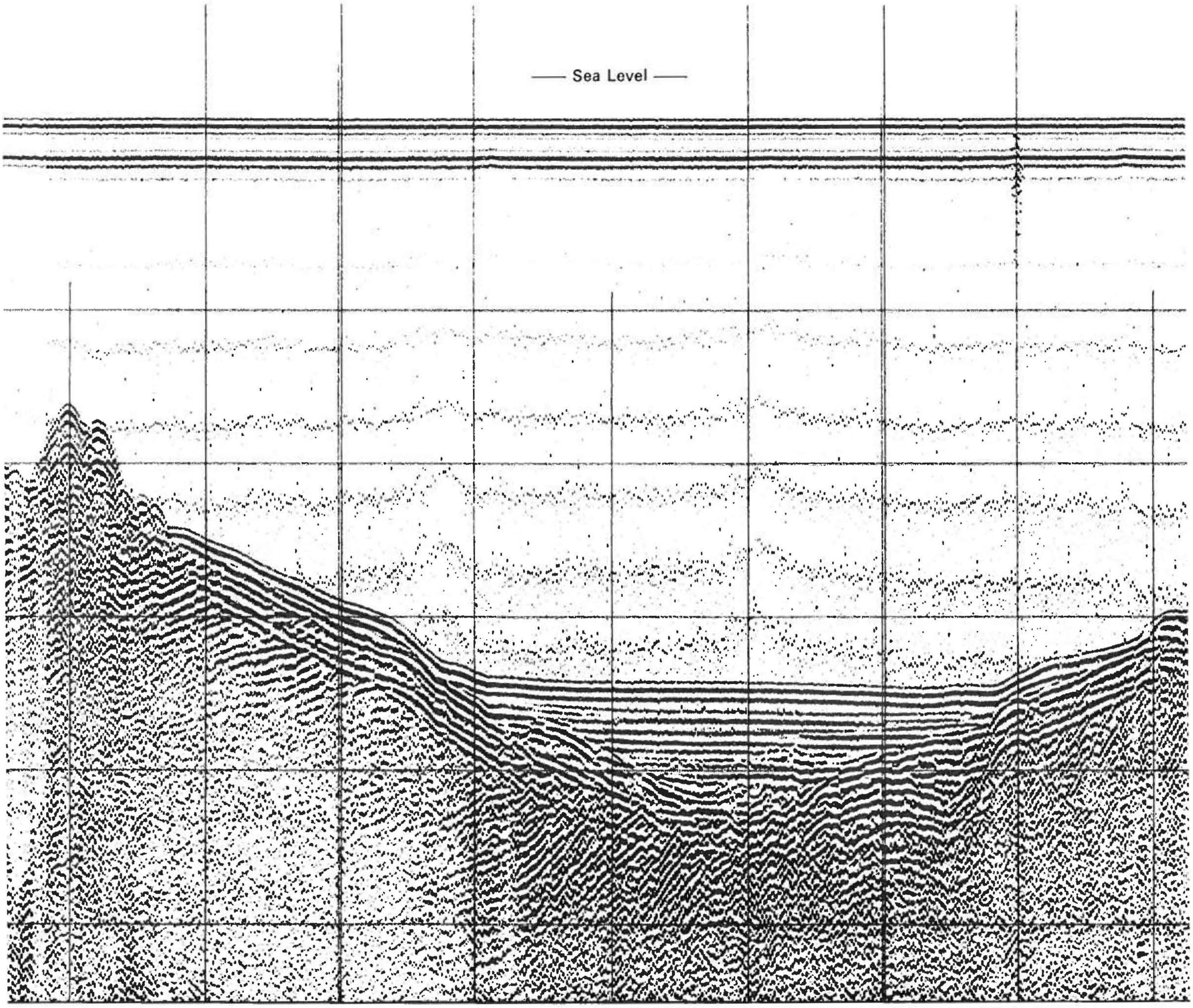
70°08′ 70°17

53°06′ 53°29

15 km



Petroleum geology

Gilroy Henderson

Fig. 396. GGU seismic reflection record across Vaigat showing Quaternary sediments infilling a channel cut in dipping Cretaceous sediments. The small hummock on the left of the section may be a remnant of a lateral moraine. Water depth in centre of section about 600 m.

Introduction

Greenland is appropriately classified by petroleum geologists as a frontier area, but like other Arctic areas it has attracted increasing interest in recent years. Encouraging finds of gas and oil have already been made in the Canadian Arctic Islands, and oil has been discovered in the Romulus well on the western side of Ellesmere Island (latitude 80°N) only 300 km from the coast of North Greenland. Two wells on the Labrador shelf yielded substantial amounts of gas on test during 1974. No wells have been drilled onshore or offshore Greenland at the time of writing.

The presence of thick sections of bituminous shale and of mud volcanoes producing gas in the Nûgssuaq peninsula of central West Greenland had been pointed out by A. Rosenkrantz, University of Copenhagen, in February 1939. However, until the mid-1960s only sporadic interest in the petroleum potential of the region had been shown, although systematic mapping had produced a considerable amount of information on the Cretaceous–Tertiary sediments and overlying Tertiary basalts (see Rosenkrantz & Pulvertaft, 1969). The presence of commercial source rocks was shown by analyses of marine shales in 1968. The oil and gas prospects of this part of central West Greenland were reviewed by Henderson (1969) and Henderson & Stevens (1969). Emphasis was placed on the onshore area, but the implications for the offshore continental shelf were also mentioned (see also Henderson, 1973).

In the period 1969–1972 more than 20 companies and groups interested in petroleum held prospecting licences covering parts of West Greenland and the West Greenland continental shelf, and a considerable

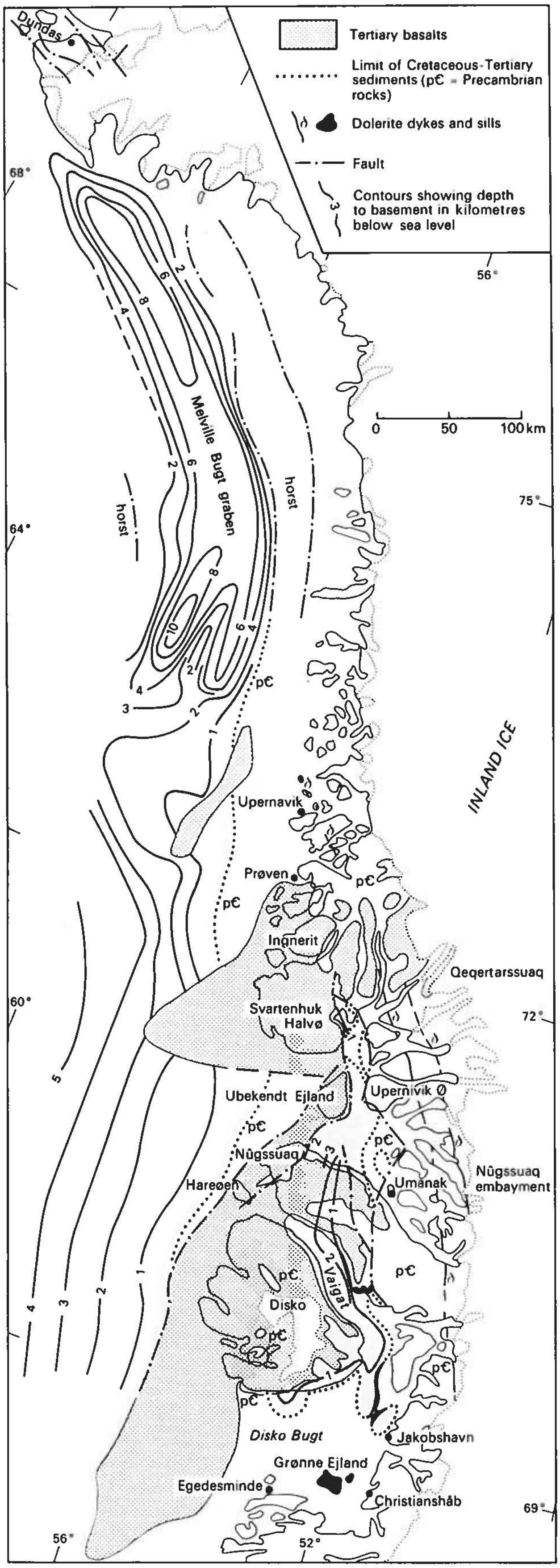


Fig. 397. Northern part of the West Greenland basin showing the Nûgssuaq embayment and the Melville Bugt graben.

amount of geophysical work was carried out. Until late 1973 three companies held prospecting licences for petroleum on land in North Greenland. One mining company holds an exclusive concession in central East Greenland that includes petroleum rights over the sedimentary area on land. Much interest has been expressed in the East Greenland continental shelf, but no licences or concessions have yet been granted. The first exclusive concessions over parts of the central West Greenland shelf were granted in early 1975.

This chapter considers the main sedimentary areas of Greenland, West Greenland, North Greenland and East Greenland – especially with respect to criteria affecting their prospects for the occurrence of petroleum in commercial quantities.

All source rock and porosity analyses mentioned in the text have been carried out for the Survey by Olexcon International B.V., The Hague.

West Greenland

A very extensive sedimentary basin is now known to be present along the coast of West Greenland between northern Baffin Bay and Kap Farvel. The basin lies mainly offshore, where it forms an extension of the known sedimentary area of central West Greenland.

In previous publications (Henderson & Stevens, 1969) the term West Greenland basin was applied to the area of Cretaceous–Tertiary sediments outcropping on land and present below the fjords in central West Greenland. The term West Greenland basin will henceforth be used in an extended sense to define the entire sedimentary area of onshore and offshore West Greenland.

The northern part of this basin is shown in fig. 397. Two structural units have been delineated in this area: (1) the Nûgssuaq embayment and (2) the Melville Bugt graben.

No drilling has yet been undertaken offshore and our knowledge of the sedimentary section here stems almost entirely from geophysical work. The onshore area will therefore be discussed first.

Nûgssuaq embayment

The Nûgssuaq embayment (fig. 397) comprises the sediments of Cretaceous–Tertiary age outcropping on land in central West Greenland and present below the fjords between the various peninsulas and islands in this area.

The embayment is bounded to the east by Precambrian rocks. The present limit is a system of faults, although west of the faults basement outcrops below the sediments, and in large areas of Disko Bugt the original sedimentary cover has been removed by glaciers (Denham, 1974). Some of the faults were active during the sedimentation, in particular the Ikorfat fault and the fault limiting the small Cretaceous outcrops on the north-west corner of Upernivik Ø (Rosenkrantz & Pulvertaft, 1969). However, the lithology of the sediments close to the boundary faults shows that much if not most of the movement along these faults took place after the sedimentation (Schiener, 1975).

Schiener's work on palaeocurrent directions has shown that the main source of the sediments was to the south (Henderson *et al.*, this volume). The depositional environment was deltaic. Very little of the southernmost part of the sedimentary sequence has been preserved. There is an outcrop of sandstones and cherty shales preserved below a resistant dolerite sill on the easternmost island of the Grønne Ejland group, but most of Disko Bugt is underlain by Precambrian rocks whose cover of sediments has been totally eroded. Thus the detailed palaeogeography of the southern termination of the embayment cannot be determined.

To the west of the embayment lies the N–S trending Disko gneiss ridge, whose northernmost outcrop is found in central Disko. If the trend of the ridge is continued northwards to the Vaigat, there is a zone immediately east of this where the sediments have a N–S strike and dip east at angles up to 22°. This is interpreted as being due to post-sedimentary uplift along the gneiss ridge. The Tertiary basalts along part of the south coast of Nûgssuaq rest unconformably on these dipping sediments, but evidence from Disko suggests that there were still movements along the ridge during the earlier period of volcanism (A. K. Pedersen, 1973). The effect of this ridge during the Cretaceous–Tertiary sedimentation is uncertain, but the fact that the palaeocurrent directions are mainly northwards indicates some confining influence attributable to it (Schiener, 1975).

Sediment thickness

The thickest sedimentary section continuously exposed is that along part of the north coast of Nûgssuaq where marine sediments of Lower Santonian to Upper Danian age form a sequence of 1450 m thickness. The Lower Santonian beds are the oldest sediments exposed in this particular area. Farther east along the north coast of Nûgssuaq, where Precambrian rocks are exposed, the overlying sediments are sandstones and shales of Barremian to Turonian age up to 800 m in thickness. In Svartenhuk Halvø to the north Lower Cretaceous rocks also rest on Precambrian rocks. Thus the geological evidence alone points to the presence of some 2000 m of sediments above and below sea level in outer Nûgssuaq.

Recent seismic work on land has added to our knowledge of sediment thicknesses in this area. Sharma (1973) estimated the depth below sea level to the top of the Precambrian rocks in the western part of the north coast of Nûgssuaq to be about 2500 m. Elder (1975) estimated a maximum depth to basement of about 3000 m below sea level in the same general area, and in the Vaigat to 2000 m below sea level. Taking the geological and geophysical evidence together the maximum thickness of sediments in the central part of the Nûgssuaq embayment can thus be shown to be up to 3500 m. Much of the sedimentary sequence is now exposed above the bottom of the fjords which is an unfavourable factor from the point of view of finding petroleum. However, there are some areas such as the Auvfarssuaq and Itivdle valleys where a sufficient thickness may be preserved below land surface and sufficiently far from the fjords to be of potential interest.

Source rocks

Source rocks for petroleum are known to be present in the dark grey shales of the Nûgssuaq embayment. Fifty-nine samples were collected for source rock analysis during the period 1968–1973. Of these samples eight proved to be commercial source rocks (Stevens, *in* Henderson, 1969; Stevens *et al.*, 1974; GGU unpublished reports).

Seven of these were collected at or south of the north coast of Nûgssuaq, west of Ikorfat; the eighth was collected from the south coast of Nûgssuaq, north-east of Hareøen. The ages of the samples are all within the range Campanian to Danian. Conditions that have been conducive to the formation of source rocks in one area of the West Greenland basin may also have prevailed in other areas. The prevailing climate, water temperature and types of organic matter are only some of the factors involved. The climate of this area in Upper Cretaceous – Lower Tertiary times was clearly warmer than it is today.

According to Heer (1883) the floras of the Kome Formation (Barremian–Aptian) indicate a subtropical climate with a mean annual temperature of 21–22°C. The climate during the deposition of the Atane Formation (Upper Turonian–Coniacian) was also subtropical. The flora of the Pautut Formation (Upper Santonian–Lower Campanian) contains an

Fig. 398. The mud volcano Qapiortoq kangigdleq in the Auvfarssuaq valley, central Nûgssuaq. (Photo: A. Rosenkrantz).

admixture of temperate forms but it still has strong affinities with the earlier floras.

Both Heer (1883) and Koch (1963) considered that Tertiary floras in this area indicate a temperate climate, Heer concluding that the mean annual temperature was 12°C. Rosenkrantz (1970) considered that the Upper Danian fauna of central Nûgssuaq indicates a temperate or more likely warm temperate climate.

Reservoir rocks

The sedimentary sequence in the Nûgssuaq embayment consists almost entirely of sandstones and shales, sandstones being dominant in the southern and eastern parts of the embayment. While potential reservoir rocks must be sought amongst the sandstones, study of the porosity and permeability of these sandstones is only now being undertaken. Nevertheless, certain gross features can be distinguished already.

In general, the lowermost quartz sandstones (Kome Formation) in the eastern part of Nûgssuaq have appreciable amounts of kaolinitic matrix. This fact, despite the local occurrence of friable sandstones, reduces the porosity and even more the permeability of the rocks. Higher up, in the Atane Formation, the amount of the kaolinitic matrix decreases, which together with better sorting gives better porosity and permeability values.

From preliminary investigations in south-east Nûgssuaq and north-east Disko (Mudderbugten area) it appears that in contrast to the Cretaceous rocks the Tertiary sandstones display much better reservoir properties. Additionally, individual sandstone units are appreciably thicker (up to 15 m) with accordingly reduced proportions of clay-rich units (E. J. Schiener, personal communication).

The sandstone intercalations in the dark grey shaly sequences of northern Nûgssuaq are in general impure, with relatively high clast/matrix ratios. In addition they tend to be very well cemented. This, together with their limited lateral extent, eliminates them as possible reservoir rocks.

Evidence of hydrocarbon migration

Mud volcanoes are present in several areas onshore, and have been observed in valley floors in Svartenhuk Halvø, Nûgssuaq (fig. 398) and Disko. They were discussed in some detail by Henderson (1969), who collated evidence from earlier expeditions (see, for example, Rosenkrantz, 1943).

The mud volcanoes in West Greenland are built up of Quaternary deposits, and in those that are active, gas and water come up to the surface in a central crater. The water is highly alkaline. The gas is rich in methane, and probably originates from the shales, which have a high organic carbon content, although a source in coal seams cannot be excluded. It should nevertheless be noted that methane was not encountered in the coal mine at Qutdligssat on Disko.

Bitumen-impregnated sandstone was found at one locality on the island of Qeqertarssuaq (fig. 399). The composition of the bitumen is near to that of aromatic hydrocarbons. Hydrocarbons of an aromatic type are commonly found in seepages, whereas paraffinic and other types are more usually found in the underlying source rocks forming part of the same sedimentary sequence.

Hydrocarbons have thus been able to migrate within the sedimentary sequence, and this fact is of importance to both the onshore and offshore areas.

Traps

There are good possibilities for the presence of structural and stratigraphic traps below surface in the sediments of the West Greenland basin as a whole. Henderson (1969) discussed the prospects for traps in the light of knowledge of the onshore area.

Compressional folds are not present in the sediments on land. Such folds as exist are probably warps associated with movements along major faults. The presence of faults gives possibilities of fault trapping. As an example of a warp associated with fault movement, mention can be made of the central part of the Vaigat where upward movement along the Disko gneiss ridge is presumed to be the cause of tilting of the sediments in a 10 km wide belt with strikes approximately N–S and dips up to 22°E.

There is a major fault system associated with the present eastern limit of the sediments and parts of this have been active during the deposition of the sediments and basalts. Fault conglomerates containing very large boulders (up to 2 m across) occur in sediments at the base of a fault scarp on the northwestern corner of Upernivik Ø and on the downthrown side of the Ikorfat fault of north Nûgssuaq. Such features and the common occurrence of sedimentary cycles show repeated instability during the sedimentation. There are unconformities at three levels in the sedimentary sequence and in many places the Tertiary volcanic rocks rest unconformably on the sediments. In view of the very long structural history of this area, with a long phase of rifting apparently ending in a phase of sea floor spreading (see Henderson, 1973) successive movements along major faults and consequent evidence of these movements in the sediments can only be expected.

Both primary and secondary stratigraphic traps may be expected. Lateral changes of facies combined with either tilting caused by fault movements, or simply regional dips, will give possibilities for primary stratigraphic traps. Fault movements and related tilting during the sedimentation, with renewed sedimentation after the movements, have resulted in unconformities, with the possibility of secondary stratigraphic traps.

Thus knowledge of the onshore geology leads to the prediction that fault traps and stratigraphic traps could be expected offshore.

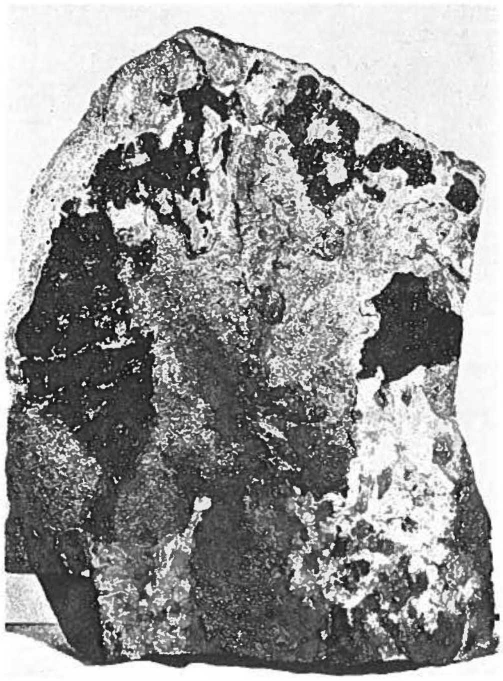


Fig. 399. Bitumen and calcite on fracture surface in sandstone from west Qeqertarssuaq. The width of the base of the block is 18 cm.

Melville Bugt graben

Barrett & Manchester (1969; *in* C. E. Keen *et al.*, 1972), Hood & Bower (1970; 1973) and M. J. Keen *et al.* (1972) have shown the presence of a deep sediment-filled graben in Melville Bugt, parallel to the coast, north of Svartenhuk Halvø.

Additional geophysical work was undertaken over the graben by Bedford Institute in 1971, and Ross & Henderson (1973) have given a detailed interpretation of the results obtained to date. This interpretation is shown in fig. 397. Some slight changes have been made at the southern end of the graben to allow a tie-in with the results of Denham (1974).

The surveys showed that the graben is about 400 km in length, 50–75 km wide and at the deepest part contains about 10 km of sediment. Manchester & Clarke (1973) reported that a seismic profile across the graben showed about 150 m of acoustically transparent sediments overlying an erosional surface below which there are folded and faulted sediments.

The graben thus contains a very thick section of folded and faulted sediments which would be of immediate interest for petroleum geology were not Melville Bugt an area with prolific icebergs. If the iceberg problem can be solved this area will certainly be attractive in the future.

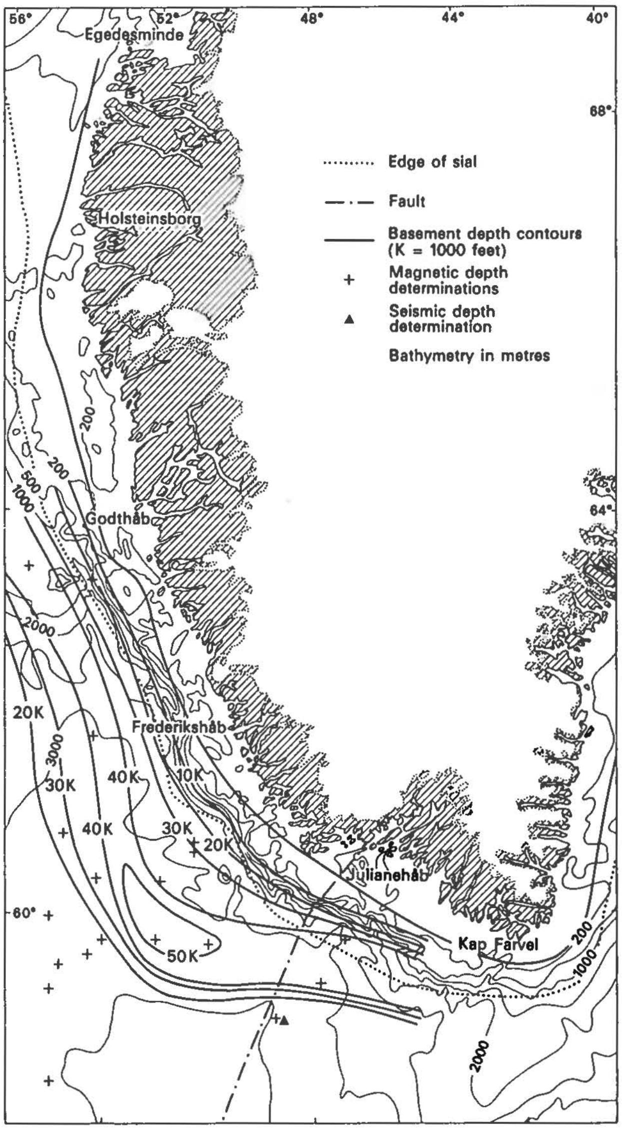


Fig. 400. Basement contour map of the south-west Greenland shelf. (Modified after Hood & Bower, 1973).

Continental shelf between 68° and 73°N

This part of the West Greenland shelf lies offshore from the Nûgssuaq embayment. The interpretation given in this part of fig. 397 is based on reconnaissance surveys by Bedford Institute and Dalhousie University, and the Geological Survey of Greenland (Park *et al.*, 1971; Ross & Henderson, 1973; Denham, 1974). Immediately south of the Melville Bugt graben is an area of shallow magnetic basement that was previously thought to be part of the offshore extension of the West Greenland Tertiary basalts (Park *et al.*, 1971). Later investigations (Denham, 1974) have shown that the granulite facies gneisses of the Upernavik area are strongly magnetic and that the magnetic pattern over most of this area can be better explained as indicating Precambrian basement rather than basalt.

A major N–S fault with easterly downthrow is shown by Denham (1974) marking the westwards limit of the basalts offshore from Disko and Nûgssuaq. On the upthrown side Precambrian basement probably outcrops in places on the sea floor, or is at shallow depth. The basement dips gradually westwards, reaching a depth of about 5 km below sea level. The structural picture shown here is undoubtedly oversimplified.

The significance of this area for petroleum exploration is that the western part contains a thick sedimentary section with possibilities for stratigraphic traps.

Continental shelf south of 68°N

The information that has so far been published on the West Greenland shelf south of 68°N is of limited extent. Hood & Bower (1973) have published a small-scale map showing depths to magnetic basement along the continental margin south of 68°N. This map is reproduced here as fig. 400. This naturally gives only a very simplified picture. It shows the inner limit of the offshore sediments running approximately parallel to the coast. The line is shown touching offshore islands at 68°N and at Kap Desolation, south of 61°N. At other places the boundary is some distance off the coast, as for example off Godthåb, where it is shown to be 50 km offshore.

These authors show a gradual increase in depth to basement westwards from the shelf across the continental slope, with considerable sediment thicknesses (in places over 5 km) below parts of the continental slope.

The results from two seismic lines run off Julianehåb have been published by Mayhew *et al.* (1970). The line normal to the coastline showed a thick layer of sediments (2.0 km/s) overlying a 3.9 km/s layer. The basement (6.3 km/s) apparently outcrops midway down the continental slope.

The results of dredging by the U.S. Naval Oceanographic Office between Godthåb and Kap Farvel have been reported on by Johnson *et al.* (1972). The material collected consisted of sandy limestones, sandy mudstones, sandstones and coal deposited in shallow marine to non-marine environments. Much of the material was originally considered on the basis of palynology to be of Mesozoic age, but subsequent study of the nannofossil content has given Tertiary ages for most of the samples; the Mesozoic fossils are considered to be reworked (Johnson *et al.*, 1974).

Holtedahl (1970) discussed the main morphological features of the West Greenland shelf and drew comparisons with the Norwegian shelf. He recognised

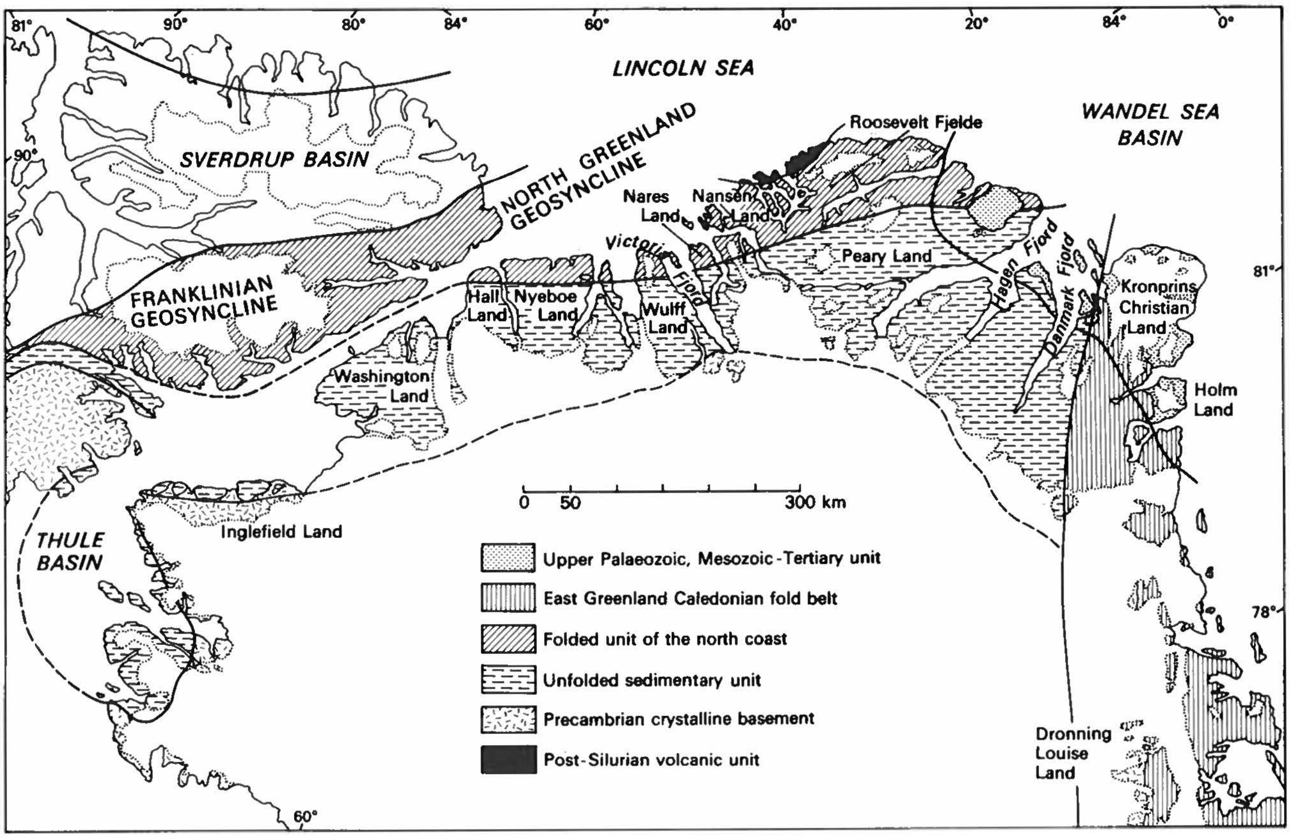


Fig. 401. Map showing the main geological units of Greenland north of 76° N and their counterparts in adjacent Ellesmere Island. (Modified from Dawes, 1971).

the presence of an inner uneven submarine platform separated by a system of coast-parallel marginal channels from the fishing banks, which are submarine platforms of shallow depth and low relief. The fishing banks are separated from each other by transverse channels normal to or oblique to the coastline.

Bathymetric data is best for the offshore region between 59° and 69°30′N. The Survey has prepared 1:100 000 maps with 10 m contour intervals for this region based on detailed surveys made by the Danish Hydrographic Office in the period 1947–1967.

A considerable amount of geophysical surveying has been undertaken by the oil industry in this area. Although none of the results have been released, the continuing interest shown by oil companies in this part of the shelf makes it clear that the prospects are sufficiently encouraging to warrant further work.

Petroleum potential of West Greenland in general

In summary it can be stated that recent work has shown that the West Greenland continental margin encompasses thick sedimentary sequences. These sediments have accumulated in a largely marine environment that developed between Greenland and Canada. It is known from work on land that the various requirements for considering the Upper Cretaceous – Lower Tertiary sediments to have petroleum potential are fulfilled. Whether or not there are *in situ* sediments of pre-Cretaceous age is not known, but this is highly likely.

North Greenland

In North Greenland two sedimentary sequences of different ages must be considered in any discussion of the petroleum prospects. The sequence that has by far the greatest interest at the present time, for reasons of both the volume of the sediments involved and access to them, is the Palaeozoic sequence forming part of the North Greenland geosyncline and part of the foreland of the Caledonian fold belt in the eastern part of North Greenland. The second sequence comprises the Upper Palaeozoic to Tertiary sediments of the Wandel Sea basin in eastern North Greenland. The two sedimentary areas are shown in fig. 401.

Palaeozoic sequence

Dawes (this volume) discusses the sedimentary sequence in the North Greenland geosyncline and the foreland of the Caledonian fold belt. The age span of the sediments is from Proterozoic to Lower Devonian. The oldest Proterozoic sediments within the Thule basin, which is regarded as being a separate basin south of the western part of the geosyncline, are between 1500 and 1200 m.y. old (see Dawes *et al.*, 1973). The oldest sediments in the western part of the geosyncline (Rensselaer Bay Formation in Inglefield Land) are also of this age. In southern Peary Land, which is in the eastern part of the geosyncline, the oldest sediments have been shown to be at least 1000 m.y. old (Henriksen & Jepsen, 1970).

The sequence of unmetamorphosed sediments that underlies the fossiliferous Lower Cambrian sediments comprises throughout much of the area both Proterozoic and Eocambrian beds. The Proterozoic beds were intruded by sills and dykes before the Eocambrian beds were laid down.

The Proterozoic and Eocambrian sediments in the area are thickest east of the Victoria Fjord arch (Dawes & Soper, 1973); in southern Peary Land, the sequence is up to 1200 m thick, the lowest 900 m consisting of feldspathic sandstone and conglomerate, overlain by tillite up to 100 m thick with about 200 m of dolomite at the top of the section. The dolomite may be all or in part of Lower Cambrian age. The sequence on the west side of Hagen Fjord, in the foreland of the Caledonian fold belt, is according to Haller (1971) even thicker, being more than 1750 m thick, and consisting of eroded Proterozoic sandstones overlain by 1000 m of clastic rocks, followed by 400 m of shales, sandstones and limestones, with 350 m of dolomite above.

There has been no evidence so far that this older part of the sedimentary succession in North Greenland has any petroleum potential. Descriptions of the lithologies suggest that whereas the sandstones could constitute potential reservoir rocks the conditions were probably not favourable for source rock formation in this area during deposition. Moreover, the Proterozoic beds have been extensively intruded by sills and dykes. However, it should be borne in mind that indigenous hydrocarbons have been found in rocks as old as these in other parts of the world. In the Amadeus basin of central Australia commercial source rocks were discovered in Proterozoic shales, but the Proterozoic section as a whole had insufficient porosity (Murray, 1965).

The North Greenland geosyncline in which these Palaeozoic beds occur is an eastern continuation of the Franklinian geosyncline of the Canadian Arctic Islands. The youngest beds in the Canadian sequence are Upper Devonian in age. It is now known that the North Greenland sequence extends up into at least the Lower Devonian (Bendix-Almgreen & Peel, 1974; Berry *et al.*, 1974).

The Palaeozoic beds were deposited in an E–W trough that developed along the northern margin of the crystalline shield. Two main sedimentary environments have been recognised, an area of platform sedimentation in the south passing gradually north into an area of unstable trough sedimentation. The area of platform sedimentation is continuous with the area of Lower Palaeozoic sediments forming the foreland of the Caledonian fold belt in eastern North Greenland.

It is believed that unstable trough sedimentation set in during the late Precambrian (Dawes, this volume).

The sections (fig. 402) illustrate the facies changes and changes in structural style from north to south across the area.

A number of basic dykes considered to be of Cretaceous age cut the rocks of the fold belt east of Nares Land and the rocks of the platform sequence east of the Victoria Fjord arch.

Sediment thickness

The total thickness of the Palaeozoic section of the platform sequence is estimated to be at least 3000 m (Dawes, this volume). The sequence is largely a carbonate and shale sequence, but sandstones are present in the lower part. These are thickest in southern Peary Land, where the Cambrian Buen Formation comprises 425 m of sandstone, shale and greywacke, and in the Hagen Fjord – Danmark Fjord basin, where the Kap Holbæk Formation of probable Lower Cambrian age comprises 135 m of sandstone and quartzite; sandstones are also known from the Cambrian section in the Victoria Fjord arch and to the west, in Inglefield Land and in Washington Land.

A reef complex at least 1500 m thick characterises the upper part of the Ordovician and the whole of the Silurian (?and Devonian) section between western Washington Land and western Peary Land. Reef development may have started in the Middle Ordovician (the Gonioceras Bay Formation of Washington Land may be a reef development). In the lower section of the complex the Ordovician and part of the Lower Silurian (Llandoverian) limestones are biostromal limestones with local patch bioherms. These are overlain by Llandoverian and Wenlockian limestones with extensive bioherm sections.

Off-reef shales and siltstones in Nyeboe Land have

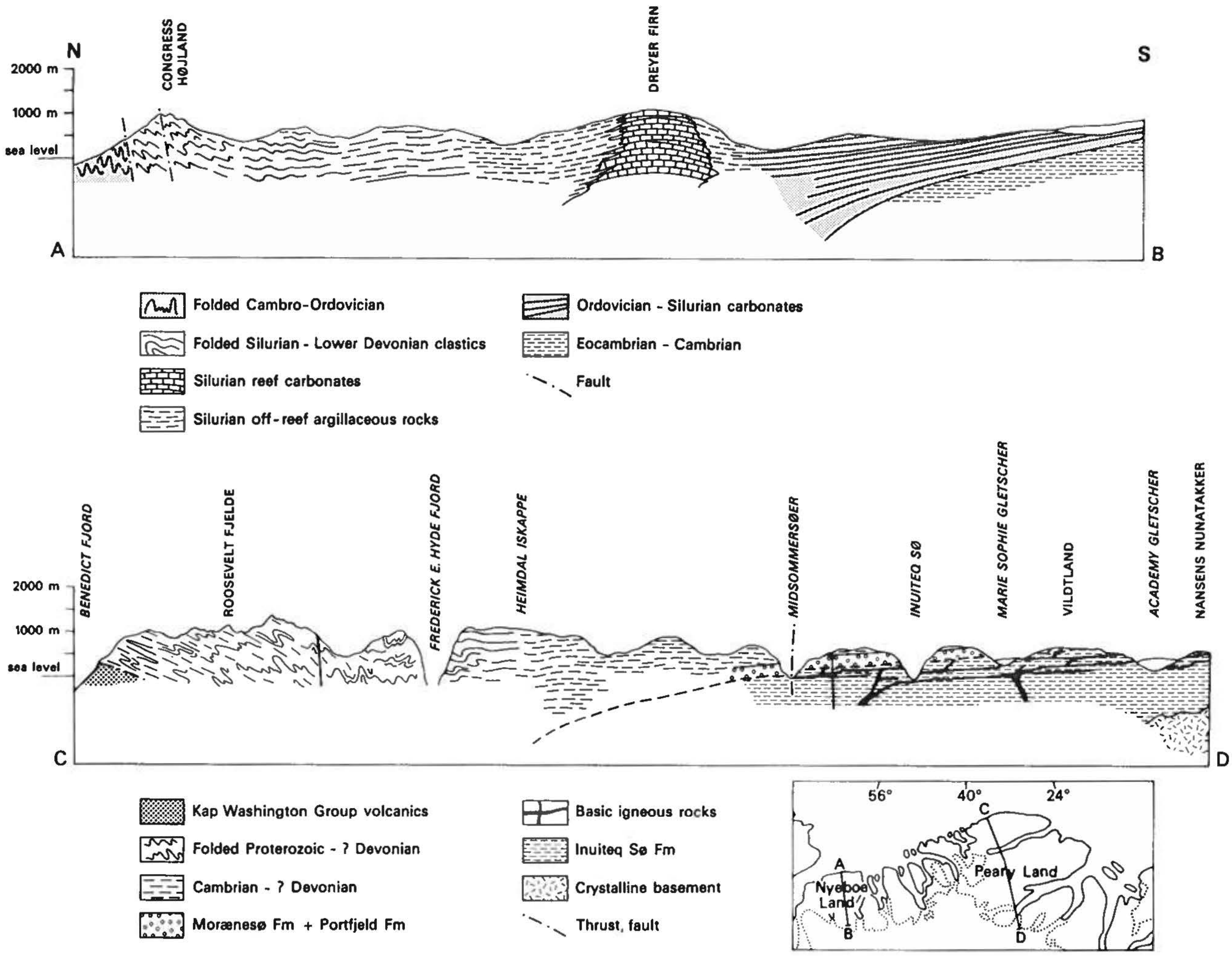


Fig. 402. Diagrammatic north-south cross-sections through the east and west parts of the North Greenland fold belt (Modified from Dawes, 1971).

yielded a fauna of Ludlovian age, which may well be the age of the youngest reefs in the area.

An E–W trending belt of bioherms extends from Washington Land to western Peary Land. One very large bioherm in this belt occurs at Kap Tyson on the west coast of Hall Land. Stratigraphic sections have been measured in detail in this area by Norford (1972), who states that the Kap Tyson bioherm attains a maximum thickness of about 350 m (fig. 403).

Off-reef rocks consisting of argillaceous limestones and graptolitic shales form a fore-reef zone north of the bioherm belt and in places form a back-reef zone.

The reef complex in North Greenland is an eastwards continuation of the Palaeozoic reef complex of the Canadian Arctic Islands (Kerr, 1967; Norford, 1972).

The total thickness of the unstable trough sequence including the Proterozoic sediments is at least 5000 m (Dawes, this volume). The base of the section is not exposed.

The oldest rocks so far recognised in this sequence are found in northern Wulff Land, where there is a section of dolomites, sandstones and conglomerates at least 250 m thick. The basal part of this section is probably Proterozoic, the upper part being regarded as Cambrian in age.

These clastic rocks are overlain by carbonate rocks and Ordovician shales.

The Ordovician – Lower Devonian section of the coast of Hall Land comprises 500 m of dolomite and limestone of which the basal part at least is of Ordovician age overlain by 1000 m of Silurian – Lower Devonian clastic rocks, mainly sandstones, mudstones and shales. Much of the Silurian – Lower Devonian sequence is a turbidite suite indicative of an unstable sedimentary environment.

In northern Peary Land the sections of clastic rocks are thick. In Nansen Land there are over 1000 m of sandstone, greywacke and shale (or slate). In Roosevelt Fjelde the sequence has been divided into three groups of which the uppermost (Sydgletscher

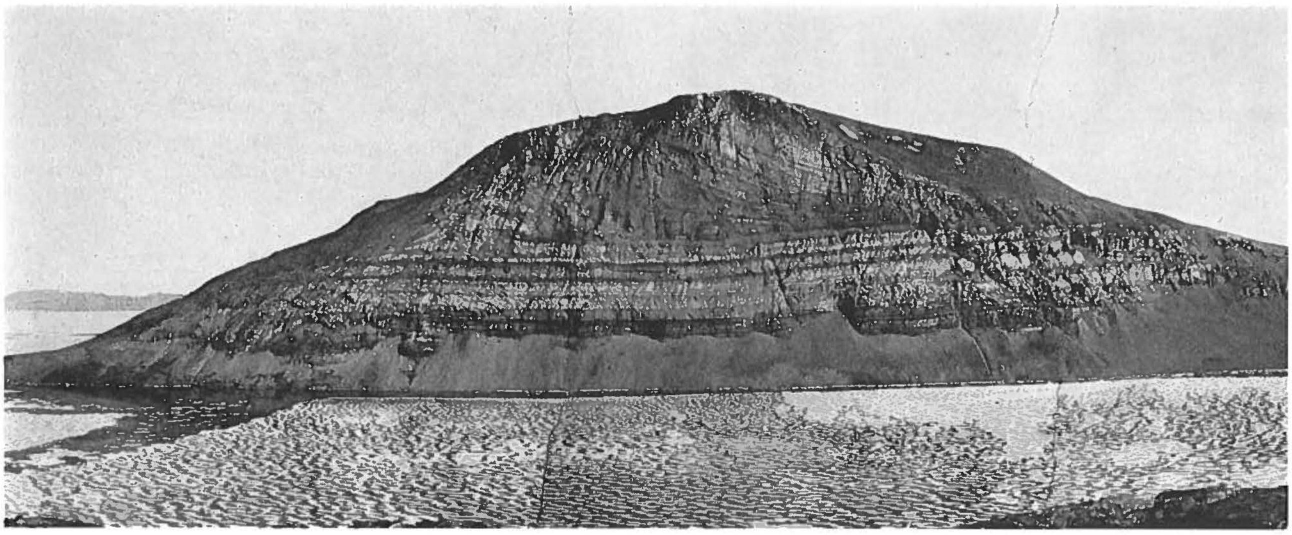


Fig. 403. Kap Tyson (Hall Land) viewed from the south-west. Biohermal limestone with depositional dips rests on flat-bedded biostromal and associated limestones. Offley Island Formation.

Group) comprises over 950 m of sandstones, shales and mudstones.

Source rocks

No publications exist on any systematic sampling of the rocks of the area—either on a regional scale or on a local scale—with a view to establishing their source rock potential. One sample of Silurian fore-reef shale from Hall Land proved to be a commercial source rock (GGU unpublished report).

Norford (1972) has drawn attention to the potential interest of the off-reef rocks in the Kap Schuchert section of Washington Land. Samples collected by him proved to contain significant amounts of organic carbon (Norford, 1972, table 1). Norford also found petroleum residue in vugs in the bioherm at Kap Tyson (1972, p. 22 and table 1).

Indirect evidence of the possible presence of source rocks in pre-Carboniferous rocks in eastern North Greenland was provided by the analyses of three Permo-Carboniferous limestone samples from the rocks of the Wandel Sea basin in the area of Station Nord, Kronprins Christian Land of which one sample contained migrated hydrocarbons. These hydrocarbons may have migrated from the underlying older Palaeozoic rocks or laterally from other Permo-Carboniferous rocks (GGU unpublished report).

Reservoir rocks

As pointed out by Norford (1972, p. 22) subsurface development of the biostromal and biohermal rocks of the Silurian Offley Island Formation would form a potential reservoir for oil and gas. In general the reef limestones of North Greenland could be potential reservoir rocks in this particular environment.

Norford states that porosity is rare in the outcropping limestones of the Cape Schuchert and Offley Island Formations. Vugs filled with sparry calcite are common and if localities exist with vugs free of calcite, porosity would be substantial. Permeability is an unknown factor.

Evidence of hydrocarbon migration

No active oil or gas seeps have been reported in the literature on this area. Amongst the samples from western North Greenland sent for source rock analysis one, a fossiliferous black Silurian limestone from Nyboe Land, proved to contain migrated hydrocarbons (GGU unpublished report).

Traps

The sediments of the platform sequence show monoclinal dips northwards of about 10° (Dawes, this volume). If the fore-reef argillaceous limestones and shales have acted as source rocks for petroleum, stratigraphic traps may have been formed by reef limestones (particularly bioherm limestones) such as those that occur in outcrops between western Washington Land and western Peary Land. Whether such limestones exist at depth within the zone mentioned and whether they extend farther east into Peary Land is not yet known.

Comparison with the Canadian Arctic Islands

Rocks of comparable age to the North Greenland sequence occur along the strike to the west in the Canadian Arctic Islands. Here Fortier *et al.* (1963)

referred to the occurrence of solid hydrocarbons in the Lower Palaeozoic rocks. Sproule (1966, p. 60) gave a generalised columnar section in which bitumen and rocks with petroliferous odour are shown at various levels in the Ordovician–Devonian section. Although recent encouraging finds have resulted in a concentration of interest in the younger Sverdrup basin, numerous wells have been drilled outside the basin (see Thobe, 1973, p. 118). The discovery of oil, although not commercial in amount, in Devonian carbonate rocks on Cameron Island in early 1974 enhances the prospects of these older rocks in general.

Wandel Sea basin

This sedimentary basin, which is of Carboniferous to Tertiary age, is present on land in the north-eastern corner of Greenland, from eastern Peary Land to Holm Land, on the east coast of Kronprins Christian Land. The deposits on land occur in a number of isolated areas, the largest of which, on Kronprins Christian Land, is about 140 km by 90 km, including permanent ice cover and some Caledonian crystalline inliers.

An aeromagnetic profile flown by the U.S. Air Force offshore suggests a continuation of the basin below the continental shelf.

The composite section probably exceeds 2500 m, the rocks being mainly marine, but with non-marine beds at the base.

The oldest rocks outcrop on Holm Land, and comprise at least 200 m, possibly over 500 m, of non-marine sandstones and sandy shales with coal seams and a fossil flora similar to the Lower Carboniferous flora of Spitzbergen. They have been termed the Terrestrial Group, and are succeeded by the Lower Marine Group, a 500–600 m sequence starting with a basal conglomerate overlain by alternating limestones and sandstones with some marl and shale and containing, in Holm Land, a 150 m thick conglomerate in its upper part. This group is probably of Lower Carboniferous age.

The Upper Marine Group, which rests disconformably on the Lower Marine Group, is probably Lower Permian in age, and consists of alternating limestone and dolomite with some siliceous rocks.

The Peary Land sequence contains a Triassic section at least 630 m thick, consisting of sandy shales and sandstones overlain by medium and coarse-grained sandstones with some shale layers.

The youngest beds are Cretaceous–Tertiary in age, and outcrop in eastern Peary Land and on the north coast of Kronprins Christian Land, in which area they comprise 300 m of sandstone.

The beds have been affected by large to medium-scale open symmetrical folds with NNW-trending axes and by faulting.

Although the onshore outcrops of sediments of the Wandel Sea basin are isolated and individually limited in area there is a substantial thickness of sediments, and these are largely marine. From the descriptions of the lithologies it would seem that there are good possibilities for porous sandstone reservoirs and for structural traps. Nothing is known about source rock potential here, but as mentioned earlier one sample of Permo–Carboniferous limestone contained migrated hydrocarbons.

Were it not for the presence of year-round pack ice offshore, the continuation of the sedimentary area out to sea would be of interest. As it is, the limited sedimentary areas onshore must be regarded as of marginal economic interest only, but should not be completely neglected.

East Greenland

Upper Palaeozoic – Mesozoic sediments of the onshore area

In central East Greenland, after the main phase of the Caledonian orogeny, sequences of over 12 000 m of Devonian to Lower Permian molasse sediments were deposited in intermontane basins (Henriksen & Higgins, this volume). These are mainly continental clastic deposits, but the Devonian part of the sequence contains some volcanic material as lava flows and tuffs. These sediments are not considered prospective for petroleum.

The Upper Permian marks the start of a long period of predominantly marine sedimentation in East Greenland. Sediments of Upper Permian – Cretaceous age occupy an elongated area along the coast of East and North-East Greenland between Scoresby Sund and Germania Land, a distance of 800 km (fig. 404). The sedimentary area is widest in the south, being about 140 km wide in Jameson Land, and tapers gradually northwards (Birkelund & Perch-Nielsen, this volume).

South of Scoresby Sund the place of the sediments is taken up by Tertiary basalts. Magnetic surveys have located the boundary of the sediments with the basalts below Scoresby Sund, just south of the coast of Jameson Land, and it is considered likely that the Jameson Land sediments continue at least for some distance south under the basalt cover (Bidstrup, 1972).

Outcrops of sediments of Cretaceous and possibly

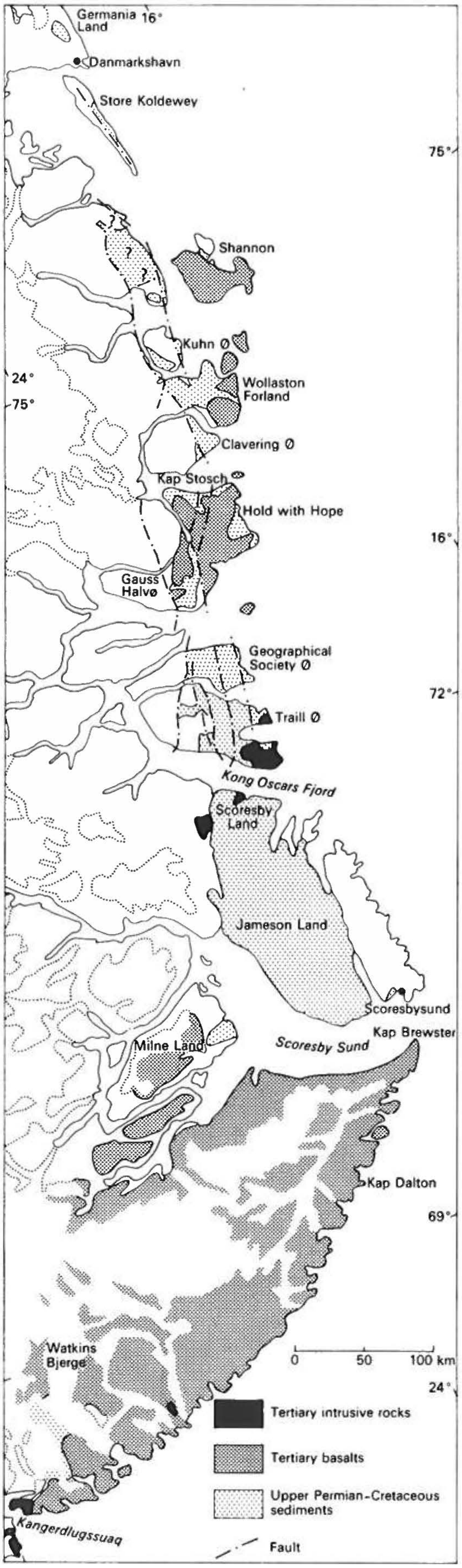


Fig. 404. Map showing the distribution of Upper Permian – Cretaceous sediments and Tertiary igneous rocks in East Greenland.

Tertiary age occur north-east of Kangerdlugssuaq fjord, well south of the main sedimentary area (fig. 404).

In addition, there are small outcrops of Tertiary sediments at Kap Brewster and Kap Dalton, south of Scoresby Sund.

Sediment thickness

The oldest rocks of the basin are marine Upper Permian rocks of the Foldvik Creek Formation, which lie unconformably on older Palaeozoic and Caledonian crystalline rocks, and attain a maximum thickness of 300 m (Maync, 1961; Perch-Nielsen *et al.*, 1972; Birkelund & Perch-Nielsen, this volume). From Gauss Halvø northwards Maync distinguished seven members of the Foldvik Creek Formation. A basal conglomerate is sporadically developed, and can exceed 100 m in places while the overlying sediments are mainly carbonates with some shales. Gypsum is present in places at or near the base of the formation. In Wollaston Forland the formation contains red beds, including calcareous and arkosic sandstones and conglomerates. The succession is illustrated in fig. 405.

Maync's classification can be used south of Gauss Halvø with certain reservations, the main difference being the presence in the upper part of the formation of brown arkosic sandstones, which are not red beds (Perch-Nielsen *et al.*, 1972, p.47).

The most extensive areas of Triassic sediments are those of Scoresby Land and Jameson Land. Perch-Nielsen *et al.* (1974) have termed the beds the Scoresby Land Group, with a total thickness of 1000 to 1500 m, of which less than half is composed of marine sediments. Four formations are recognised. In some areas the lowest beds of the group rest paraconformably on the Permian beds; in other areas the boundary is transitional.

The lowest formation, the Wordie Creek Formation, which ranges in thickness from 70 m to 350 m, consists mainly of marine shales with subordinate glauconitic or arkosic sandstones. This is overlain by a formation, the Pingo Dal Formation, which is dominated by sandstones, arkoses and arkosic conglomerates and is about 700 m thick in Scoresby Land. Marine fossils are only known from the lowermost part of the formation. These sandstones and conglomerates are overlain mainly by gypsum-bearing silty shales with arkose and sandstone intercalations, the Gipsdalen Formation; gypsum-cemented arkoses

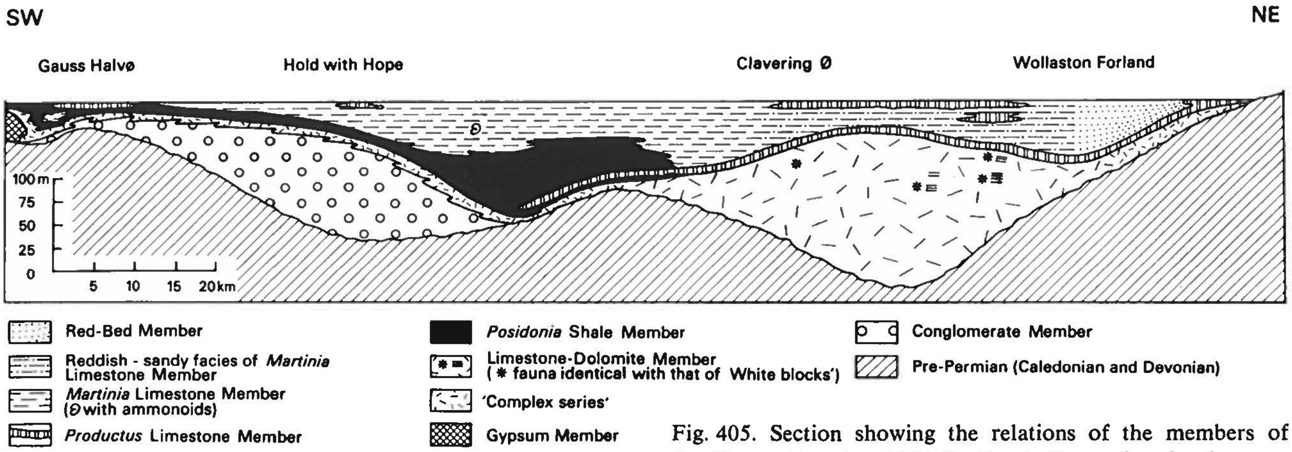


Fig. 405. Section showing the relations of the members of the Upper Permian Foldvik Creek Formation in the area between Gauss Halvø and Wollaston Forland.

with siltstones are a facies variant. Bands of limestone, and black, marly sometimes bituminous shales ('*Myalina* limestones', cf. Grasmück & Trümpy, 1969) form marker horizons. The formation is up to 225 m thick, but is not present throughout the area. The highest formation, the Fleming Fjord Formation, comprises mainly siltstones, sandstones, oolitic and algal limestones in the lower part, siltstones, mudstones and sandstones in the middle part, and sandstones, arkoses and dolomite in the upper part, with a thickness that ranges from 50 m to more than 420 m.

Farther north, the Triassic beds on the southern coast of Traill Ø are nearly 1000 m thick (Trümpy, 1961). Triassic beds are also present on Geographical Society Ø, Gauss Halvø, Hold with Hope and Clavering Ø. The section at Kap Stosch, on the northern end of Hold with Hope, comprises 500 to 700 m of mainly shales and sandstones belonging to the Wordie Creek Formation.

Conformably overlying the Triassic Scoresby Land Group in Scoresby Land and Jameson Land is a thick sedimentary sequence ranging in age from Upper Triassic (Rhaetian) to Lower Cretaceous. The sequence has been divided into seven formations, six of which span the interval from the Upper Triassic (Rhaetian) to the Upper Jurassic (Volgian) and are termed collectively the Jameson Land Group, while the seventh is of Lower Cretaceous (Ryazanian) age.

The sediments of the Jameson Land Group cover large areas on Scoresby Land and Jameson Land. The thickness in the type area ranges from 1100 to 2400 m. Sediments of the same age and facies are found on Milne Land to the west, and northwards as far as Store Koldewey (76°–77° N).

The sediments of the group commence with fluviatile arkoses, shales and coals of Rhaetian–Liassic age belonging to the Kap Stewart Formation. Sections measured show a range from 180 to 350 m in thickness. These are followed by alternating thick sequences of marine sandstones and shales belonging to the following formations (from below): Neill Klinter Formation, Vardekløft Formation, Olympen Formation, Hareelv Formation and Raukelv Formation (Surlyk *et al.*, 1973).

The Lower Cretaceous Hesteelv Formation, which ranges in thickness from 10 to 120 m, has been deposited in a small synclinal trough and rests with angular unconformity on older sediments at the margins of this trough. The formation comprises shales overlain by a shell conglomerate, with coarse sandstones at the top.

Although the youngest beds preserved in Jameson Land and Scoresby Land are of Ryazanian age, younger Cretaceous beds occur on the islands and peninsulas to the north as far as Store Koldewey. Not all stages are represented. The youngest beds are glauconitic, sandy shales or argillaceous sandstones of Upper Campanian age on Traill Ø and Geographical Society Ø (Donovan, 1961).

The sediments of the Kangerdlugssuaq area to the south (68° 30′ N) consist of about 180 m of sandstone with some sandy shales, and conglomerate. They are shallow water and estuarine beds of probable Senonian – Lower Tertiary age (Wager, 1947).

Some 40 m of Tertiary beds conformably overlying Tertiary basalt are present in a down-faulted block in Tertiary basalts at Kap Dalton. They consist of sandstones, shales and tuffs with a marine fauna, which Ravn (1933) assigned to the Eocene but which Hassan (1953) considered to range from Eocene to Oligocene.

Marine Tertiary beds present at Kap Brewster comprise about 130 m of mainly sandstones with some marls, and a basal conglomerate separated from the underlying Tertiary basalts by a fossil soil horizon. They contain a fauna ranging in age from Eocene to Oligocene and have been termed the Kap Dalton Formation. A separate sedimentary sequence of probable Miocene age termed the Kap Brewster Formation is 76 m thick and commences with a basal sedimentary breccia or conglomerate, which is overlain by sandstones and coarser clastics, the beds resting directly on basalt (Hassan, 1953; Birkenmajer, 1972).

While these two small areas of Tertiary sediments have no importance for the onshore area they are taken as being only part of a much larger sedimentary area below the continental shelf.

The sediments in the southern part of Jameson Land and those of Scoresby Land and areas further north are intruded by numerous Tertiary dykes and sills.

Source rocks

Thirty-two samples from the Upper Permian – Lower Cretaceous sequence of the Scoresby Sund area have been analysed as potential source rocks. Four samples were found to qualify as commercial source rocks (Perch-Nielsen *et al.*, 1972, p. 58; GGU unpublished reports). The four samples came from the following levels:

(1) The *Posidonia* Shale Member of the Upper Permian Foldvik Creek Formation,
(2) *Myalina* limestone within the Middle Triassic Gipsdalen Formation,
(3) The boundary between the Hareelv and Raukelv Formations and from the Raukelv Formation. Both formations are Upper Jurassic in age.

In addition, one sample from the *Posidonia* Shale Member of the Foldvik Creek Formation showed the chemical characteristics of an oil shale but the lithology was not that of a typical oil shale.

The source rocks discovered so far have all been collected in areas close to the margin of the basin. The presence of source rocks of this quality at a short distance from the basin rim would suggest that source rocks of even better quality would be present offshore and that their thickness would be greater.

Source rocks of Kimmeridgian age are of no interest for the onshore area since the Kimmeridgian beds are high in the outcrop sequence. The upper Permian and Middle Triassic source rocks can be important here.

R. Trümpy (personal communication) has drawn attention to the basal members of the Triassic Wordie Creek Formation as being possible source rocks. In some places, notably on Traill Ø, these rocks are highly bituminous.

Reservoir rocks

No account has yet been published of any systematic studies of the potential reservoir rocks of the basin. Some visual porosity analyses undertaken on samples from various formations in Jameson Land and Scoresby Land showed the presence of porous sandstones in the Triassic and Jurassic sequences (GGU unpublished reports).

Sandstones form a substantial part of the total Mesozoic sequence in East Greenland and should constitute potential reservoir rocks.

Evidence of hydrocarbon migration

One sample collected from *Myalina* limestone of the Triassic Gipsdalen Formation proved to contain migrated hydrocarbons (GGU unpublished reports).

Features very similar to the mud volcanoes of West Greenland are present in East Greenland and were termed 'dyndvulkaner' (mud volcanoes) by Noe-Nygaard & Rosenkrantz (1950). Rosenkrantz considers (personal communication) that the chemical composition of the waters of some of these suggests that methane-rich gas was formerly emitted at these localities.

Traps

The Upper Permian – Cretaceous sediments of East Greenland have not been affected by any compressional folding. Although evaporites are present in the Upper Permian and Triassic sequences these are restricted to anhydrite, gypsum and gypsiferous marls and shales. Moulds and casts of halite crystals have been found (fig. 406) but the process of evaporation has not resulted in the formation of any substantial amounts of halite or of potassium salts (Birkelund & Perch-Nielsen, this volume). No structures of the type associated with salt tectonics have been found onshore, not even in the centre of the Jameson Land – Scoresby Land area. This could suggest that salt is not present in any substantial amount away from the basin rim in this particular area. Salt could be present farther offshore.

Anticlinal traps cannot therefore be expected in the onshore area since the structures affecting these sediments reflect tensional conditions. The sediments are least disturbed in Jameson Land, where the structure is that of a broad syncline with southwards-plunging axis (Surlyk *et al.*, 1973, plates 10 and 11).

In Scoresby Land the sediments are cut by numerous N–S faults and the extension of the basin farther north is affected by numerous faults, mainly

NNE-trending, well illustrated on Traill Ø (Putallaz, 1961, plate 4).

Two types of traps can be expected. Stratigraphic traps could be present, for example on the flanks of the Jameson Land syncline. Fault traps could also be present in the area from Scoresby Land northwards.

East Greenland continental shelf

In relation to the very large area involved very little work has so far been undertaken on the East Greenland shelf and the rocks underlying it.

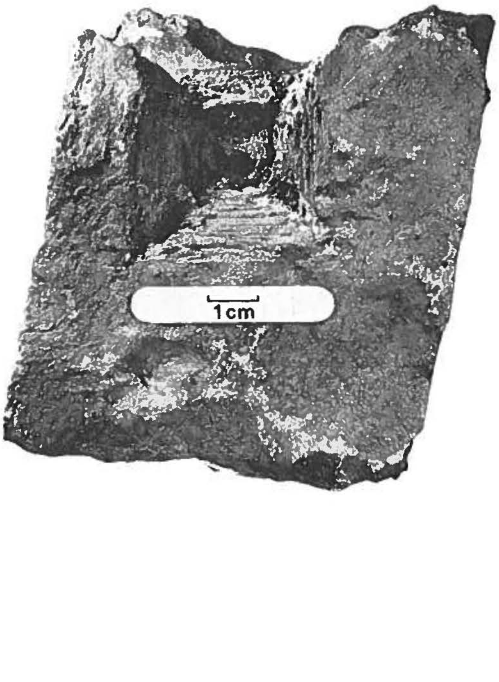
Over the years a number of aeromagnetic lines have been flown over Greenland and its continental margins (fig. 407). Marine seismic data in the northern part of the East Greenland shelf are restricted to a single line of sub-bottom profiling undertaken from a drifting ice island (Ostenso & Pew, 1968).

During the last few years work has been done by the U.S. Naval Oceanographic Office in waters east of Greenland. This work included seismic and magnetic profiling, and bottom sampling. Most of this work has been done in deep water, but Vogt (1970) reported the presence of magnetised basement outcrops on the south-eastern Greenland shelf.

Examination of aeromagnetic profiles indicates the presence of two large elongate sedimentary areas below the East Greenland shelf (fig. 407).

The first of these is situated between 72° and 81°N with its long axis trending NNE–SSW parallel to the coast. The depth to magnetic basement is 10 km in the centre of the area. There are indications of volcanic rocks or minor intrusions in the section. This area seems to be an offshore continuation of the sedimentary area on land. The sediments on land

Fig. 406. Mould of halite crystal in siltstone of the Triassic Kap Seaforth Member, near Solfaldsdal. GGU 112276.



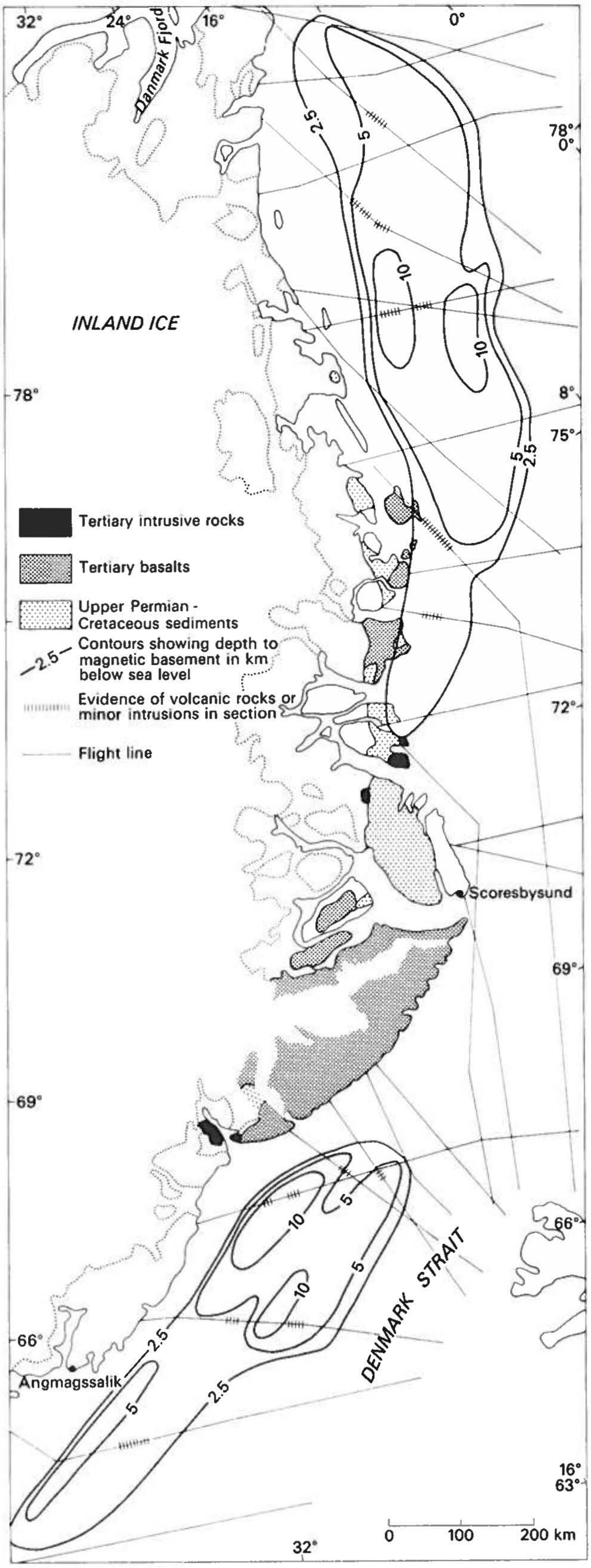


Fig. 407. Map showing the probable extent of major sedimentary occurrences below the East Greenland continental shelf, based on aeromagnetic surveys flown by the Dominion Observatory (Hannaford & Haines, 1969), the U. S. Air Force and the U. S. Navy. Interpretation by L. R. Denham.

contain numerous sills, so the presence of minor intrusions offshore would not be surprising.

The second area is situated between 63° and 68°N with its axis trending NE–SW parallel to the coast. The depth to magnetic basement is 10 km in the centre of the area and here also there are indications of volcanic rocks or minor intrusions in the section. This area is not obviously connected to the onshore sediments, but detailed work closer inshore may reveal a closer relation than is suggested by this first, very preliminary interpretation.

Moreover it should be noted that owing to the uncertainty of the interpretation the first depth contour shown is the 2.5 km contour. Sections of sediment thinner than 2.5 km may well be present closer to the coast. Furthermore, the magnetic basement immediately north of 68°N may well be Tertiary basalts, in which case there could be substantial amounts of sediments below the basalts.

Source rock analysis of samples collected on land has shown the presence of source rocks at three levels, Upper Permian, Middle Triassic and Upper Jurassic. The presence of source rocks close to the margin of the depositional area is encouraging. The quality of the source rocks may be expected to be better offshore and their thickness should be greater. Porous sandstones may be expected to constitute potential reservoir rocks.

The Upper Permian and Triassic sections on land contain evaporite beds with gypsum. Although salt is not present in quantity in the onshore area it is possible that salt is more abundant offshore. Both the Upper Permian (Zechstein) and Upper Triassic (Keuper) in the North Sea area are known to contain salt. The presence of salt would have important tectonic implications.

In pre-drift reconstructions of the North Atlantic region as it was 65 m.y. ago (e. g. Bott & Watts, *in* Bott, 1973) central East Greenland is shown close to the Shetland Islands and to south-western Norway. Thus the Upper Permian to Cretaceous sediments of onshore central East Greenland would have accumulated before the separation took place and hence in the same depositional basin as that in which sediments of comparable age were deposited in the northern part of the North Sea. Dunn *et al.* (1973) have stated that Jurassic shales are probably the source rocks for oil discoveries in the southern North Sea and for oil shows in the central North Sea area. These accumulations occur in rather localised mid-Jurassic sand reservoirs. The implications of pre-drift reconstructions for the petroleum potential of the East Greenland shelf are obvious in the light of recent years' developments in the North Sea.

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