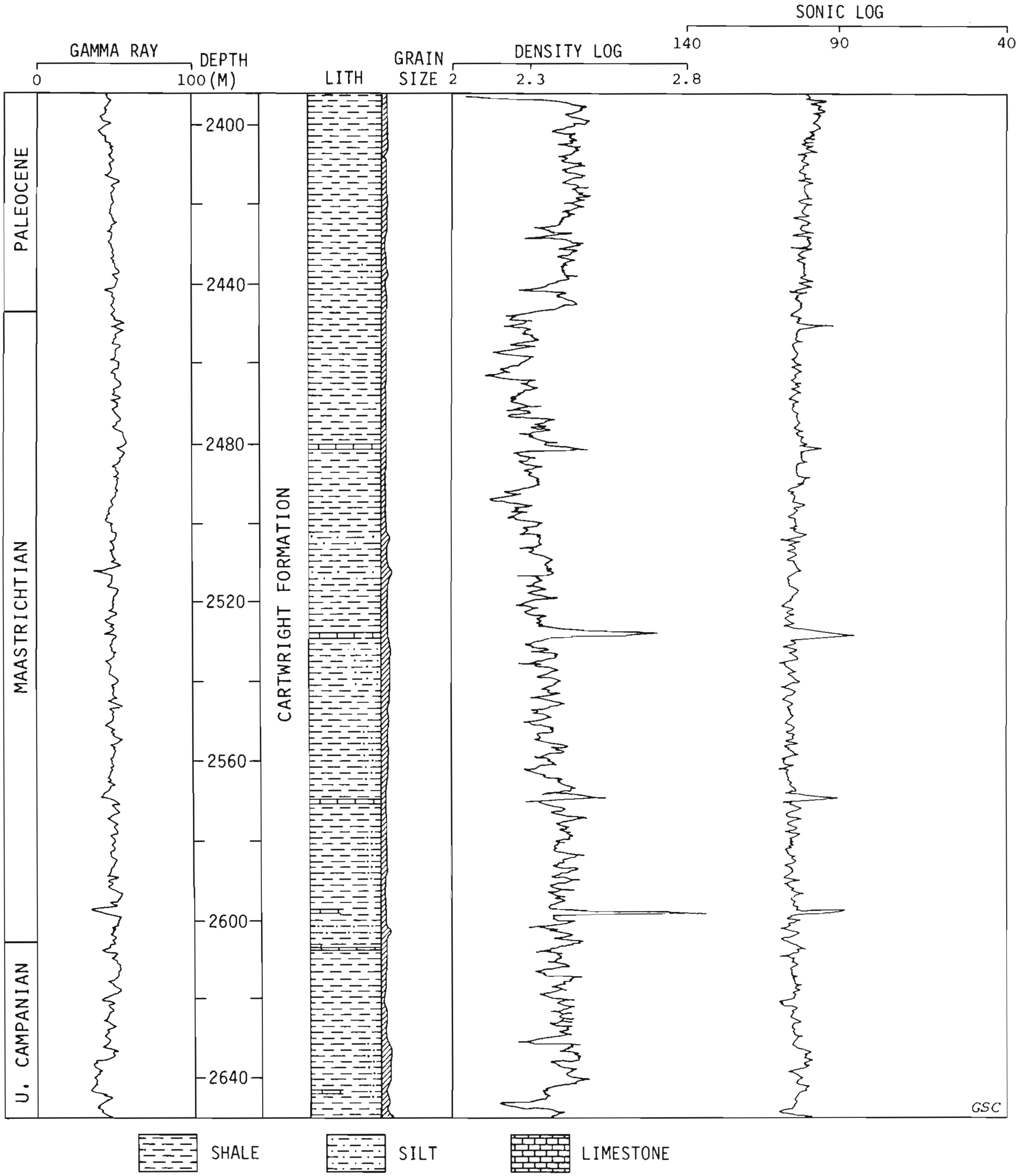


Figure 17. Lithological details and mechanical logs, Cartwright Formation, 2650-2393 m, Gudrid H-55.

Freydis Sand Member

Between 1789 m and 1734 m in Freydis B-87, a 55 m thick sand is developed. The lithology and mechanical logs over this interval are plotted on Figure 18.

The sand is coarse, poorly sorted, arkosic, with abundant white clay and light grey silty matrix. Porosity averages 15 per cent. Upwards the grain size decreases to mixed fine and medium and the sand becomes glauconitic. The contact with the underlying Bjarni Formation is unconformable and the contact with the overlying shales of the Cartwright Formation is sharp and conformable.

A continental aspect is indicated for most of this sand; however, in its upper part, it is marine since it contains foraminifers and is transitional between the continental sequences below and the predominantly marine shaly sequences above. Palynological and foraminiferal evidence both date this sequence as Coniacian to early Santonian.

Similar sand developments have been encountered in other wells where they unconformably overlie older rocks and grade upwards into grey mixed marine and nonmarine shales of the Cartwright Formation. These lateral equivalents of the Freydis Sand Member encountered to date are diachronous and thin.

1. At Leif M-48 a 3 m thick silty and sandy shale of Maestrichtian age at 1835 m unconformably overlies the Alexis Formation Unit (Eastcan, 1975).
2. At Cartier D-70, a 3 m thick sequence of red and green shales and red-brown silts immediately overlies crystalline basement (Eastcan, 1977c). This sequence is overlain by a 6 m thick bed of medium-grained friable arkosic sand with abundant kaolinite matrix at 1903 m.
3. Overlying Upper Paleozoic dolomite at 2650 m in Gudrid H-55 is a bed of red silt containing grey nodules. According to Eastcan (1976b), these nodules are composed of nontronite, a sodium and ferric iron montmorillonite. This mineral may originate from the deposition of iron-rich, subaerially-weathered basalts in a marine environment. Overlying beds are composed of thinly bedded red and grey-green silts grading to greenish shales and containing thin light grey, very fine sand stringers. The total thickness of these basal correlatives of the Freydis Sand Member at Gudrid is only 12 m. Palynology indicates a Campanian age.
4. Unconformably overlying the Bjarni Formation at Bjarni H-81 is a 9 m thick bed of light grey calcareous and argillaceous fine grained sand occurring at 2146 m. The sand is friable, has a white kaolinitic matrix and has been dated as Maestrichtian.
5. A correlative of the Freydis Sand Member occurs at Snorri J-90. Below 3020 m, a 6 m thick sequence of red, grey and green silty shales with thin brown micrite interbeds occurs. This sequence is nonmarine and is of Paleocene age.

The relationships of these diachronous Campanian to Paleocene varicoloured basal clastic equivalents of the Freydis Sand Member are shown on Figure 10.

Gudrid Sand Member

This member is typically developed between 2393 m and 2179 m in Gudrid H-55 and is named after this well. Eastcan, in well completion reports, named this unit the Cartier Sand. However, the unit is best developed in Gudrid H-55, where it consists of arkosic sand with abundant clay matrix. Clasts of rounded and frosted varicoloured quartz and nearly fresh feldspars occur in approximately equal amounts. Also present are clasts of a greenish white mineral, which is probably chlorite. The upper part of the member is extremely friable due to abundant clay cement and logs show this part to have porosity values to 25 per cent. The porosity is probably secondary after the dissolution of carbonate cement and below 2280 m are thick intervals with dolomitic cement occluding the porosity. The generalized lithology and tracings of appropriate mechanical logs are shown on Figure 19.

The Gudrid Sand Member has a continental character, particularly in the lower part where thin lignite beds are present. The poor sorting and arkosic nature suggest lower delta plain deposition. The sand is devoid of marine fauna but palynomorphs indicate a Paleocene to lowermost Eocene age. This is confirmed by both foraminiferas and palynomorphs of lower Eocene age occurring in overlying mudstones.

At Gudrid H-55, the Gudrid Sand Member is overlain sharply and conformably by the Brown Mudstone Member. In all other wells, whether the sand is developed or not, the two shale units grade into each other. The increased silt content of the Cartwright Formation gives a characteristic concave kick towards lower transit time values on sonic logs which enables the base of the Brown Mudstone Member to be defined. Log markers used to define this and other contacts are shown on Figure 20.

Cartier D-70, 34 km to the southeast, has a similar and coeval sand development. The Gudrid Sand Member at Cartier consists of two sand developments totalling 111 m in thickness. The thick sands at Gudrid H-55 and Cartier D-70 are opposite Hamilton Inlet and perhaps the locus of an extensive sand development on the lower reaches of an ancestral Churchill River. Bjarni H-81 and Leif M-48, the wells which flank this area, have only thin, poorly developed silty and slightly sandy shale at this horizon, suggesting an interfluve location.

Sands of Paleocene age are also developed at Snorri J-90 (Eastcan, 1978b). These occur as discrete beds up to 15 m thick, are interbedded with shale and are better sorted and less arkosic than the Gudrid Sand Member farther south. Cores of the sand at Snorri show frequent laminated and graded units to 1 cm thick with numerous sand-filled borings, indicating a shallow subtidal origin.

A third development of the Gudrid Sand Member is at Freydis B-87 (Eastcan, 1977a), where 79 m net sand occurs at between 1792 m and 1387 m, belonging to the same facies as in Gudrid H-55.

Eocene and Younger

In early Eocene times depositional environments changed rapidly from shallow marginally marine to deeper water regimes. Sediments deposited after this change form a simple clastic wedge, outbuilding and upbuilding to form the present shelf. Lithologically, these sediments consist of thick, rather monotonous mudstones which gradually become sandier and siltier upwards. In Oligocene times the clastic wedge was generally built up to base level; deeper water conditions resumed during the early Miocene.

Each unit making up this clastic wedge thickens eastwards and northwards towards the Saglek Basin depocentre off northern Labrador (Fig. 1). Thus off southern Labrador, Eocene and younger sediments average 1800 m; eastwards in Indian Harbour M-52 this increases to 2900 m. In northern Labrador these sediments are 3000 m thick in Karlsefni H-13, on the western edge of the Saglek Basin depocentre.

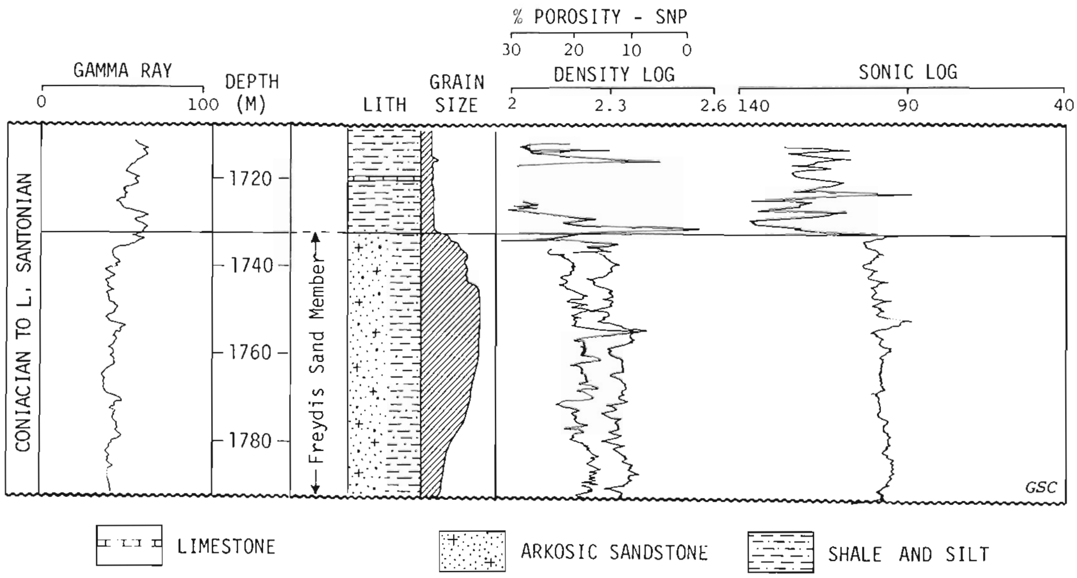


Figure 18. Lithological details and mechanical logs, Freydis Sand Member of the Cartwright Formation, 1789-1734 m, Freydis B-87.

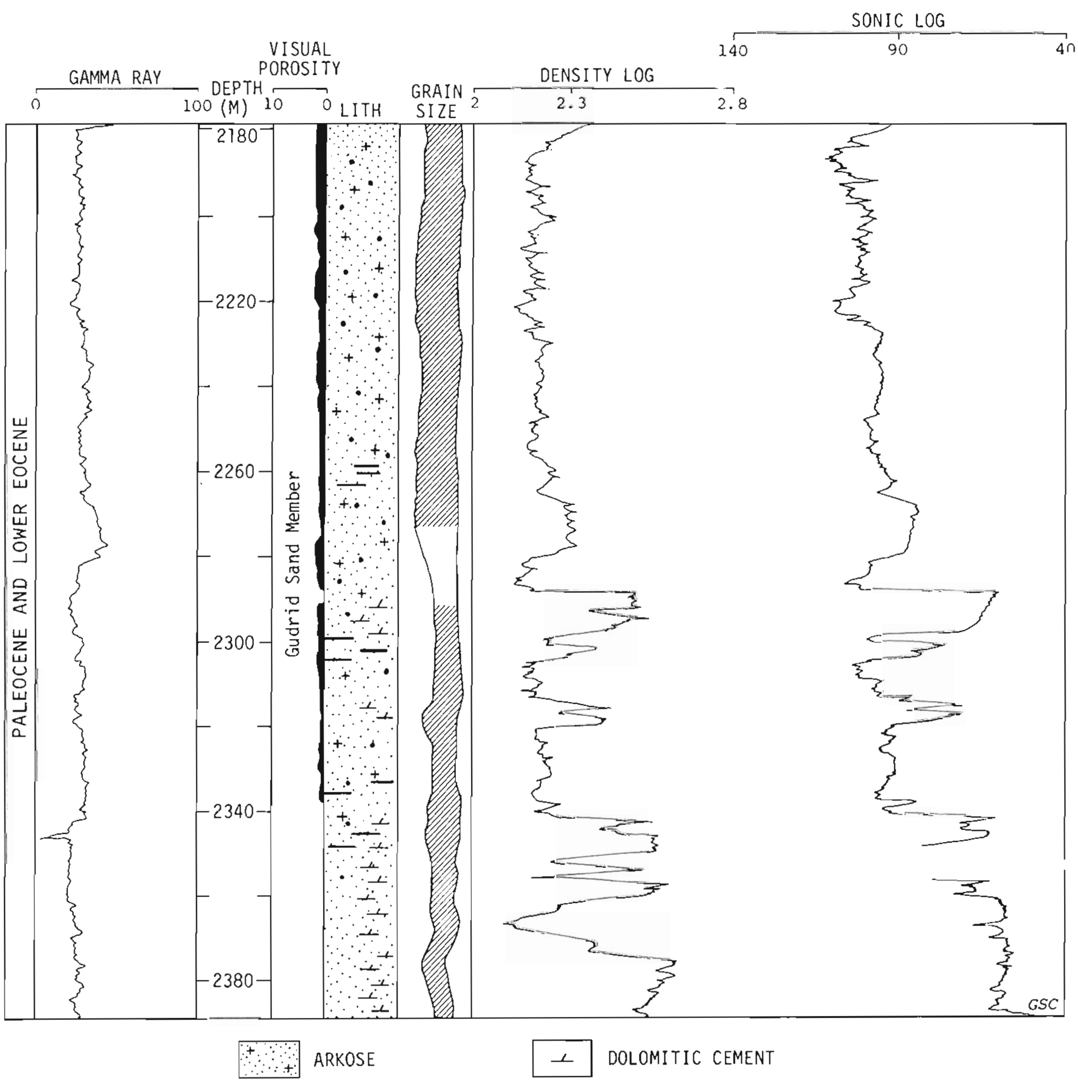


Figure 19. Lithological details and mechanical logs, Gudrid Sand Member of the Cartwright Formation, 2393-2179 m, Gudrid H-55.

Saglek Formation

The formation conformably overlies the Cartwright Formation, the contact with which is transitional and is best defined on sonic logs (Fig. 20). The formation is presently all in wells, and the type section is chosen between 1131 m and 1027 m in Freydis B-87. The generalized lithology and tracings of mechanical logs over the lower part of the Saglek Formation are shown in Figure 21. However, it is best developed at Karsefni H-13, where it is at least 2500 m thick. The Saglek Formation includes two members as well as undifferentiated beds. At the base, the Brown Mudstone Member – a series of dark brownish grey mudstones of Early Eocene age. In the middle of the Saglek Formation is a series of sandy developments, the Leif Sand Member of late Eocene age.

The Saglek Formation consists of variably silty and sandy mudstones, predominantly grey coloured with brown to red-brown tinges. Towards the base the amount of silt is lower and the colours darker. This section comprises the Brown Mudstone Member. The middle part of the Saglek Formation is sandy (the Leif Sand Member). Occasional beds with 20-30 per cent sand are present, with the sand occurring in three modes – intimately mixed with silty mudstone matrix; as wisps of pure, fine to very fine quartzose sand; and as thin laminations interbedded with silty mudstone laminae.

Thin beds of micrite and occasional glauconite-rich layers suggest this formation was deposited in an exclusively marine environment. Both foraminiferas and palynomorphs are present and indicate a late Eocene age. The Saglek Formation appears to be a series of turbidites, the rates of sedimentation average 7 $cm/10^3y$ suggesting rapid deposition outbuilding and upbuilding a sedimentary wedge in water still having appreciable depth.

That part of the Saglek Formation above the top of the Leif Sand Member consists of variably silty and sandy mudstones. Lithologically this sequence is similar to that part of the Saglek Formation between the top of the Brown Mudstone Member and the base of the Leif Sand Member. Paleontology shows this sequence to be of early Oligocene to late Miocene age.

The upper part of the Saglek Formation is recognized in all the wells drilled to date. It has variable thickness (310 m to 780 m) but is not datable with certainty because of reworking of fossils. The contact between the top of the Saglek Formation and the overlying unnamed beds of Plio-Pleistocene unconsolidated sand and clays is generally transitional. However, locally, in Gudrid H-55 and Bjarni H-81, the late Miocene and therefore the uppermost part of the Saglek Formation is absent.

In describing the deposition of the Saglek Formation, distinction must be made between subsidence rates and sedimentation rates. In the early Eocene subsidence of the basin greatly exceeded rates of sedimentation, which were themselves high. At this time the Brown Mudstone Member was deposited under conditions of increasing water depth in water depths corresponding to a outer neritic-upper bathyal milieu. During late Eocene times, basin floor subsidence occurred at a greatly reduced rate and because of continued rapid rates of sedimentation water depths decreased. Thus the uppermost beds of the lower part of the Saglek Formation were deposited in an outer to inner neritic environment. Water depths were shallowest in the latest Eocene, when the Leif Sand Member was deposited, and in the Oligocene, when a condensed sequence, including marginal-marine coal measures, was deposited. This shallowing in late Eocene and Oligocene times is a consequence of the rapid outbuilding of sediments of the proximal part of the clastic wedge of the Labrador Shelf. Coeval distal sediments were probably deposited in deeper water.

In the Lower Miocene, renewed rapid subsidence of the basin occurred and during this stage sedimentation rates were almost as high. Thus the proximal part of the upper part of the Saglek Formation was deposited in water depths corresponding to an inner to outer neritic environment.

No transgression occurred during the Tertiary. Seismic reflection profiles suggest shorelines remained nearly stationary throughout. The rapidly changing environments of deposition are therefore due to two periods of accelerated subsidence. A consequence of a "still stand" in mid-Tertiary times is the apparent thinness of Oligocene sediments on the Labrador Shelf. This attenuation is probably due to the Oligocene consisting of condensed sequences representing all stages of the Oligocene separated by lacunae which consist of two parts, the hiatus (corresponding to nondeposition) and the degradation vacuity (corresponding to the removal of the top part of a sequence by erosion).

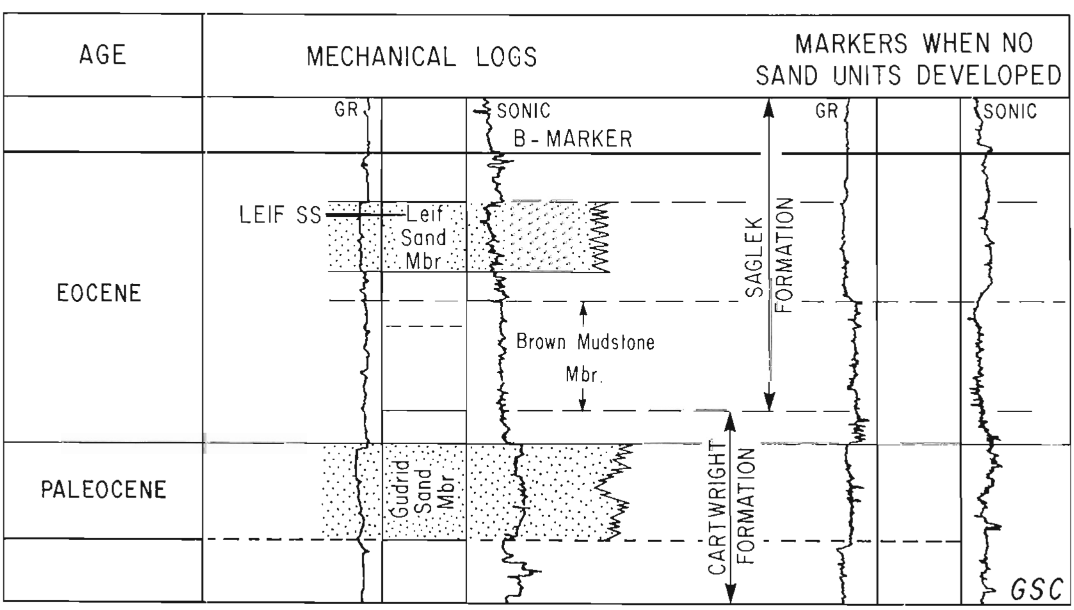


Figure 20. Log markers, showing boundaries of Paleogene formations, Labrador Shelf.

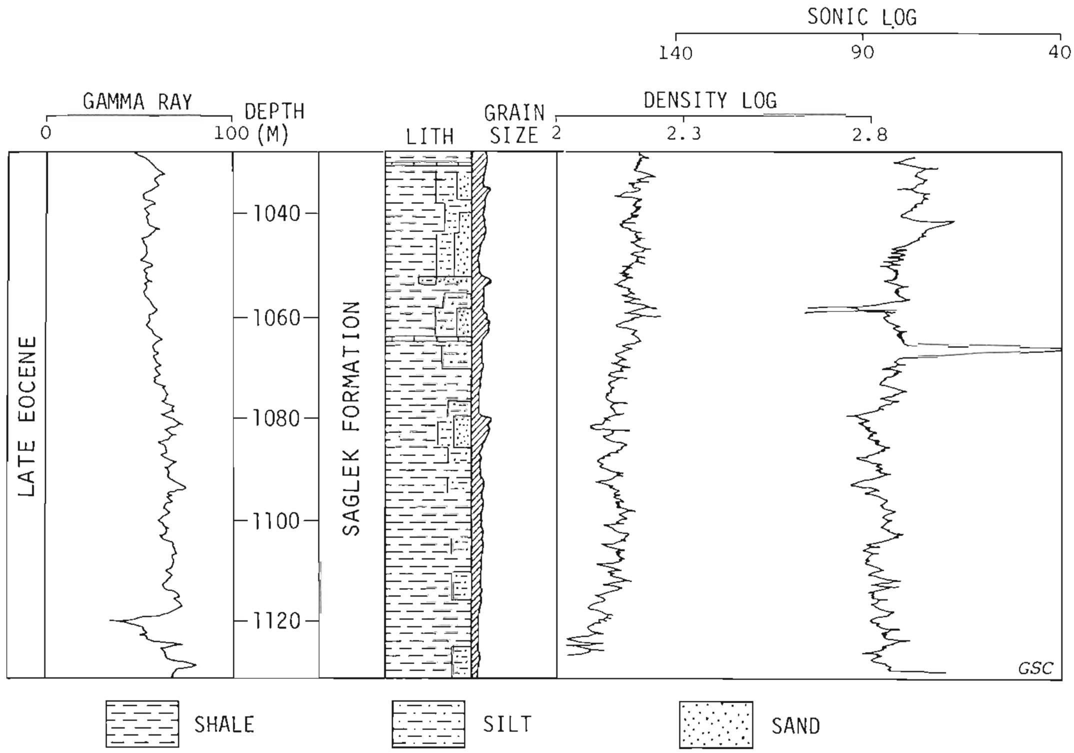


Figure 21. Lithological details and mechanical logs, lower part of the Saglek Formation, 1131-1027 m, Freydis B-87.

Brown Mudstone Member

The type section of the Brown Mudstone Member is between 1321 and 1131 m in Freydis B-87 (Fig. 22) where it consists of brown grey to dark grey mudstone. Interbeds of hard, brown-grey micrite and finely crystalline limestone occur throughout. The unit is generally massive though laminations of subtle colour variations are present.

The contact with the underlying Cartwright Formation is transitional and is picked on sonic logs at the top of a characteristic kick towards lower transit time values (Fig. 20). The contact with the overlying part of Saglek Formation is also transitional and is taken at the lowermost silty sand development in this upper unit. This contact is also apparent on sonic logs (Fig. 20).

Foraminifera and palynology indicate the member is of Early to Middle Eocene age. It is entirely marine. The homogeneous unbedded nature, apparent rapid rate of deposition (up to 7 $cm/10^3y$) and general lithology suggest a turbidite sequence. Periods of mass transport of mudstones as turbidites irregularly alternated with periods of low sedimentation rate during which thin argillaceous micrites were deposited. Some of the calcareous beds, seen on sonic logs as dense streaks (Fig. 21), may be due to the migration of carbonate during diagenesis to form intermittent, thin beds.

Water depths at the time of deposition were appreciable, perhaps as much as 500 m. No evidence of a former shelf exists so that reference to the morphology of modern continental shelves is invalid. This member represents the initial stages of outbuilding and upbuilding in a deep, newly and rapidly formed early Eocene basin.

Leif Sand Member

The type section of the Leif Sand Member is between 2394 and 2191 m in Karlsefni H-13. Similar sequences are developed in other wells. The lithology and mechanical logs over this unit are plotted in Figure 23. Clasts of sand size are not necessarily dominant; sandy and silty mudstones occur more frequently. The member is a sandy and silty development of the Saglek Formation with sand occurring in the same three modes.

Intervals plotted as discrete sand on Figure 23 consist of light brown-grey to white, fine quartzose sands; intervals showing mixed lithology consist of sand and silty mudstone in which the sand is dispersed throughout the matrix. An approximate visual analysis of the sandier beds is: sand 40%, silt 30%, and mud 30%. However, the Eocene and younger sequences of the Labrador Shelf are very unconsolidated so that the proportions of the components may be altered during washing operations.

The contact with the overlying part of the Saglek Formation is sharp and coincides with a prominent log marker (McWhae and Michel's B-marker, 1975) which is caused by the rapid increase in quartz clasts just above the main sand (Fig. 23). Beds immediately below the B-marker contain thin sands associated with white recrystallized shelly limestones and hard, silica-cemented, dark brown glauconitic sands. The main sand occurs 50-60 m below the B-marker.

Palynology and foraminifers indicate a late Eocene age for the Leif Sand Member. Foraminiferal evidence suggests that deeper water conditions prevailed. However diagnostic depth-indicating species found in this interval could have been reworked as other criteria suggest deposition in shallow water or even marginal marine conditions.

In Herjolf M-92, equivalents of the Leif Sand Member between 1557 and 1371 m contain coal seams. Sonic logs indicate that these seams are up to 30 cm thick. The presence of true coals at this level suggest that in late Eocene times the basin was locally filled to base level and temporary marginal marine conditions existed. At Bjarni H-81, 3.7 km southeast of Herjolf M-92, the Leif Sand Member contains no coal and the proportion of sand-sized clasts is lower.

During the early and middle Eocene, a relatively deep water regime is thought to have existed near the basin margin (i.e. the present day Marginal Trough). During late Eocene times, the proximal part of the sedimentary wedge appears to have built up to within wave depth perhaps during a temporary halt in the overall subsidence. This condition persisted into the Oligocene, which is relatively thin on the Labrador coast. A shallower water inner neritic to marginal marine origin for the Leif Sand Member is therefore favoured.

Plio-Pleistocene Sediments

During the early Pliocene, rapid and sudden subsidence of the Labrador Sea basin occurred. This renewed subsidence, accompanied by increased sedimentation rates (up to 23 cm/10^3y), resulted in the shelf being outbuilt and upbuilt to the present day sharp shelf edge and the mass transport of vast amounts of sediment to the deeper parts of the basin.

Summary

Compaction curves for four wells on the Labrador Shelf are shown on Figure 24. These curves are similar to the "geohistory diagrams" of van Hinte (1978) and were constructed using the compaction curves of Perrier and Quiblier (1974).

The subsidence curves summarize tectonic-stratigraphic events. Figures 24.3 and 24.4 are drawn for wells (Karlsefni and Cartier) from which Lower Cretaceous rocks are absent.

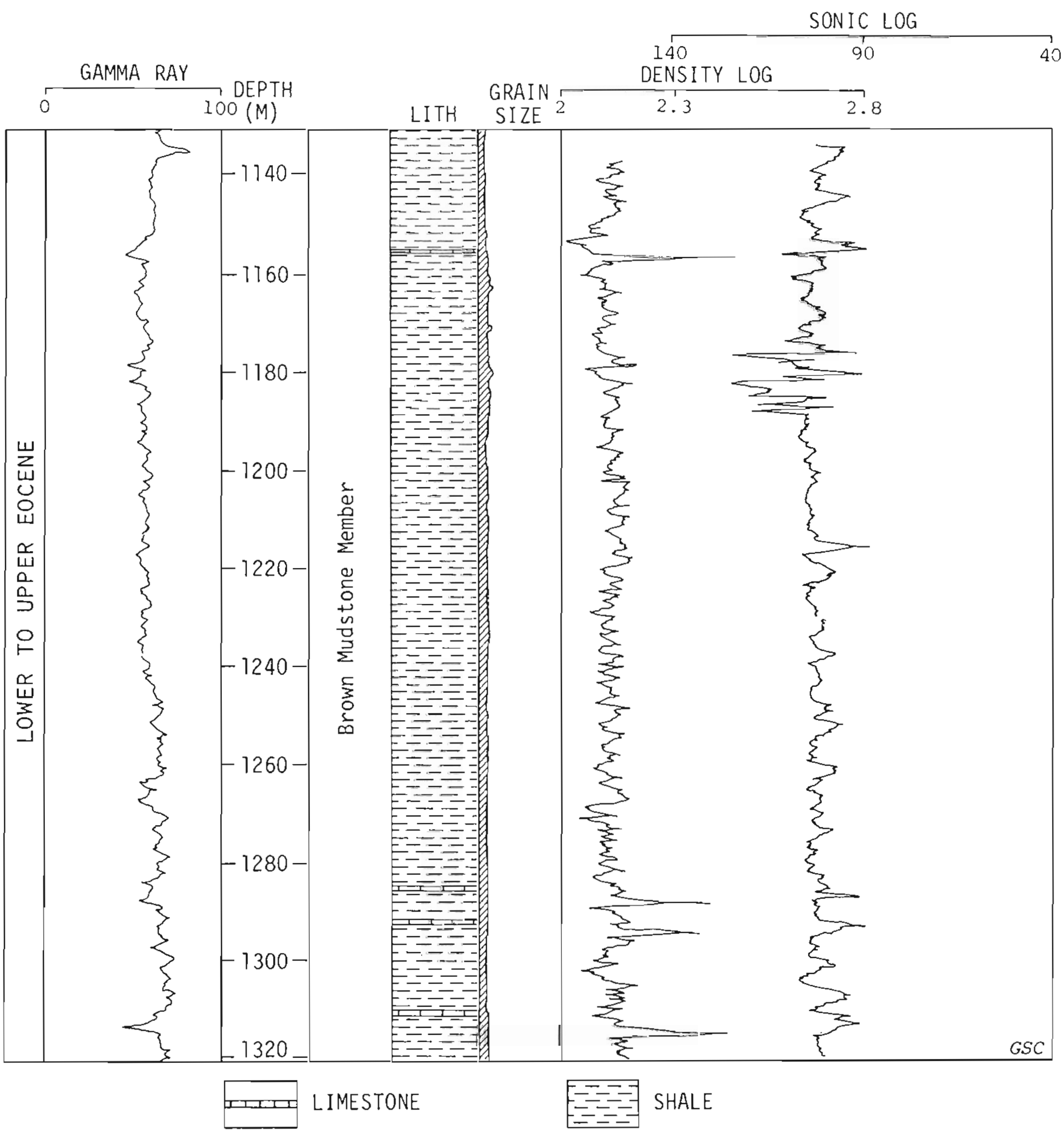


Figure 22. Lithological details and mechanical logs, Brown Mudstone Member of the Saglek Formation, 1321-1131 m, Freydis B-87.

However, rocks of this age occur off the structure on which Cartier D-70 was drilled but are absent from this well as a consequence of mid-Cretaceous tectonism. Karlsefni H-13 appear to be situated west of the Lower Cretaceous inshore basin. Both subsidence curves are similar and show pronounced rapid sagging of the Labrador Sea Margin throughout the Tertiary with a period of reduced subsidence in late Eocene and Oligocene times. At Cartier D-70, initial sagging (Campanian and Paleocene) was gentle; during this interval the Cartwright Formation, including the Gudrid Sand Member, was deposited. Subsidence was rapid during the Eocene when the lower part of the Saglek Formation, including the Brown Mudstone Member, was deposited. During the period of reduced sagging in late Eocene and Oligocene times, the Leif Sand Member, probably condensed sequences of the lowest beds of the upper part of the Saglek Formation, were deposited. During the second period of increased subsidence, the remainder of the upper Saglek Formation was deposited.

Karlsefni H-13 shows a similar stratigraphy with the important difference that rapid subsidence occurred here first in the early Paleocene. Elsewhere on the Labrador Shelf rapid subsidence is an Eocene phenomena. This suggests that although similar processes have occurred along the Labrador Sea margin, important temporal differences do exist. The Paleocene at Karlsfni appears to have been deposited in deep water and the Cartwright Formation in this well is lithologically similar to the Saglek Formation.

Figure 24.2 shows the subsidence curve for Herjolf M-81, a well penetrating the most complete sequence found to date on the Labrador Shelf including a thick Lower Cretaceous-Cenomanian series of continental clastics. The unconformity between the lower Cenomanian and lower Campanian in Herjolf H-81 is due in part to readjustments on faulted basement blocks with consequent erosion in mid-Cretaceous times. Apparent on Figure 24.2 is the long period of nonmarine deposition (Berriasian to lower Cenomanian) corresponding to extrusion of the Alexis Formation and deposition of overlying coarse continental clastics of the

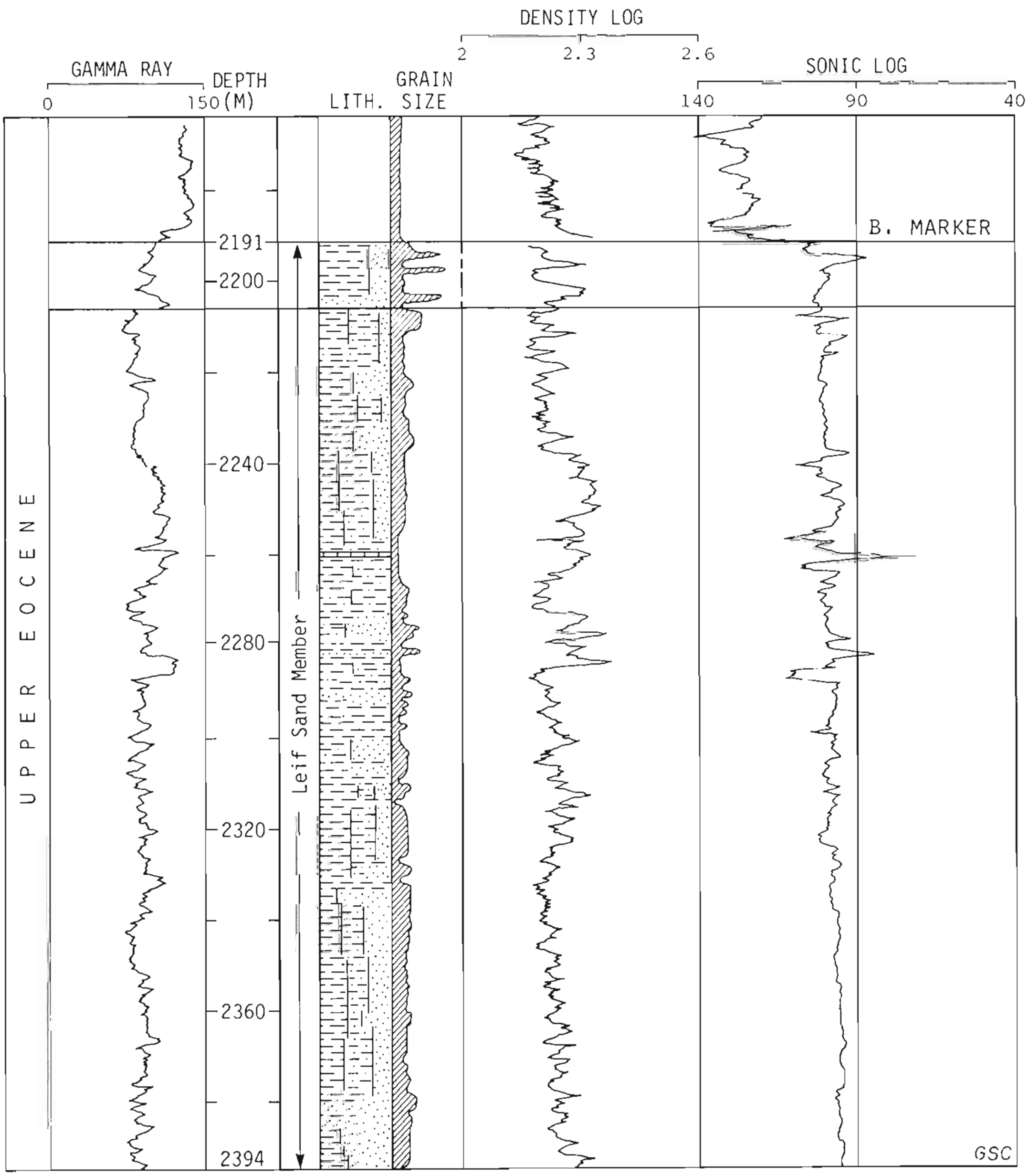


Figure 23. Lithological details and mechanical logs, Leif Sand Member of the Saglek Formation, 2394-2191 m, Karlsefni H-13.

Bjarni Formation. The late Cretaceous and Paleocene Cartwright Formation was deposited during a phase of rapid subsidence but with equally high sedimentation rates so that the basin was kept "full" and shallow water sediments dominate. Accelerated subsidence occurred during the Eocene with subsidence curve for the remainder of the Tertiary similar to that for Karlsefni H-13 and Cartier D-70.

The subsidence curve for Snorri J-90 is essentially similar to that of Herjolf M-92 with the important difference in that mid-Cretaceous tectonism removed most of the Bjarni Formation. Thus at Snorri J-90, the only Lower Cretaceous sequence present is the coal measures of the Snorri Member of the Bjarni Formation. The subsidence history at Snorri J-90 from late Cretaceous times is typical for the Labrador Shelf.

Superimposed on the subsidence curves are geotherms for 50°C, 65°C and 100°C. The loci of these geotherms assume that the present day geothermal regime existed since basin development. This is known to be a gross approximation as present day geothermal gradients are steep because of low ambient surface temperatures. In addition there is some evidence for a lower Cretaceous high geothermal gradient so that geothermal gradients at that time differed from those existing now. Despite these known errors, superimposing geotherms on subsidence curves gives a qualitative assessment of the length of time various isotherms acted and hence an indication of whether sufficient maturation of organic matter has occurred to generate hydrocarbon.

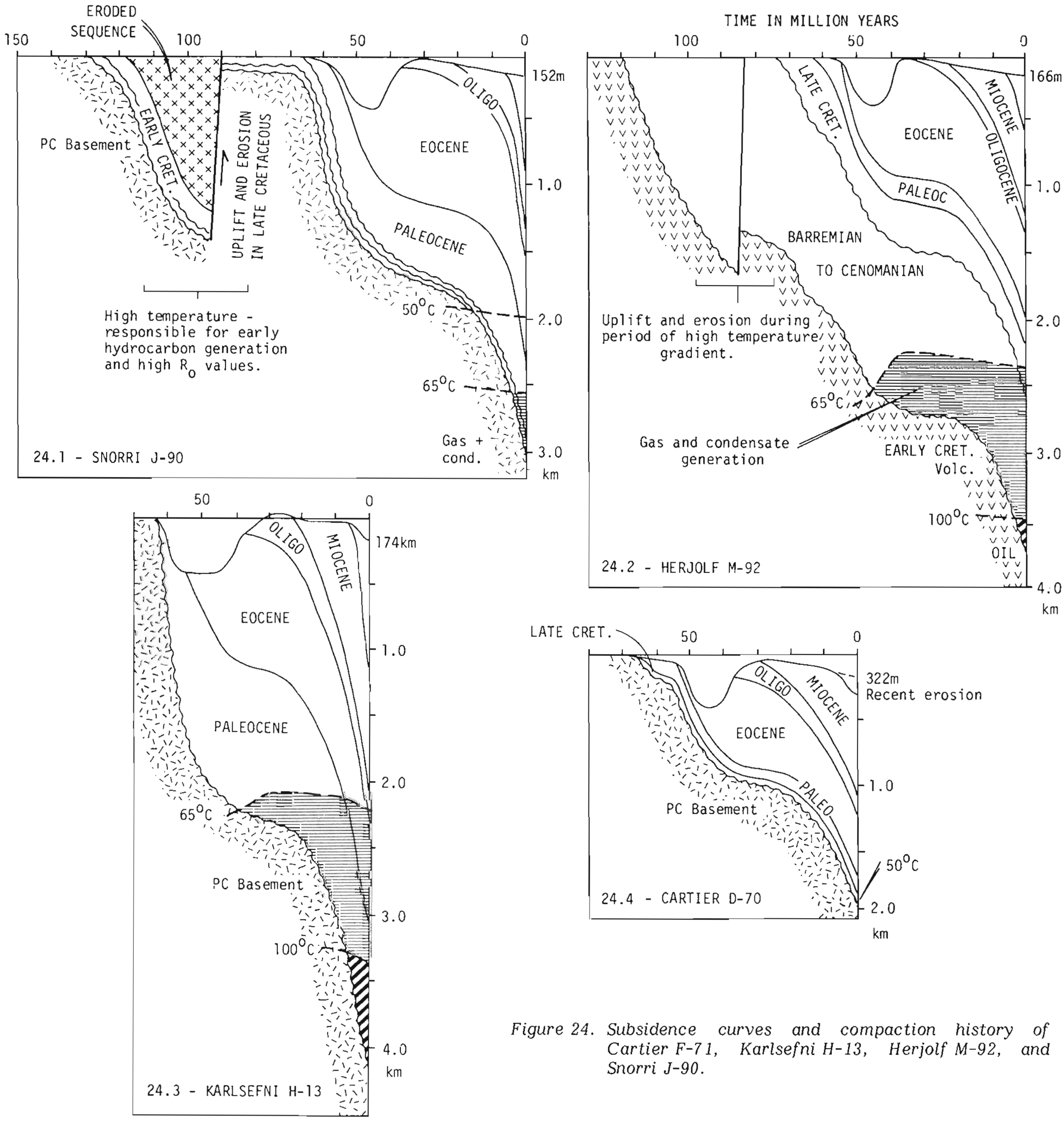


Figure 24. Subsidence curves and compaction history of Cartier F-71, Karlsefni H-13, Herjolf M-92, and Snorri J-90.

STRUCTURE OF THE LABRADOR SHELF

Three geological sections across the Labrador Shelf are shown in Figure 25. These were constructed from seismic profiles purchased from industry and show the morphology of the clastic wedge above pre-Mesozoic basin floor.

Section 1 is along the crest of the Cartwright Arch, a basement feature forming an easterly continuation of structurally high geological provinces occurring in adjacent onshore areas. The other two sections show a structural style that is characteristic of the Labrador Shelf. Lower Cretaceous to Paleocene sediments are restricted to an inshore basin. At its southern end, the inshore basin terminates on the northern flank of the Cartwright Arch. The basin is controlled by faults and contains smaller block-faulted basement structures. All faults associated with the inshore basin are en echelon and do not appear related to fault trends on the adjacent Precambrian terrane.

Another characteristic of the Labrador Shelf is the simple outbuilding and upbuilding nature of the Tertiary sequence. The "sharp" shelf edge is a young feature. Wells drilled to date are in the thinner, nearshore part of the clastic wedge where somewhat abnormal sequences are present overlying basement highs.

Little information exists on the deep crustal structure of the Labrador Shelf and the problems of boundaries between crustal types remain. Some advance was made in the joint Bedford Institute of Oceanography – Tenneco Oil and Minerals' refraction survey in 1973 across the outer shelf, rise and slope. Results of this program were summarized by van der Linden (1975a) at a time when results of drilling activity were not available. The refraction survey showed a zone of thinned crust near the present shelf edge underlying the inshore basin and a transition from continental to oceanic crust beneath the present day slope boundary.

GEOLOGICAL EVOLUTION OF THE LABRADOR SHELF

Evolution of the Labrador Shelf assuming seafloor spreading

In recent years, several schematic representations describing the evolution of the northwest Atlantic Ocean and Labrador Sea in terms of seafloor spreading have been published (for example, Laughton, 1971; van der Linden, 1975b; Roberts, 1975; Cutts, 1977; Vogt and Avery, 1974; Srivastava, 1978). A consideration of these representations is necessary when rationalizing events taking place on the margins of these oceanic areas.

Most of the schemes fail to explain the overlap which results on palinspastic reconstructions of the Labrador Sea – Davis Strait – Baffin Bay area. Beh (1975) realized this overlap problem and eliminated it by postulating a series of left-lateral transcurrent fractures cutting across the entire Greenland craton, intersecting the west coast between 67° and 72°N. There is sufficient Precambrian terrane exposed and mapped between the coast and the central icecap to question this concept (Escher et al., 1974).

Palinspastic overlap can also be eliminated if it is assumed that Greenland as a whole moved westwards as the northeast Atlantic opened thereby making Davis Strait and Baffin Bay an asymmetric system. However, regional gravity surveys indicate Baffin Bay is symmetrical (Ross, 1973), though seismic profiles suggest Davis' Strait is asymmetrical and the central zone of "oceanic crust" occupies the western part of the strait (Wallace, 1973, Fig. 6).

Accelerated basin subsidence occurred in Early Miocene times, approximately 20 Ma after the cessation of supposed seafloor spreading in the Labrador Sea. This period of subsidence took place after too long an interval to be related to any seafloor spreading. Instead, it is related to some other mechanism of basin evolution.

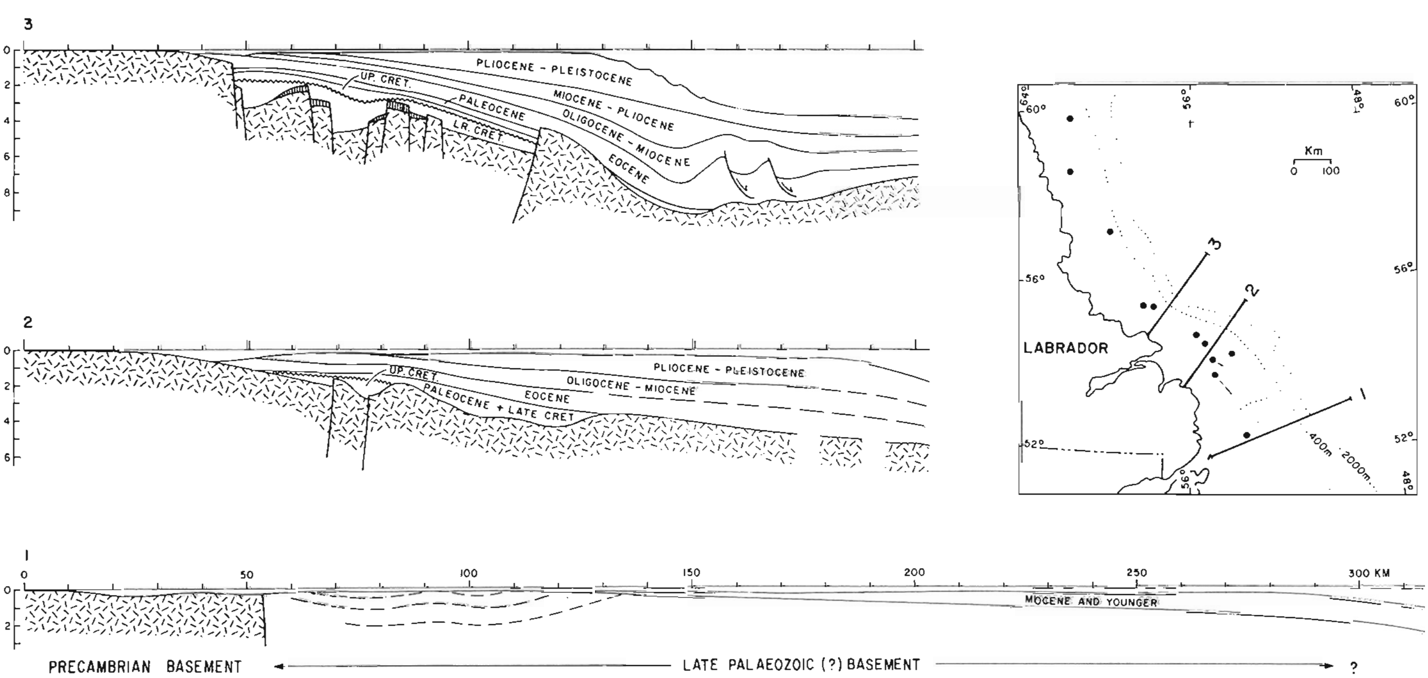


Figure 25. Geological sections across the Labrador Shelf.

Though geographically remote from the subject area, evidence from the North Greenland Fold Belt (Dawes, 1976) and its continuation in northern Ellsmere Island cannot be neglected. This fold belt is a Lower Paleozoic feature. Facies belts, structural features and metamorphic zones can be correlated along strike without any major discontinuity, between northern Greenland and Ellesmere Island. Kennedy Channel, a linear seaway between these two areas, appears to be the locus of a normal fault, down-thrown to the east. Stratigraphic horizons exposed in northeast Greenland are younger than those exposed on the Canadian side of Kennedy Channel. Greenland and Ellesmere Island thus apparently behaved as a single cratonic unit. If Baffin Bay formed by seafloor spreading, then the width corresponding to a strip of seafloor injected between Baffin Island and west-central Greenland will be found in rifted channels in the Arctic Islands.

Despite the shortcomings for the classical seafloor spreading history of the Labrador Sea – Baffin Bay area, a generalized sequence of events has been made for the Labrador Sea. Stratigraphic events on the shelf are correlatable with "oceanic" tectonic features of the deep ocean basin. Thus van der Linden (1975a), expanding on data and theories developed by earlier workers, gave a new account of the evolution of the Labrador Sea and emphasized its stepwise evolution. An evolution in stages was also indicated by McWhae and Michel (1975) and is described below.

In pre-Santonian times, a rift or narrow epicontinental seaway existed in the area now covered by the Labrador Sea. This seaway formed in latest Jurassic or earliest Cretaceous times in response to a taphrogenic phase with localized igneous activity, to form a epicontinental extension of the newly developed Atlantic Ocean north of the Gibbs Fracture Zone (Fig. 5).

During the interval Santonian to early Paleocene (82-64 Ma), the North Atlantic craton was disrupted along a northwest-southeast trend, approximately parallel to the trend of the earlier rift system. According to the seafloor spreading hypothesis, mantle injection occurred along a midocean ridge consisting of linear segments offset by transform faults. During this phase of development, marine marginal-basin deposits were superimposed on the earlier rift basin.

In Early Paleocene and Early Eocene times (64-53 Ma) there was continued disruption of the North Atlantic craton along a subparallel axis and with the addition of a triple junction south of Greenland. The northwest arm of this triple junction continued to separate Greenland from North America. The northeast arm of the triple junction became active during this phase separating Greenland from the Rockall Plateau as the northeast Atlantic developed.

After the Early Eocene, the northeast Atlantic continued to develop but the northwest spreading axis became extinct during the early Eocene. This extinction resulted in the foundering of the Labrador Sea Basin so that deep-water sediments were deposited to within a short distance of the paleo-shorelines, shorelines which maintained approximately the same position as in the Cretaceous.

Accelerated deposition during the early Tertiary built a marginal sedimentary wedge outwards and upwards under the present Labrador Shelf. Sediments in the deeper part of the Labrador Sea Basin are mainly younger than Eocene.

Maps showing the relative position of craton fragments and intervening ocean areas at each of the above stages are shown in Figure 26, 1-4.

Evolution of the Labrador Margin assuming the Undation Theory

The transition of one crustal type to another and zones of thinned crust are fundamental features of certain types of passive margins. The Atlantic margin, the northern part of the North Sea southwest of Norway may be similar. The Labrador Sea-Baffin Bay system can be regarded as a peripheral sea in the sense that it is peripheral to an oceanic area, the Atlantic Ocean, which is underlain by oceanic crust and which formed by seafloor spreading. The peripheral sea itself is probably underlain by modified continental or transitional crust.

The deep crustal structure interpreted from the 1973 refraction survey forms the basis for the following account of the evolution of the Labrador Sea, an account resembling that given by van der Linden (1975a). Both use a variant of the Undation Theory (van Bemmelen, 1949, 1972).

A basic tenet of the Undation Theory is that large surface features, commonly cutting across geologically stable areas, are caused by irreversible and/or reversible deep seated physicochemical processes. The size of the surface feature is proportional to the depth and the magnitude of the deep seated processes. Thus a minor undation is a surface feature a few tens of kilometres wide and is manifested by upthrown fault blocks and rift valleys. It is formed by changes at the level of the deep crust and overlies crust that has been thinned from below. Its origin along a preferred direction may not be a prerequisite but the postulated megashear referred to above may provide such a pathway. A surface elevation above the minor undation will exist only as long as its causative processes are active. On reaching equilibrium, the undation will become gravitationally unstable, collapsing to leave a surface depression or basin, whose dimensions reflect the dimensions of the original deep peturbation.

A mega-undation is essentially similar but because of its deeper origin, has larger surface dimensions (up to several hundred kilometres). Its growth, decline and collapse are related to physicochemical changes in the upper mantle. Partial and passive replacement of continental crust by molten mantle products cause upper crustal levels to be replaced by more basic crustal types. Subsequent gravitational collapse results in the formation of a large sedimentary basin.

An advantage of this theory is that overlaps on palinspastic reconstructions are avoided, the resulting system may be symmetrical or asymmetrical, and long, translational movements of the crust, varying in time and space, are not required. Separation of adjacent cratonic areas is apparent in the sense that the separation occurs by the alteration of intervening crust into transitional or "oceanic" types.

Fischer (1976) in a recent analysis of basin formation gave as the basic cause of surface depressions, gravitational collapse in response to instabilities caused in the deeper crust by irreversible phase changes such as intra-lithosphere volcanism, phase changes per se, or injection of mantle materials into the upper crust.

A consequence of the crustal thinning by mantle injection from below would be the presence of "hot" phenomena due to prevailing higher heat fluxes under the inshore basin (minor undation). In addition to surface volcanism, two other phenomena have been observed.

Coal seams at the base of the Bjarni Formation, in the Snorri Member, at Snorri J-90 and Herjolf M-92 have vitrinite reflectance values of 0.88 and 0.92 respectively (P. Hacquebard, pers. comm.). According to Karweil (1956) such a vitrinite reflectance reading requires a temperature of 80-90°C be maintained for the 125 Ma or so since the coal formed or a later, shorter period of temperatures higher than 80-90°C to elevate the rank of these coals to be observed values. Present-day temperatures at the depth of these coal-bearing formations are only 75°C. A former period of high heat flow is thus indicated.

Jeffreys (1959) implied that in regimes of normal heat flux, the insulating effect of sediments increases the temperature of the base of a sedimentary sequence shortly, geologically speaking, after burial. He suggested a 90°C temperature increase after 13 Ma burial but warns that this value will vary widely according to such factors as sediment type and depth of burial. In areas of above-normal flux, temperatures higher than 90°C at the base of a sedimentary sequence can occur and give high coal reflectance values.

Secondly, sedimentary sequences on the Labrador Shelf have a clay mineral stratigraphy (Umpleby et al., 1978). The deepest wells show that montmorillonite, which dominates sequences of Late Cretaceous and Paleocene age, has been transformed to illite, the crystallinity of which increases with depth. In one well, kaolinite, which dominates Early Cretaceous sequences, has also been transformed to illite. Powers (1967) suggested that the transformation of montmorillonite to illite occurs at a temperature of 120-130°C; values not possible with the present day temperature of these depths.

Although evolution of the Labrador Sea by the seafloor-spreading hypothesis is favoured by most workers, the Undation Theory provides an alternative evolution that is remarkably similar in many respects and one I prefer. The following scheme, arbitrarily divided into eight stages, describes a possible evolution resulting from the growth and decline of a minor undation and a mega-undation.

Stage 1: Late Jurassic (Fig. 27.1)

During the latest Jurassic, a minor undation beneath the present-day Labrador margin was in decline, collapsing in response to its gravitational instability, to form a narrow, fault-bound basin by earliest Cretaceous times. The surrounding North Atlantic craton, including the areas now occupied by the Labrador Sea, was emergent.

Localized basalt volcanism occurred in the fault-bound basin which received predominantly continental clastic sediments. The southern terminus of this basin is the northern flank of the Cartwright Arch, a feature which remained emergent until mid-Tertiary times.

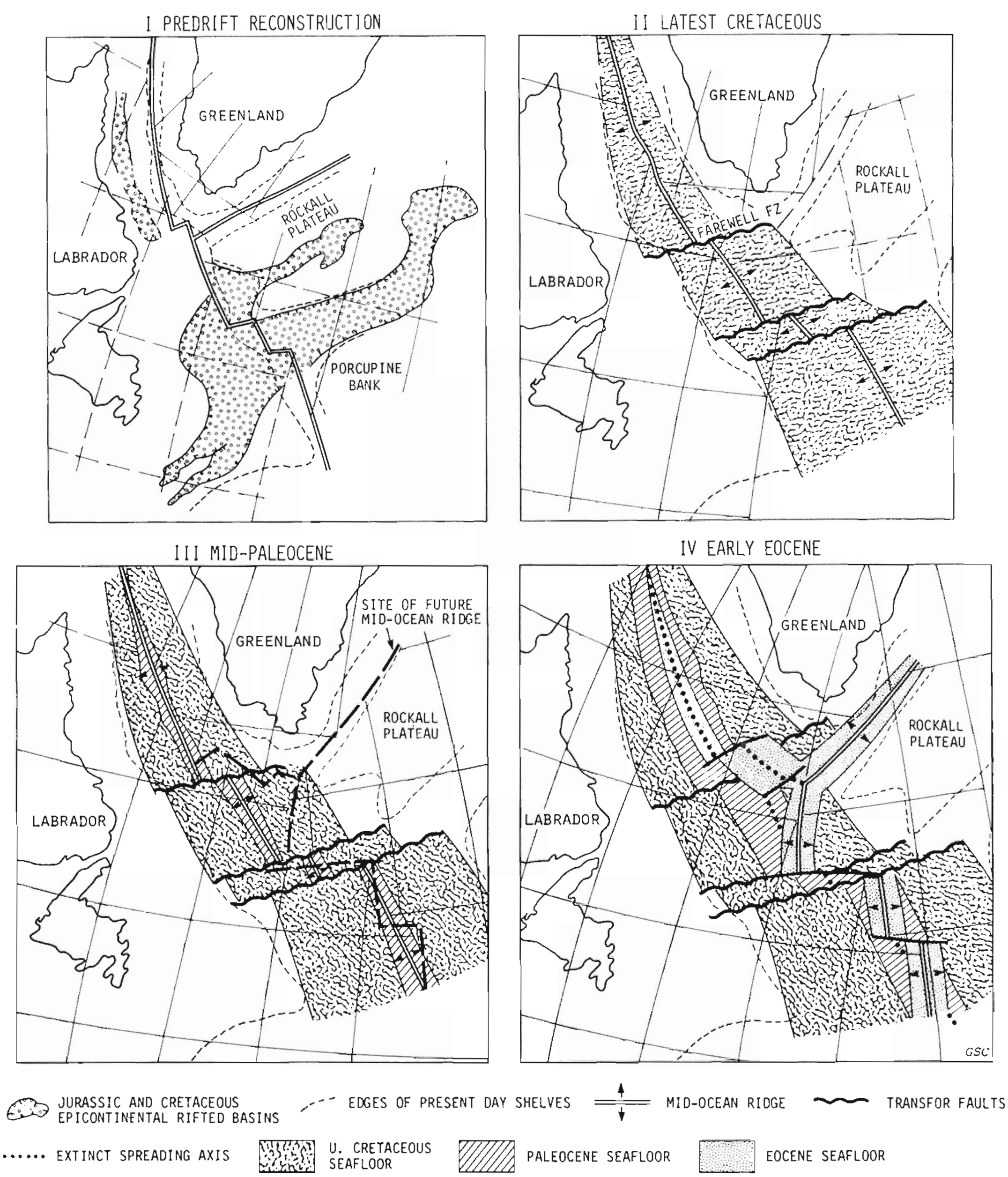


Figure 26.

Diagrammatic evolution of the Labrador Sea.

I Predrift reconstruction of Labrador Sea area, showing Jurassic and Cretaceous rifted basins in northeast Newfoundland, Rockall Bank and Porcupine Bank area

II Labrador Sea opening in latest Cretaceous times.

III Labrador Sea opening in Paleocene times.

IV Labrador Sea opening at the time the northeast Atlantic started to form.

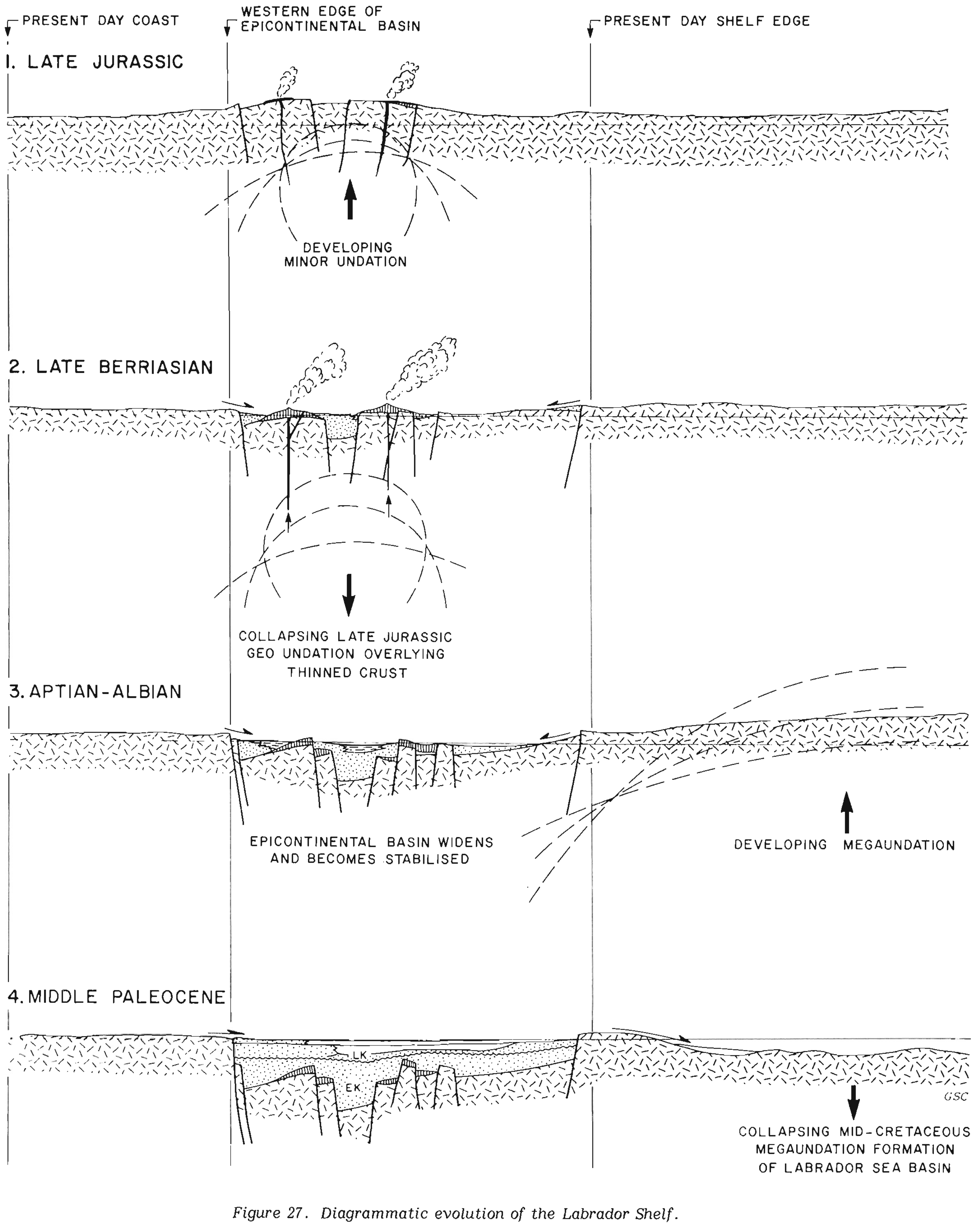


Figure 27. Diagrammatic evolution of the Labrador Shelf.

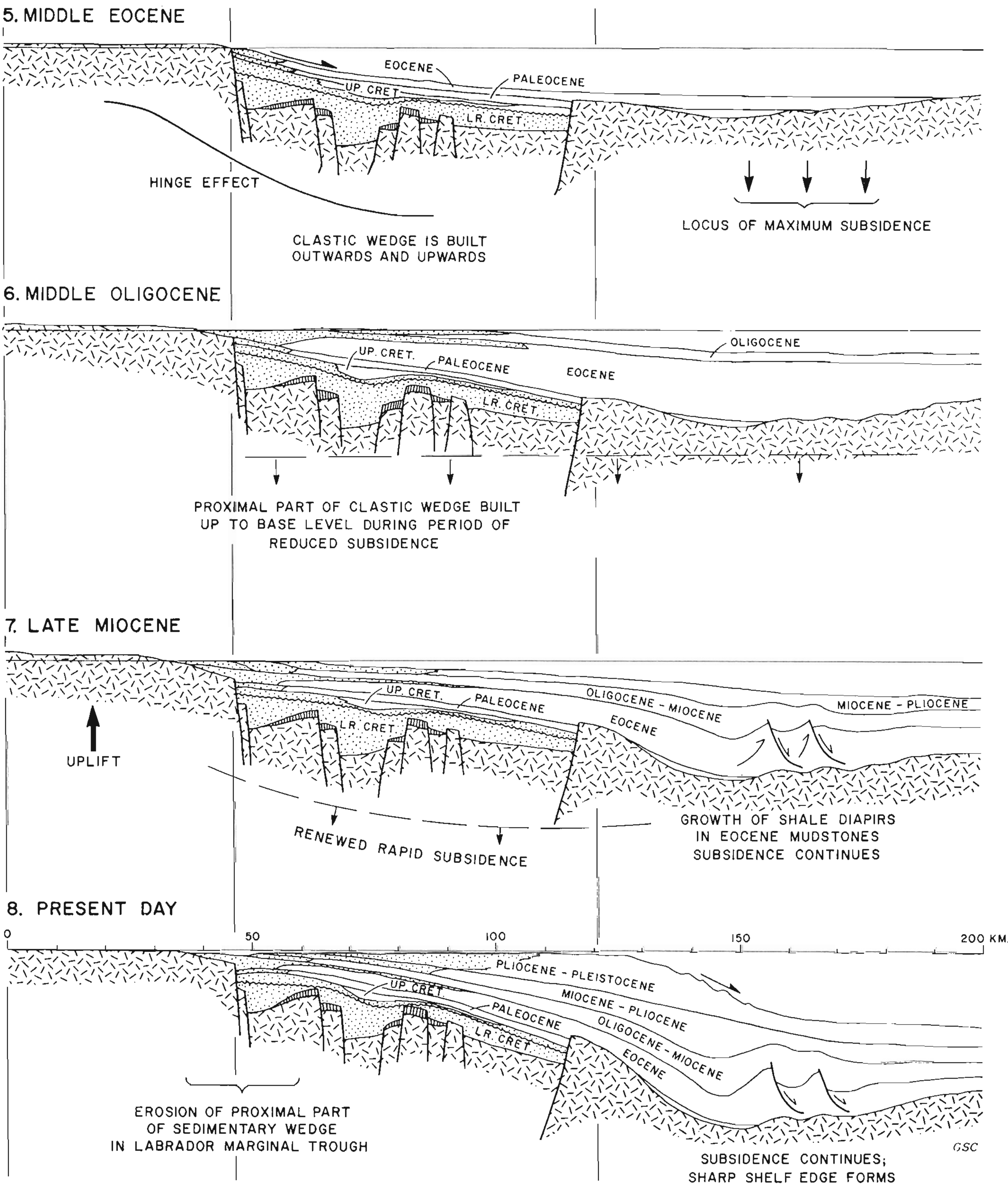


Figure 27 continued

Stage 2: Late Berriasian (Fig. 27.2)

By Berriasian times, a shallow linear basin formed. This trended northwest-southeast and was bounded by en echelon arcuate faults. Seismic reflection data suggest the basin was initially 20 km wide and that it contains en echelon fault-bounded basement highs.

Collapse of the late Jurassic minor undation caused fractures to reach the surface locally thereby enabling residual magma reservoirs to be tapped causing the extrusion of subaerial basalt flows. Volcanism appears to have been confined to isolated centres. Relief between the floor basin and adjacent cratonic areas was probably not very large, as continued downfaulting and warping kept pace with the extrusion and erosion of the subaerial volcanics. At the same time deposition of clastics of nonvolcanic origin occurred.

Local depocentres formed adjacent to fault blocks. Thus the coarse clastics of the Bjarni Formation show large thickness variations which were aggravated by penecontemporaneous erosion as basement blocks were readjusted upwards relative to the general downwarping tendency of adjacent areas. During the Neocomian, the basin widened, becoming 80 km wide by Barremian times when clastic sedimentation became dominant.

Stage 3: Aptian-Albian (Fig. 27.3)

At this time, the inshore epicontinental basin stabilized tectonically and general deposition commenced within it. In Aptian-Albian times, the basin was flanked by cratonic areas so that clastic sediments were derived from both sides. Though narrow, the basin may be very long but is traceable with certainty only to 57°N as north of this its recognition on seismic profiles is not possible because of sparse control, increased depth of burial by younger sediments, and severe multiples. It appears to be present east of Karlsefni H-13 while Snorri J-90 was drilled on the western part of the basin. Farther north, it may connect through fault-bound basins on the western part of Davis Strait (Wallace, 1973) to the fault-bound Nugssuaq Embayment (Henderson et al., 1976) on the east side of Baffin Bay and possibly the Melville Bugt Graben.

The first marine influences are seen in the Labrador sequence in rocks of Albian age. The direction of the marine connection is not known; emergent cratonic areas existed to the west, south and east. An impoverished arenaceous foraminiferal fauna of Albian age may have northern affinities (Gradstein, pers. comm., 1978). The basin is open-ended to the north and faunal evidence supports the existence of a narrow, linear basin connected in mid-Cretaceous times to a northern oceanic area. This idea was originally postulated on megafaunal evidence.

During Aptian-Albian times, a mega-undation was developing east of the epicontinental seaway. This undation developed independently of the earlier minor undation along a subparallel axis. Van der Linden's scheme (1975a) is similar to this and his Figure 3 shows a high feature over the present Labrador Sea with paired basins on either side. However, the minor undation implies that the inshore basin is a single linear feature and tectonic events associated with the mega-undation during and after Late Cretaceous times disrupted this basin, dividing it into segments of which the grabens under Davis Strait, the Nugssuaq Embayment and the Melville Bugt Graben, may be remnants. Birkelund (1965) summarized evidence for this seaway based on ammonite faunas in the Nugssuaq Embayment.

Stage 4: Middle Paleocene (Fig. 27.4)

The Labrador Sea formed by the collapse of the mid-Cretaceous mega-undation which caused the apparent and/or real separation of Greenland and Labrador during the late Santonian to early Eocene. This separation of craton fragments was most rapid during the Maestrichtian and Paleocene (Vogt and Avery, 1974; Laughton, 1971), the undation still had residual buoyancy. The Davis Strait area, a high feature probably underlain by less severely altered crust, is presumably an area of incomplete "oceanisation" where "separation" of craton fragments is not as wide.

During the collapse of the mega-undation, the margins of the neoformed Labrador Sea were depressed and the area, including the former epicontinental seaway, was transgressed from the east and connection with open oceanic conditions resulted. The restricted connection to a northern ocean through a narrow, linear seaway is thus limited to the Albian to Coniacian interval.

In Paleocene times, when the upper part of the Cartwright Formation was being deposited, the Labrador Shelf consisted of a shallow marginal basin superimposed on the earlier inshore basin and was separated from the newly formed, larger marine basin to the east by a discontinuous belt of islands. These correspond to culminations of the eastern rim of the inshore basin. Some of the larger fault blocks within the inshore basin were also emergent at this time. The outer basin was starved of sediments as the internal basin acted as a sediment trap for all detritus, which by this time, had an exclusively western source. This differential sedimentation explains why Late Cretaceous and Paleocene strata, if present, are thin and therefore not identifiable on seismic profiles beneath the present day rise and slope.

Stage 5: Middle Eocene times (Fig. 27.5)

Apparent separation of Greenland and Labrador ceased by earliest Eocene times. At this time the mid-Cretaceous mega-undation was no longer buoyant and because of its gravitational instability, rapidly foundered to depths comparable to those existing in the Labrador Sea at present. Adjacent continental margins were dragged down with the foundering oceanic area, hinging about a locus near the Labrador Marginal Trough, so that a deep water regime was established in early Tertiary times to within a short distance of the basin margin.

Conditions on the adjacent cratonic areas changed at this time. Erosion of the formerly stabilized thick regolith was accelerated. Possible climatic changes due to the formation of a wide, newly formed ocean may, after a relaxation period, have caused this rapid denudation. Near-shore shallower areas were quickly filled to base level by a copious sediment supply and Eocene mudstones started to build a sedimentary wedge outwards and upwards beyond the limit of the former inshore basin. These mudstones, deposited on slopes that progressively steepened due to continuing collapse, frequently underwent mass transport as turbidites to more distal parts of the ocean basin.

Stage 6: Middle Oligocene (Fig. 27.6)

Shallow water sand deposition dominated at least the western half of the shelf. Locally, these shallow water deposits grade into marginal marine sediments. Thus at Herjofl M-92, this coal seam occurs in the Leif Sand Member and in the overlying part of Saglek Formation of Oligocene age between 1557 m and 1341 m. Coal is also present in sequences of the same age at Karlsefni H-13.

The shallowing in late Eocene times is due to sediments accumulating up to or locally above base level, rather than to upwards movement on basement. It is probable that basin subsidence temporarily halted at this time. The subsidence curve (Fig. 24) illustrates this point.

During the late Oligocene, basin floor subsidence resumed but occurred at a greatly reduced rate. Continued rapid deposition built the clastic wedge up to base level so that the proximal part of the Oligocene is a condensed sequence which includes coal seams and the distal part consists of thick deeper water turbidites.

Stage 7: Late Miocene (Fig. 27.7)

Throughout the Neogene, as shelf sediments continued to build outwards and upwards rapid subsidence of the basin occurred. The sand fraction in these younger sediments progressively increases upwards, perhaps as increasingly larger areas of deeper regolith were exposed and winnowing of the proximal sediments occurred as increasingly larger areas of sediments were built up to base level.

During the late Miocene and Pliocene, diapirism took place locally beneath the present day rise. These diapirs originate from Eocene mudstones and are due to the rapid burial of water-laden sediments so that normal dewatering was hindered; subsequent over-pressured zones were normalized by diapirism. Similar shale diapirs originating from the older parts of rapidly deposited shale sequences are known from other continental margins, for example in the prodelta deposits of the Niger (Burke, 1972; Mercki, 1970) and Orinoco rivers (Lowrie and Escowitz, 1969).

Stage 8: Present Day (Fig. 27.8)

Throughout Plio-Pleistocene times, outbuilding of the shelf continued. The clastic wedge deposited during this interval has a markedly triangular cross-section with proximal parts having as little as 300 m and the outer shelf has at least 1500 m.

The floor of the Labrador Sea subsided rapidly in Pliocene times. This renewed subsidence is associated with corresponding uplift on adjacent land areas. Subsequent steepening of the shelf edge caused much material to be transported seawards as slide slump, debris flow and turbidity flow deposits. The bulk of the thick, poorly consolidated sediments in the deeper parts of the Labrador Sea are of this age.

The sharp shelf edge is a relatively recent feature and slump scarps seen on profiles on the upper rise indicate that these young sediments have not yet been stabilized. Presumably this is because the Labrador Sea Basin is still subsiding.

Davis Strait, on the north side of the Labrador Sea does not appear to have subsided to the same extent. Consequently, the late Tertiary sediments of the Labrador Sea are derived not only from adjacent shelf areas but also from the relatively high Davis Strait to the north. Thus the presence of spurs seen on bathymetric maps in the vicinity of latitude 61°N, longitude 57°W are probably depositional features. The Northwest Atlantic Midocean canyon is an erosional feature apparently formed by turbidity currents originating on the shelf off southeast Baffin Island. In the central part of the Labrador Sea, the canyon occupies a central position; in the northern part, it has a northwest trend, appearing to originate from a position southeast of Cumberland Sound, Baffin Island.

PETROLEUM EXPLORATION AND POTENTIAL

Summary of Petroleum Exploration activities

The presence of thick sediments draped over basement highs on the Labrador Shelf prompted industry to acquire exploration permits in the 1960s. A group of companies, Tenneco Oil and Minerals Ltd., Amerada-Hess and Eastcan were granted federal government permits (totalling over 30 million acres) over much of the Labrador Shelf in 1966-68. BP Canada and Imperial Oil Ltd. obtained permits covering smaller areas on the outer shelf and rise off southern Labrador.

In 1972 Tenneco relinquished their one-third interest which was divided between Aquitaine, Sun, and AGIP. In 1974, half of the Amerada-Hess interest was transferred to Gulf Oil Canada. Percentage interests in the permits at the present time are Total-Eastcan (operator) 28 1/3; Total Petroleum (N.A.) 5; Aquitaine 13 1/3; Sun 10; AGIP 10; Amerada-Hess 16 2/3, and Gulf Canada 16 2/3.

Drilling commenced in 1971 using the drillship **Typhoon** at the Tenneco et al. Leif E-38 site (Fig. 8). This well was abandoned at 1090 m without encountering hydrocarbons. In 1973, the drill ship **Pelican** drilled a new well on the same structure, the Eastcan et al. Leif M-48 which bottomed in subaerial lava flows at 1867 m also without encountering hydrocarbons.

Eastcan et al. Bjarni H-81, 215 km northwest of Leif was also drilled in 1973 to a total depth of 2516 m after encountering basaltic lavas. Immediately above the lavas is a thick sand, the Bjarni Formation, which proved to be gas-bearing on logs but could not be tested that year.

Operations the next year started with the drilling of Eastcan et al. Gudrid H-55, situated on a separate structure 84 km north of Leif M-48. Gudrid was drilled to a total depth of 2839 m, in crystalline basement which is overlain by porous dolomite of Carboniferous age. The dolomite is overlain by 2500 m of Upper Cretaceous and Tertiary sediments. Logs showed the dolomite to be gas-bearing and subsequent testing confirmed this. Later in the 1974 season, the Bjarni H-81 well was tested and the presence of gas confirmed.

Wells drilled since 1974 are: Freydis B-87, 48 km southeast of Leif M-48 and which reached a total depth of 2314 m, in Ordovician carbonates, after penetrating 1898 m, Upper Cretaceous and Tertiary sediments. Cartier D-70, 53 km northwest of Leif M-48, bottoming in crystalline basement at 1927 m and overlain by Late Cretaceous and Tertiary sediments. Karlsefni H-13, 615 km northwest of Leif M-48 reached Precambrian basement at 4149 m after penetrating 4115 m Tertiary sediments. Herjolf M-92, 3.7 km northwest of Bjarni M-81, abandoned at 4086 m in crystalline basement after penetrating 258 m volcanics of the Alexis Formation; 1153 m coarse clastics of the Bjarni Formation and 1998 m Upper Cretaceous and Tertiary fine grained clastics.

Snorri J-90, 434 km northwest of Leif, was drilled to 3210 m in Precambrian basement which is overlain by Cretaceous and Tertiary sediments. Porous sands equivalent to the Gudrid Sand Member recovered gas and condensate.

Permits east and south of the Eastcan Group holdings are held by the BP Group comprising British Petroleum, Chevron, Columbia Gas, Gulf Canada and Petrocan. In 1976, the BP et al. Indian Harbour was drilled, 90 km east of Leif M-48, on a basement feature on the eastern edge of the Cretaceous inshore basin and was abandoned at 3961 m in carbonates of Paleozoic age. A lapilli tuff 227 m thick of possible early Cretaceous age overlies the Paleozoic carbonates and is in turn overlain by 3090 m fine grained sediments of Maestrichtian and Tertiary age.

Hydrocarbon Occurrences

By the end of 1977, nine deep wells had been drilled on the Labrador Shelf. Three of these (Bjarni H-81; Gudrid H-51, and Snorri J-90) encountered hydrocarbons. All penetrated Cretaceous and Tertiary sediments overlying economic basement, defined here as including all rocks incapable of generating hydrocarbons in commercial quantities. All rocks older than Cretaceous on the Labrador Shelf are regarded as economic basement. This concept allows for hydrocarbon accumulation but not hydrocarbon generation within basement. This is the outlier of Carboniferous dolomite which unconformably overlies Precambrian crystalline basement in Gudrid H-55 where it acts as a reservoir rock.

The distribution of rock units within economic basement is poorly known except in offshore areas where no Cretaceous or Tertiary cover rocks exist, such as below Notre Dame Bay and overlying the Cartwright Arch (Haworth et al., 1976). In these areas, shelf carbonates of Ordovician age and clastics and carbonates of Carboniferous age are known to occur. Correlatives of these are known to be locally present beneath younger cover rocks on the adjacent Labrador and Northeast Newfoundland shelves (for example, Freydis B-87 and Gudrid H-55). Cutt and Laving (1977) suggests that extensive areas of Paleozoic rocks may have been preserved on the outer parts of the Labrador Shelf.

Gudrid H-55

Maestrichtian and Tertiary clastic rocks overlie fractured porous dolomite encountered at 2663 m in Gudrid M-55. The dolomite is buff to grey-brown, fine to medium crystalline and has leached fossil, interfossil and intercrystalline porosity scattered throughout. The unit is 153 m thick, with 98 m averaging 10 per cent porosity. Porosity values to 18 per cent occur in some beds. Permeabilities are generally low; maximum values being 245 md. However, the fractured nature of the dolomite may enhance bulk permeability. Details of the lithology and mechanical logs over this interval are given in Figure 28.

A conventional core, cut at 2676 m, showed that the rock was initially a micrite containing oncolites and crinoids. Later diagenesis dolomitized both matrix and clasts and subsequent leaching formed vugs to 1 cm in diameter. Intercrystalline porosity is also present. Near the base of the dolomite, some vugs show later infilling by sparry calcite. One such vug in the cored section, has, according to the operator, been filled with geopetal calcite and later with internally deposited micrite. The boundary between the two fillings is at an angle of 45° to the core axis, suggesting that this angle is the dip. Similarly steep dips are also shown on dipmeter logs, suggesting the dolomite occurs as a small outlier perched cuesta-like on a fault-generated basement block (Fig. 29).

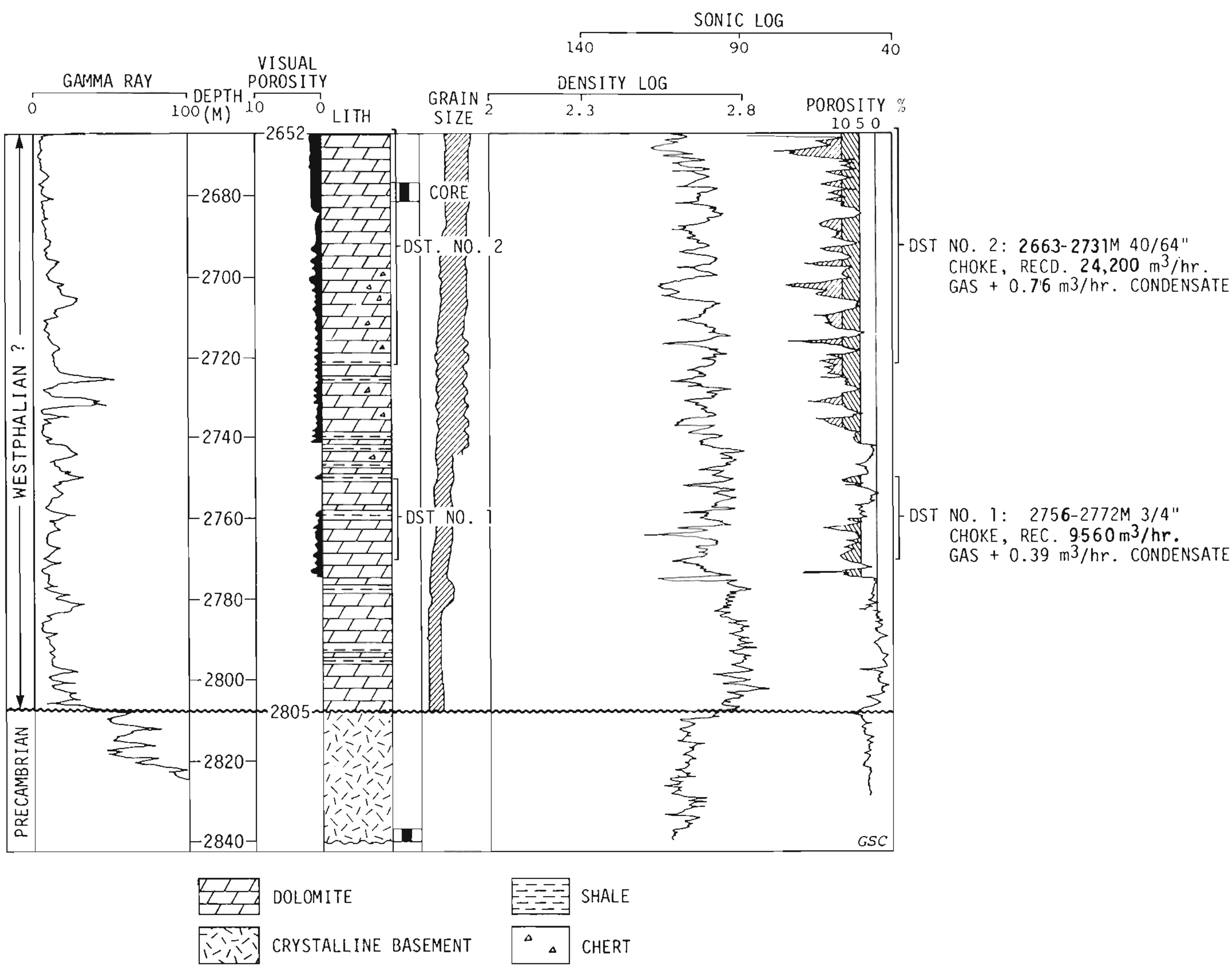


Figure 28. Details of the gas and condensate reservoir, Gudrid H-55.

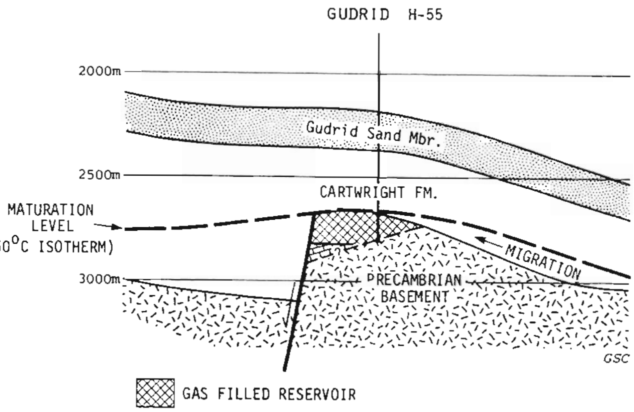


Figure 29. Diagrammatic cross-section, Gudrid structure.

The age of the dolomite is somewhat controversial. The operator (Eastcan, 1976b) dates it as Viséan and Westphalian. The latter is confirmed by Barss (pers. comm.).

Two drillstem tests were conducted in this reservoir interval. Immediately above a nonporous section near the base of the unit, between 2772 m and 2756 m, gas was recovered at flow rates of up to 9560 m^3/h (8.097 mmcfd) with 0.39 m^3/h light oil of density 0.78, giving a GOR of 24,446 m^3/m^3(Eastcan, 1976b). The gas has a density of 0.614 and consists of 91.2% methane, 5.86% ethane, 1.3% propane, and 0.54% butane. No water was recovered and only traces of carbon dioxide and nitrogen were detected. A second test near the top of the reservoir was run between 2731 m and 2663 m, recovering gas and condensate having a composition similar to that from the previous test. This test flowed gas at rates of 24 200 m^3/h (20.500 mmcfd) with 0.86 m^3/h condensate.

The dolomite immediately overlies crystalline basement which has been radiometrically dated at 1710 Ma (Hudsonian). Adjacent Precambrian terranes contain metamorphosed infolded supracrustal sediments which were folded during the Hudsonian Orogeny (Taylor, 1972) and would therefore yield ages of about 1700 Ma.

Relationships between the dolomite and the basement are unknown as these two units cannot be distinguished with certainty on seismic profiles. Certainly the basement forms a high feature bound by normal faults on the west side; seismic reflection data show the overlying Cretaceous beds which are draped over this structure are not affected by the faulting. There is some evidence that the dolomite forms an isolated outlier of limited extent on this basement high (Fig. 29).

The source of the gas is not known. Logs show a bottomhole temperature of 70°C suggesting the most likely source to be the Upper Cretaceous Cartwright Formation downdip and consequently in a higher thermal regime. Cuttings analysis show these shales to have above average organic carbon contents and exsolved gases from cuttings have over 50 per cent ethane, propane, and butane (Rashid, pers. comm.), suggesting these shales have some maturity. The organic matter type is mostly phyrogen and melanogen (Bujak et al., 1977) suggesting a gas source. The thermal alteration index (TAI) of this organic matter is 2 to 2+, or within the top of the oil window where some unidentified labile organic component, possibly of terrestrial origin, is yielding gas and condensate. In contrast, according to chemical geochemistry, gas and condensate has an origin in the lower part of the oil window.

In the Carboniferous dolomite, the organic matter is of the same type as that of the overlying Cartwright Shale Unit but has a TAI of up to 3-, below the oil window for this kerogen type. There is a possibility that, in view of the very different environments of deposition of the two rock units, the more altered phyrogen and melanogen is caved from the base of the Late Cretaceous. If this is the case, the wet gas originates from a mature source and bottom-hole temperatures are either not equilibrium values or higher temperatures existed in the past.

Because the extent of the reservoir is not known, total reserves of the Gudrid structure cannot be estimated.

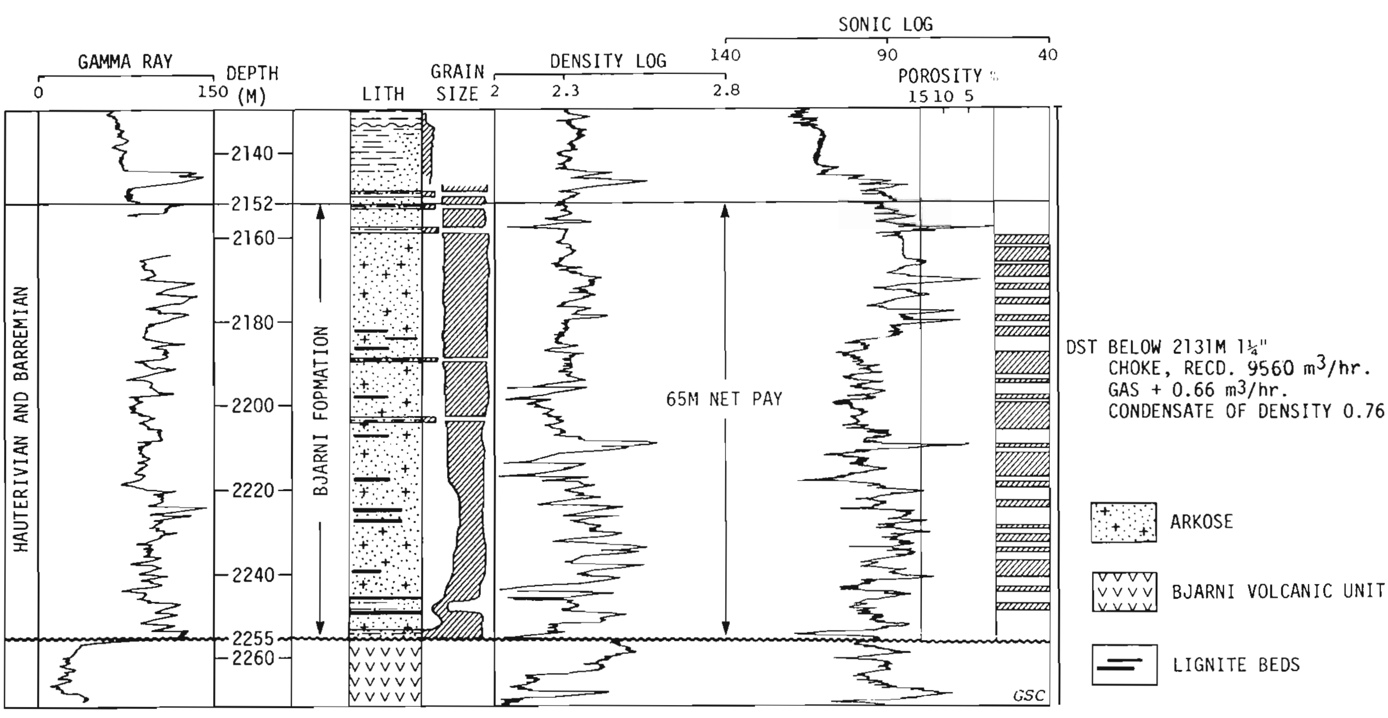


Figure 30. Details of the gas and condensate reservoir, Bjarni H-81.

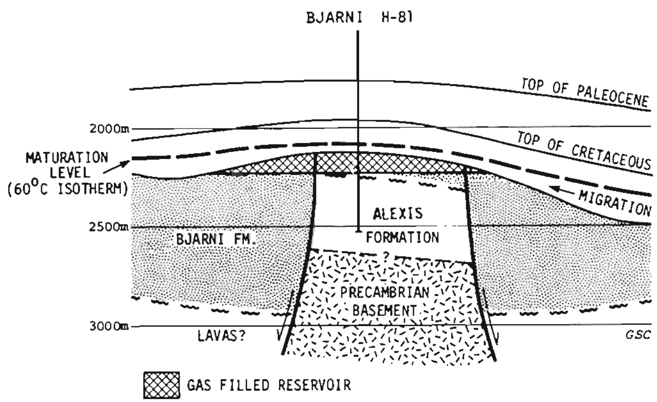


Figure 31. Diagrammatic cross-section, Bjarni structure.

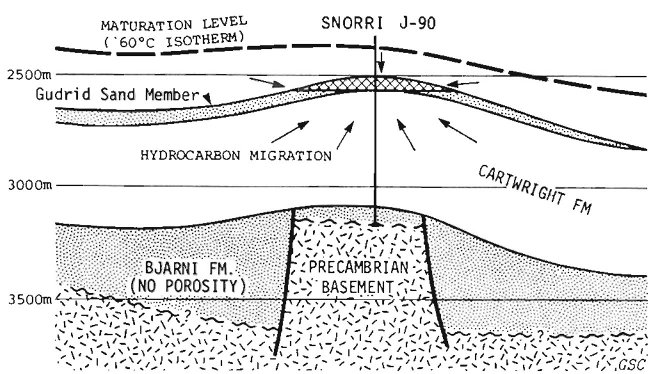


Figure 33. Diagrammatic cross-section, Snorri structure.

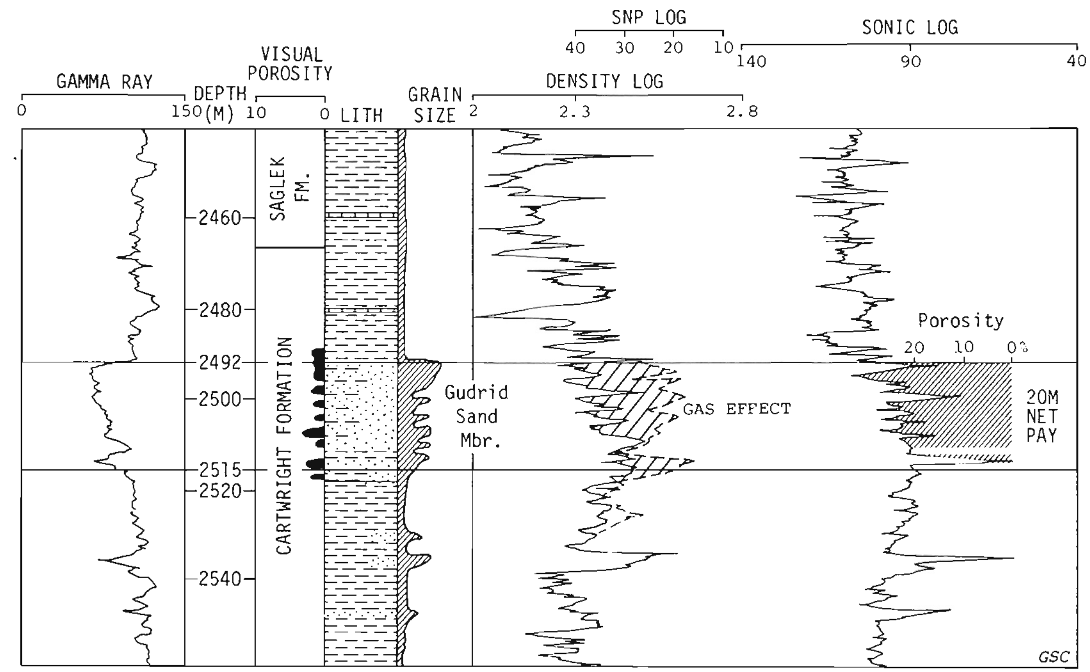


Figure 32. Details of the gas and condensate reservoir, Snorri J-90.

Bjarni H-81

The lithology of the Bjarni Formation, the reservoir at the Bjarni gas discovery has already been described (Fig. 11). Reducing the gross sand thickness of 106 m for intervals of low porosity or high water saturation leaves a net pay of 65 m for intervals of low porosity or high water saturation leaves a net pay of 65 m (Fig. 30). Porosity values average 15% with permeabilities to 207 md (Eastcan, 1976a).

A drillstem test run over the entire sand interval flowed gas at rates of up to 15 255 m^3/h (12.92 mmcfd) with 0.66 m^3/h light oil or condensate to give a gas oil ratio of 23 113 m^3/m^3. The gas has a gravity of 0.683 and is composed of 83.6% methane; 8.4% ethane; 3.5% propane, and 1.6% butane. Only traces of carbon dioxide and 1.6% nitrogen were detected.

A schematic cross-section over the Bjarni structure is shown on Figure 31. A prominent seismic marker occurs near the top of the Bjarni Sand Unit which drapes over a faulted basement high feature. Offstructure at Herjolf M-92, 3.7 km northwest of Bjarni H-81, the sand unit thickness greatly increases but is saltwater wet.

Because of post-Neocomian movements along faults bounding the structure an effective seal above the sand could not have existed until Late Cretaceous times. It is unlikely the gas originated in beds older than this. Shale of Maestrichtian age, the Cartwright Formation, overlies the sand reservoir and downdip occurs in a higher thermal regime. This shale has an above-average organic content (Rashid, pers. comm.). The organic matter type is phyrogen and melanogen, altered (Bujak, et al. 1977) only to 2-, that is above the oil window. This thermal alteration index is too low for the nature of gas and condensate recovered.

Geochemical data presented by McWhae and Michel (1976, p. 378) suggest that there is sufficient organic carbon and maturation from about 1220 m to generate hydrocarbons and oil phases could have been generated below 1830 m (the top of the Cartwright Formation). The gas and condensate recovered from the Bjarni Formation at Bjarni H-81 may therefore be an overmature product generated from the Cartwright Formation in a downdip, thermally higher location that has migrated into the nearest available reservoir.

Using reservoir parameters shown on Figure 30 and assuming circular structure 8 km in diameter, gas in place at Bjarni may be 8.0 x 10^3 m^3.

Snorri J-90

The Gudrid Sand Member, the reservoir in this well is porous over a 22 m interval below 2492 m. A core, 8 m long was cut at 2496 m and shows the sand to be a shallow subtidal deposit. Details of this sand and adjacent beds are shown on Figure 32. Log analysis shows a porosity of 18% and greater over 18 m. Superimposing the SNP and density logs show the sand to be gas-bearing. This was confirmed by testing which realized flow rates of 11 567 m^3/h (9.8 mmcfd) and 1.56 m^3/h condensate (Eastcan, 1978b). Neither the gravity nor the composition of the gas are known.

The Snorri J-90 discovery is significant, despite thin net pays, as it is the first indication of hydrocarbons in the Gudrid Sand Member. This sand is probably the best quality, though probably only locally developed, reservoir encountered to date on the Labrador Shelf. This reservoir overlies a thick shale sequence, the Cartwright Formation, believed to be the hydrocarbon source at both Gudrid and Bjarni. A diagrammatic section through the Snorri structure is shown in Figure 33.

The organic matter type, content and alteration index of these shales at Snorri are not known. However, a bottomhole temperature of 83°C and the existence of bituminous coals with an R_o value of 0.88 (Hacquebard, pers. comm.) at the base of the Bjarni Formation indicate maturity and hence hydrocarbon generation. Because the basal Lower Cretaceous sands are not porous, these hydrocarbons have migrated into the nearest available sealed reservoir, the Gudrid Sand Member.

Lack of sufficient data preclude estimates of reserves at this time.

Conclusions

The existence of source beds and some sealed reservoirs under the Labrador Shelf has been demonstrated. In general, geothermal gradients calculated from temperatures reported on logs are 2.74 to 3.4°C/100 m. Analysis of exsolved cuttings gas and thermal alteration indices show maturation levels that are too low to generate appreciable quantities of hydrocarbons. These maturity parameters suggest biogenic gas and, in the deeper wells, heavy oil will be generated. This is at variance with the gas and condensate actually recovered. Organic geochemical philosophy predicts this product comes from an over-mature source, below the oil window.

The discrepancy between maturation indicators and hydrocarbon product actually generated has two possible explanations. The preferred one is that some unidentified, labile component of the organic material is generating wet gas at low maturity levels. Alternatively a higher thermal regime existed in Paleocene and earlier times so that the thermal alteration indices for these sequences are actually higher than observed values. Evidence for this higher thermal regime was presented earlier.

The geological history of the area suggests that the Labrador margin foundered in early Eocene times about a hingeline near the present day Marginal Trough. A consequence of this is that the drape of Paleocene and older horizons over some basement features has been eliminated. The foundering may have caused the redistribution of any early formed hydrocarbons. As previously suggested, Paleocene and older units may have been subjected to a higher thermal regime than is indicated by present geothermal gradients. Hydrocarbon generation accompanied this period of higher heat flux. The present occurrence of an over-mature hydrocarbon (gas and condensate) in an apparently immature or marginally mature section may be due to dismigation (secondary migration) (Chiarelli and du Rochet, 1977). Eocene and younger units were deposited in a regime of relatively low heat flux and present-day temperatures are maximum values for this part of the sequence.

DISCUSSION

Analysis of the sequences penetrated by wells on the Labrador Shelf has given new insight to the interpretation of the geology of this area. This permits the proposal of a formalized stratigraphy which divides the Mesozoic and Cenozoic into two phases. A lower one, of earliest Cretaceous to Paleocene age contains continental to shallow water marine rocks overlying subaerially extruded basalt flows. The upper part of Eocene and younger age contains sediments deposited in an inner to outer neritic environment. The four formations and constituent members of the Labrador Shelf sequence have been described and their limits defined.

The lower part of the sequence, Lower Cretaceous to Paleocene, is apparently largely restricted to a fault-bound inshore basin. This lesser basin formed at a time when an oceanic regime existed south of the present day Grand Banks but when the area now occupied by the Labrador Sea was emergent. A hiatus of late Early to early Late Cretaceous age may be associated with megatectonic events that occurred during the formation of an oceanic regime off eastern Newfoundland, in the area between the Newfoundland-Azores and Gibbs fracture zones.

Relationships between sedimentary and tectonic events in the Tertiary for the Labrador Sea basin are difficult to assess. The core of this difficulty lies in the lack of unequivocal evidence regarding the mode of origin and geological structure of this area. At its southern end the Labrador Sea apparently has the characters of a true oceanic area. A rift valley, interpreted as an extinct spreading axis occupies a medical position, is flanked by symmetrically disposed magnetic lineations on each side. Basement velocities greater than 7.3 km/s have been recognized suggesting upper mantle occurs at a relatively shallow depth. On the other hand, at the northern end, the magnetic lineations are less ordered, tend to be asymmetrically arranged and no extinct spreading axis can be seen. Moreover in the northeast part an area underlain by apparently continental crust (Johnson et al., 1973) has been outlined in a region previously thought, on the basis of magnetic lineation correlation, to be oceanic. Other features outside the immediate subject area, such as the structure of the Davis Strait Sill and the continuity of the Lower Paleozoic orogen between northern Greenland and Ellesmere Island cast some doubt on the evolution of the Labrador Sea in terms of simple seafloor spreading.

The analysis of sedimentary sequences underlying the Labrador Shelf unfortunately provide few clues on the mode of origin of the Labrador Sea. Subsidence curves of the Labrador Sea margin show two periods of increased subsidence rates in the Tertiary. An earlier one commenced in the north during the early Paleocene and during the early Eocene farther south. A later phase of subsidence occurred in early Miocene times. It would be tempting to correlate the earlier phase of accelerated subsidence with the decline in spreading rates of the Labrador Sea. However the earliest age for the start of this subsidence in the northern part of the Labrador Sea Margin is the reverse of what would be expected from a conventional seafloor spreading model of this area. Moreover, evidence from drilling results off the West Greenland coast in southern Baffin Bay (Manderscheid, 1978) suggests this area also underwent a phase of subsidence in Paleocene times. A consequence of accelerated subsidence in the early Tertiary reduced and in some cases removed the drape of sediments overlying some basement structures. If an early phase of oil generation did occur, another consequence of this subsidence is the dismigration (secondary migration) of this early oil into up-dip stratigraphic traps.

The Miocene subsidence phase, probably still active, affected the entire Labrador Sea basin but left the Davis Strait Sill as a relatively high feature. It is for such reasons that a development of the Labrador Sea in terms of the undation theory has been offered as an alternative.

Some details on the occurrence of hydrocarbons on the Labrador Shelf have been given. The sequence contains a favourable balance of reservoir facies and source rocks. Relatively few structures exist and some of these are areally extensive and appear to have large vertical closures. Any hydrocarbons generated could migrate into these few structures rather than be dispersed among a multitude of smaller structures to form numerous noneconomic accumulations. Although insufficient data preclude an accurate assessment of total hydrocarbon reserves, estimates prepared by the Geological Survey of Canada (Energy, Mines and Resources, 1977) gave the potential of the accessible areas of the Labrador-East Newfoundland shelves as $2.13 \times 10^6 m^3$ (2.6 Bn bbls) oil and $7.6 \times 10^{11} m^3$ (26.7 Tcf) gas at a 50% probability. Data from subsequent drilling indicates the hydrocarbon potential may not be so large. The organic matter in Late Cretaceous and Tertiary sediments appears to generate mainly gas and condensate and there is the possibility of an early phase of oil generation from Early Cretaceous rocks though this oil, if formed, may have been dissipated or dismigrated during mid-Cretaceous tectonic activity.

However, the potential for oil in the higher thermal regime of the Saglek Basin may be high so that the potential for oil over the area as a whole may approximate that for gas.

REFERENCES

Amoco Canada Petroleum Co. Ltd., and Imperial Oil Ltd.

1973: Regional geology of the Grand Banks; Canadian Society of Petroleum Geologists, v. 21, p. 479-503.

1974: Regional geology of Grand Banks; American Association of Petroleum Geologists Bulletin; v. 58, p. 1109-1123.

1975: Well History Report, Amoco-IOE et al. Spoonbill D-30: released to Open File October, 1975 by Department of Energy, Mines and Resources, Ottawa.

1976: Well History Report, Amoco-IOE et al. Egret N-46: released to Open File August, 1976 by Department of Energy, Mines and Resources, Ottawa.

Beh, R.

1975: Evolution and geology of western Baffin Bay and Davis Strait, in Canada's Continental Margins and offshore petroleum exploration: D.J. Yorath, E.R. Parker, eds., Canadian Society of Petroleum Geologists, Memoir 4, p. 453-476.

Birkelund, T.

1965: Ammonites from the Upper Cretaceous of West Greenland; Gronlands Geologiske Undersogelse Bulletin, No. 156, 192 p.

Blais, R.

1959: L'origine des minerais Cretaces due gisement de fer de Redmond, Labrador; Le Naturaliste Canadian, v. 86, p. 265-299.

Bridgewater, D., Watson, J., and Windley, B.F.

1973: Archaean craton of the North Atlantic Region: in J. Sutton and B.F. Windley, eds., Discussion of the evolution of the Precambrian Crust; Royal Society of London, Philosophical Transactions, Series A, v. 283, p. 493-512.

British Petroleum

1977: Well History Report, B.P. et al. Bonavista C-99; released to Open File August, 1977 by Department of Energy, Mines and Resources, Ottawa.

1978: Well History Report, B.P. et al. Indian Harbour M-52: released to Open File November, 1978 by Department of Energy, Mines and Resources, Ottawa.

Bujak, J., Barss, S., and Williams, G.

1977: Offshore East Canada's Organic type and color and hydrocarbon, Potential; Oil and Gas Journal, v. 75-14, p. 198-202 and v. 75-15, p. 96-100.

Burke, K.
1972: Longshore drift, submarine canyons and submarine fans in development of Niger Delta; American Association of Petroleum Geologists Bulletin, v. 56, p. 1975-1983.

Chiarelli, A. and du Rochet, J.
1977: Importance des phenomenes de migration vesticale des hydrocarbures; Institut Francais du Petrole Revue, v. 32, p. 189-208.

Currie, K.L.
1976: The Alkaline Rocks of Canada; Geological Survey of Canada, Bulletin 239, 228 p.

Cutt, B.J. and Laving, J.G.
1977: Tectonic elements and geological history of south Labrador and Newfoundland continental shelves, Eastern Canada; Canadian Society of Petroleum Geologists, v. 25, p. 1037-1053.

Davidson, A.
1972: The Churchill Province: in R.A. Price and R.J. Douglas, eds., Variation in tectonic styles in Canada; Geological Association of Canada, Special Paper 11, p. 436-452.

Dawes, P.R.
1976: Precambrian to Tertiary of northern Greenland: in A. Escher and W.S. Watts, eds., Geology of Greenland; The Geological Survey of Greenland, Copenhagen, p. 248-303.

Dorf, E.
1959: Cretaceous floras from beds associated with rubble iron ore deposits in the Labrador Trough (abstract); Geological Society of America Bulletin, v. 70, p. 1291.

Eastcan
1975: Well History Report, Eastcan et al. Leif M-48: released to Open File August, 1975 by Department of Energy, Mines and Resources, Ottawa.

1976a: Well History Report, Eastcan et al. Bjarni H-81: released to Open File October, 1975 by Department of Energy, Mines and Resources, Ottawa.

1976b: Well History Report, Gudrid H-55: released to Open File October, 1976 by Department of Energy, Mines and Resources, Ottawa.

1977a: Well History Report, Freydis B-87: released to Open File August, 1977 by Department of Energy, Mines and Resources, Ottawa.

1977b: Well History Report, Cartier D-70: released to Open File October, 1977 by Department of Energy, Mines and Resources, Ottawa.

1978a: Well History Report, Karlsefni H-13: released to Open File October, 1978 by Department of Energy, Mines and Resources, Ottawa.

1978b: Well History Report, Eastcan et al. Snorri J-90: released to Open File September, 1978 by Department of Energy, Mines and Resources, Ottawa.

1978c: Well History Report, Eastcan et al. Herjolf M-92: released to Open File November, 1978 by Department of Energy, Mines and Resources, Ottawa.

Energy, Mines and Resources
1977: Oil and Natural Gas Resources of Canada, 1976; Energy, Mines and Resources Publication EP 77-1, Ottawa, 76 p.

Escher, A., Henriksen, J., Dawes, P.R., and Weidick, A.
1970: Tectonic/geological map of Greenland 1:2,500,000; Geological Survey of Greenland, Copenhagen.

Fischer, A.G.
1976: Origin and growth of basins: in A.G. Fischer and S. Judson, eds., Petroleum and global tectonics; Princeton University Press, p. 47-79.

Fisher, R.V.
1966: Rocks composed of volcanic rock fragments and their classification; Earth Science Reviews, v. 1, p. 287-298.

Frarey, M.J., and Duffell, S.
1964: Revised stratigraphic nomenclature for the central part of the Labrador Trough; Geological Survey of Canada, Paper 64-25, 13 p.

Gradstein, F.M. and Williams, G.L.
1976: Biostratigraphy of the Labrador Shelf, Part 1; Geological Survey of Canada Open File No. 349, Ottawa, 39 p.

Grant, A.C.
1972: The Continental Margin off Labrador and eastern Newfoundland morphology and geology; Canadian Journal of Earth Sciences, v. 9, p. 1394-1430.

1974: Structural modes of the western margin of the Labrador Sea, W.J. van der Linden and J.A. Wade, eds., Offshore geology of Eastern Canada; Geological Survey of Canada, Paper 74-30, p. 217-231.

Gross, G.A.
1968: Iron Ranges of the Labrador Geosyncline; Geological Survey of Canada, Economic Geology Report 22, v. 3, 179 p.

Henderson, E.
1959: A Glacial Study of Central Quebec – Labrador; Geological Survey of Canada, Bulletin 50, 94 p.

Henderson, G., Rosenkrantz, A., and Schiener, E.
1976: Cretaceous-Tertiary sedimentary rocks of West Greenland: in A. Escher and W.S. Watts, eds., Geology of Greenland; The Geological Survey of Greenland, p. 341-362.

Holtedahl, O.
1958: Some remarks on the Geomorphology of continental shelves off Norway, Labrador and southeast Alaska; Journal of Geology, v. 66, p. 461-471.

Haworth, R.St., Poole, W.M., Grant, A.C., and Sanford, B.J.
1976: Marine geoscience survey, northeast of Newfoundland; in Report of Activities, Part A, Geological Survey of Canada, Paper 74-30, p. 7-15.

Jansa, L. and Wade, J.A.
1975: Geology of the Continental Margin off Nova Scotia and Newfoundland in W.J. van der Linden and J.A. Wade, eds., Offshore Geology of Eastern Canada; Geological Survey of Canada, Paper 74-30, p. 51-105.

Jeffreys, H.
1959: The Earth; Cambridge, England, Cambridge University Press, 420 p.

Johnson, G.L., Egloff, J., Campsi, J., Rasmussen, J., Dittmer, F., and Fritag, J.
1973: A sedimentary basin in the northern Labrador Sea; Geological Society of Denmark Bulletin, v. 22, p. 1-6.

Karweil, J.
1956: Die Metamorphose der Kohlen vom Standpunkt der physicalisches Chemie; Zeitschrift feur deutsche geologische Gesellschaft, v. 107, p. 132.

King, A.F. and MacMillan, N.J.
1975: A mid-Mesozoic breccia from the Coast of Labrador; Canadian Journal of Earth Sciences, v. 12, p. 44-51.

Laughton, A.S.
1971: South Labrador Sea and the evolution of the North Atlantic; Nature, v. 232 (5313), 612 p.

1972: The Southern Labrador Sea – a key to the Mesozoic and early Tertiary evolution of the North Atlantic (DSDP Leg 12) in Initial Reports of Deep Sea Drilling Project 12, p. 115-1179, U.S. Government Printing Office, Washington, D.C.

Le Pichon, X., Hyndman, R.D., and Pautot, G.
1971: Geophysical study of the opening of the Labrador Sea; Journal of Geophysical Research, v. 76, p. 4724-4743.

Lowrie, A. and Escowitz, E. eds.
1969: Global ocean floor analysis and research data series; volume 1, Kase 9: U.S. Naval Oceanography Office, Washington, D.C., 971 p.

Manderscheid, G.
1978: West Greenland Offshore Basin (abstract); Canadian Society Petroleum Geologists Conference on Facts and Principles of World Oil Occurrence, Calgary, 1978.

Mayhew, M.A., Drake, C.L., and Nate, J.E.
1970: Marine geophysical measurements on the continental margins of the Labrador Sea; Canadian Journal of Earth Sciences, v. 7, p. 199-214.

McWhae, J.R.H. and Michel, W.F.E.
1975: Stratigraphy of Bjarni H-81 and Leif E-48, Labrador Shelf; Canadian Society of Petroleum Geologists, v. 23, p. 361-382.

Mercki, P.J.
1970: Structural geology of the Cenozoic Niger Delta; in F.F.J. Dessauvagie and A.J. Whiteman, 1970, eds., African Geology; University Ibadan Geology Department, Nigeria, p. 630-646.

Mobil Oil Canada Ltd.
1975: Well History Report, Mobil-Gulf Adolphus 2K-41: Released to Open File September, 1975 by Department of Energy, Mines and Resources, Ottawa.

1976: Well History Report, Mobil-Gulf Dominion 0-23: Released to Open File October, 1976 by Department of Energy, Mines and Resources, Ottawa.

Perrier, R., and Quiblier, J.
1974: Thickness changes in sedimentary layers during Compaction History; methods and Quantitative Evaluation; American Association of Petroleum Geologists Bulletin, v. 58, p. 507-520.

Powers, M.C.
1967: Fluid release mechanisms in compacting marine mudrocks and their importance in oil exploration; American Association of Petroleum Geologists Bulletin, v. 51, p. 1240-1253.

Rice, H.M.A.
1968: An antlion (Neuroptera) and a stonefly (Plecoptera) of Cretaceous Age from Labrador, Newfoundland; Geological Survey of Canada, Paper 68-65, 11 p.

Roberts, D.C.
1975: Structural development of the British Isles, the Continental Margin and the Rockall Plateau: in C.A. Burke and C.L. Drake, eds., The Geology of Continental Margins; New York, Springer-Verlag, p. 343-360.

Ross, D.I.
1973: Free air and simple Bouguer gravity maps of Baffin Bay; Geological Survey of Canada, Paper 73-37, 11 p.

Ruffman, A. and van Hinte, J.E.
1973: Orphan Knoll – a "chip" off the North American "plate"; Geological Survey of Canada, Paper 71-23, p. 407-449.

Schiener, E.J.
1975: Basin study – Central West Greenland onshore Cretaceous-Tertiary sediments; IX^{me} Congres International de Sedimentologie, theme 5, tome 2, Nice, p. 379-385.

Srivastava, S.P.
1978: Evolution of the Labrador Sea and its bearing on the early evolution of the North Atlantic; Geophysical Journal of the Royal Astronomical Society, v. 52, p. 313-387.

Taylor, F.C.
1972: The Nain Province: in R.A. Price and R.J. Douglas, eds., Variations in tectonic styles in Canada; Geological Association of Canada Special Paper 11, p. 436-452.

Taylor, J.M.
1950: Pore space reduction in sandstones; American Association of Petroleum Geologists, v. 34, p. 707-716.

Umpleby, D.C., Stevens, G.R., and Colwell, J.A.
1978: Clay minerals analysis of Mesozoic-Cenozoic sequences, Labrador Shelf; in Current Research, Part B, Geological Survey of Canada, Paper 78-1B, p. 111-114.

van Bemmelen, R.A.
1949: Geology of Indonesia; 1A General Geology; The Hague Government Printing Office, 732 p.

1972: Geodynamic Models: Amsterdam, Elsevier Publishing Co. 267 p.

van der Linden, W.J.M.
1975a: Central attenuation and sea floor spreading in the Labrador Sea; Earth and Planetary Sciences Letters, v. 27, p. 409-423.

1975b: Mesozoic and Cenozoic opening of the Labrador Sea, the North Atlantic and the Bay of Biscay; Nature, v. 253, p. 320-324.

van der Linden, W.J.M. and Srivastava, S.P.
1975: The Crustal Structure of the Continental margin off central Labrador: in W.J.M. van der Linden, and J.A. Wade, eds., Offshore Geology of eastern Canada; Geological Survey of Canada, Paper 74-30, p. 233-245.

van Hinte, J.E.
1978: Geohistory analysis – application of micropalaeontology in exploration geology; American Association of Petroleum Geologists Bulletin, v. 62, p. 201-222.

Vogt, P.R. and Avery, O.E.
1974: Detailed Magnetic Surveys in the northeast Atlantic and Labrador Sea; Journal of Geophysical Research, v. 79, p. 363-389.

Wade, J.A., Grant, A.C., Sanford, B.V., and Barss, M.S.
1977: Basement Structure, Eastern Canada and adjacent areas; Geological Survey of Canada Map 1400A.

Wallace, F.K.
1973: Geology of Davis Strait Bathymetric Sill and associated sediments, Offshore Baffin Island, Canada: in J.D. Aitken, and D.J. Glass, eds., Canadian Arctic Geology; Geological Association of Canada and Canadian Society of Petroleum Geologists, p. 81-97.

Wynne-Edwards, H.R.
1972: The Grenville Province: in R.A. Price and R.J. Douglas, eds., Variations in tectonic styles in Canada; Geological Association of Canada Special Paper 11, p. 436-452.

Zajac, I.S.
1974: The stratigraphy and mineralogy of the Sokoman Formation in the Koch Lake area, Quebec and Newfoundland; Geological Survey of Canada, Bulletin 220, 159 p.