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Oil and gas prospects in the Cretaceous-Tertiary basin of West Greenland

by

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OIL AND GAS PROSPECTS IN THE CRETACEOUS-TERTIARY BASIN OF WEST GREENLAND

by

G. Henderson

with Appendix

by

N. B. H. Stevens

With 9 figures and 3 tables

1969

Abstract

The West Greenland basin contains marine and non-marine sediments ranging in age from Lower Cretaceous (Barremian-Aptian) to Paleocene (Upper Danian). The marine sediments are at least 1500 m thick in parts of Nûgssuaq and may reach 2000 m; the non-marine sediments attain a thickness of 1500 m in Nûgssuaq and Disko. Sediments older than those exposed may be present at depth. In a considerable part of the area the sediments are overlain by Tertiary basalts, which locally attain a thickness of about 8 km. The basin is fault-bounded and its coastline was probably largely fault-determined from the onset of sedimentation.

Sandstone and shale are the main sedimentary types, and bituminous shales are an important part of the succession. Recent chemical analyses have shown that the bituminous shales include true source rocks; additional evidence in support of the existence of source rocks in the basin is provided by the presence of migrated hydrocarbons in sandstone close to a fault and by the presence of bitumen amongst the fluids brought to the surface in a mud volcano. The sandstones are regarded as good potential reservoir rocks, and there are good possibilities for the presence of structural and stratigraphic traps at depth. The first indications are encouraging and invite further exploration for oil and gas.

CONTENTS

PART I: REGIONAL DESCRIPTION

INTRODUCTION 5

REGIONAL SETTING 7

STRATIGRAPHY 11

Marine sediments 12

Svartenhuk 12

Nûgssuaq - north coast 12

Central Nûgssuaq 16

Nûgssuaq - south coast 18

Non-marine sediments 19

Svartenhuk 20

Qeqertarssuaq 20

Upernivik Ø 20

Nûgssuaq and Disko 21

Grønne Ejland 21

STRUCTURE 22

PHENOMENA ASSOCIATED WITH THE BASIN 26

Burnt shales 26

Mud volcanoes 29

PART II: ECONOMIC APPRAISAL

INTRODUCTION 38

SOURCE ROCKS 39

RESERVOIR ROCKS 42

EVIDENCE OF MIGRATION OF FLUIDS 43

TRAPS 45

Structural traps 45
Stratigraphic traps 46

POINTS OF IMPORTANCE TO FURTHER EXPLORATION 46
Cover rocks 47
Thickness of the sediments 48
Areas of interest onshore 49
Offshore area 49
Access 49
Acknowledgements 52

APPENDIX

RESULTS OF THE OIL SOURCE ROCK ANALYSIS OF SURFACE SAMPLES FROM WEST GREENLAND (by N. B. H. Stevens) 53

References 60

PART I

REGIONAL DESCRIPTION

INTRODUCTION

In recent years the search for oil and gas has spread to parts of the world where previously, because of problems of access and supply, or the sheer cost of working in such areas, little exploration had been carried out. However, a number of factors have stimulated exploration outside the traditional oil and gas areas, and this exploration has been facilitated by the development of new techniques and types of equipment.

Until not long ago the Arctic regions, with their special climatic problems, were regarded as being economically unattractive from the point of view of exploration for oil and gas; not only would exploration in the Arctic be difficult and very expensive, but there would be special difficulties involved in transporting oil or gas from the Arctic to the world market. Nevertheless demand for new reserves has been so great that these factors have not deterred oil companies and governments from directing their attentions to this part of the world. As a result there is very considerable activity in the Arctic areas today.

A glance at some of the oil journals of the past few years makes it clear how extensive these activities are. A summary of exploration work in the Arctic in 1963 is to be found in the November 1963 issue of "World Oil" (pp. 95-106). This shows exploration activity in the Canadian Arctic Islands, northern Alaska, northern USSR and the Svalbard group of islands. It can be noted that prolific oil occurrences have recently been proved in northern Alaska. Of particular interest in discussing prospects for western Greenland is the work being done in the Canadian Arctic Islands, and in the January 29, 1968 issue of "The Oil and Gas Journal" (pp. 156-161) a new exploration programme for this area is described. This is a joint project involving a number of private companies and the Canadian Government (which holds 45 per cent of the equity capital), and the amount planned to be spent in the next three years ($20 m) gives an indication of the costs of exploration in such remote terrain with its unfavourable climate.

With all this attention being focussed on the Arctic regions it was only to be expected that Greenland should come under consideration, and especially since 1957 there has been increasing interest in the prospects of finding commercial quantities of oil and gas in Greenland (see article in "Petroleum Press Service", January 1969). Companies have not only been interested in the known onshore sedimentary occurrences but also in the shelf areas, including the shelf west of the southern half of Greenland, where no sediments of post-Precambrian age other than Quaternary sediments have been shown to be present. Apart from a very small occurrence of Lower Palaeozoic rocks near Sukkertoppen (Poulsen, 1966), which shows that there has been Palaeozoic marine sedimentation in the area, the rocks comprising the coastal belt west of the Inland Ice are all of Precambrian age. However, the occurrence does suggest the possibility of marine Lower Palaeozoic rocks being present in the offshore area. The location of Sukkertoppen can be seen in fig. 9.

Interest in the possibilities of finding oil and gas in commercial quantities in Greenland stems from many years back. The presence in the Nûgssuaq peninsula of thick sections of bituminous shale and of mud volcanoes producing gas was mentioned during a lecture given by Professor A. Rosenkrantz, University of Copenhagen, to Det Grønlandske Selskab in February 1939. In the course of the lecture he also mentioned the widespread occurrence of burnt shales along the coast of the peninsula. This lecture aroused a lively discussion at the time (see article in "Fyns Socialdemokrat", February 18, 1939 and Rosenkrantz, 1962).

In 1951 a Danish civil engineer, whose interest had been aroused by reports of oil occurrences in Nûgssuaq, visited the area; one of the objects on his visit was to make a technical appraisal with a view to eventual exploration. An account of his visit is to be found in Mikkelsen (1954).

However, it was not until 1957 that the first representatives from a commercial firm visited the area. In 1957, 1958 and 1965 representatives from a Danish shipping company visited Nûgssuaq. In 1966 two field parties representing oil companies visited Nûgssuaq and Disko. None of this work was followed up by geophysical surveys or drilling.

In early 1968 the Geological Survey of Greenland decided to collect samples for source-rock analysis as part of an evaluation of the oil and gas potentialities of this region. The writer had been engaged on a photo-geological interpretation of Nûgssuaq and Disko in connection with the compilation of the 1 : 100 000 sheets 70 V. 1 N Agatdal and 70 V. 1 S Qutdligssat, and during the summer of 1968 he had the opportunity of visiting the area in the company of a group of geologists led by Professor Rosenkrantz. During the summer twenty-three samples were collected for source-rock analysis, twenty-two from Nûgssuaq and one from Disko. The report that follows gives the results of the analyses; in assessing the potentialities of the area as a whole the writer has drawn freely on the results from numerous expeditions to this part of Greenland under the leadership of Professor Rosenkrantz.

A summary account of the main features of this paper is given by Henderson and Stevens (1969).

REGIONAL SETTING

The distribution of Cretaceous-Tertiary rocks in West Greenland is shown in fig. 1. The rocks occur in the area between Svartenhuk peninsula in the north and the Grønne Ejland group of islands (east of Egedesminde) in the south. In this area a thick sequence of sediments of marine and non-marine origin was laid down between the Lower Cretaceous and the Danian (lowermost Paleocene). During the Danian the area came under the influence of the Tertiary volcanism of the Brito-Arctic province; tuff layers are found intercalated in Danian sediments and the sediments are overlain by volcanic rocks. The lowest of these volcanic rocks are pillow breccias laid down under water. The pillow breccias are overlain by a thick pile of subaerial basalts. In some areas pillow breccia recurs in the lower part of the subaerial lava sequence, thus indicating that the deposition of the lowermost subaerial lavas was accompanied by subsidence. Dykes and sills occur in the sediments and the lavas, but their distribution varies very much from one area to another.

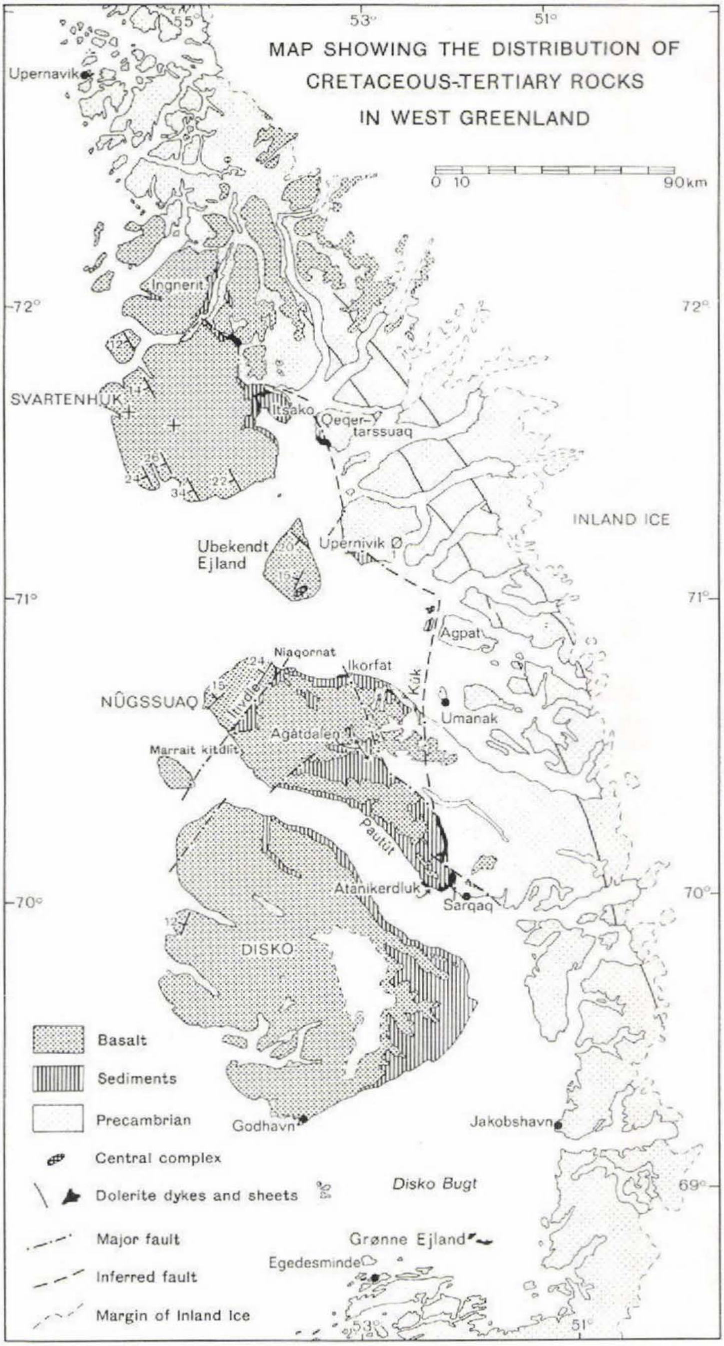

Fig. 1. (After Rosenkrantz and Pulvertaft, in press.)

The stratigraphy and structure of the Cretaceous-Tertiary rocks of West Greenland are described by Rosenkrantz and Pulvertaft (in press), and a summary of the main features is given in the following two sections of this paper. In order to understand the regional setting for the sediments of this area it is necessary to take North America into consideration as well.

The nearest sediments of comparable age on the Canadian side of Baffin Bay are to be found in the area north-west of Cape Dyer on the east coast of Baffin Island. In this area some 500 ft of non-marine sandstones, shales and conglomerates containing plant remains of probable Paleocene age are overlain by pillow breccias and picritic lavas (Wilson and Clarke, 1965; Clarke, 1965). The section in this area is very similar to what is seen in West Greenland, but there are also marine sediments and sediments of Cretaceous age as well as Paleocene age in West Greenland.

The Sverdrup Basin in the northern part of the Canadian Arctic Archipelago contains a thick sequence of rocks ranging in age from Carboniferous (Middle Pennsylvanian) to early Tertiary (Thorsteinsson and Tozer, 1960, pp. 11-14; Fortier et al., 1963, pp. 23-25). According to Fortier (loc. cit., p. 23), "The Mesozoic sequence, extending from the Lower Triassic to the Upper Cretaceous, is composed mainly of sandstone and shale, and represents an alternation between marine and non-marine conditions . . . . . Upper Cretaceous marine beds are overlain by substantial non-marine deposits that are certainly in part Tertiary in age, but which may also be in part Upper Cretaceous". There was volcanic activity in this area during the Cretaceous.

It is known that there was a marine connection between the West Greenland basin and central North America via the Canadian Arctic Islands during the period from the Upper Turonian to the Maastrichtian (Birkelund, 1965, pp. 169-170; Rosenkrantz and Pulvertaft, in press); it is probable that there was also a marine connection with Europe during the period from the Coniacian to the Maastrichtian (Birkelund, loc. cit.). During the Danian, a direct marine connection existed between West Greenland and Europe, but evidence suggesting any connection with North America is weak (Rosenkrantz and Pulvertaft, loc.cit.). The map in fig. 2 shows the boundaries of the Upper Cretaceous Sea in North America and Greenland.

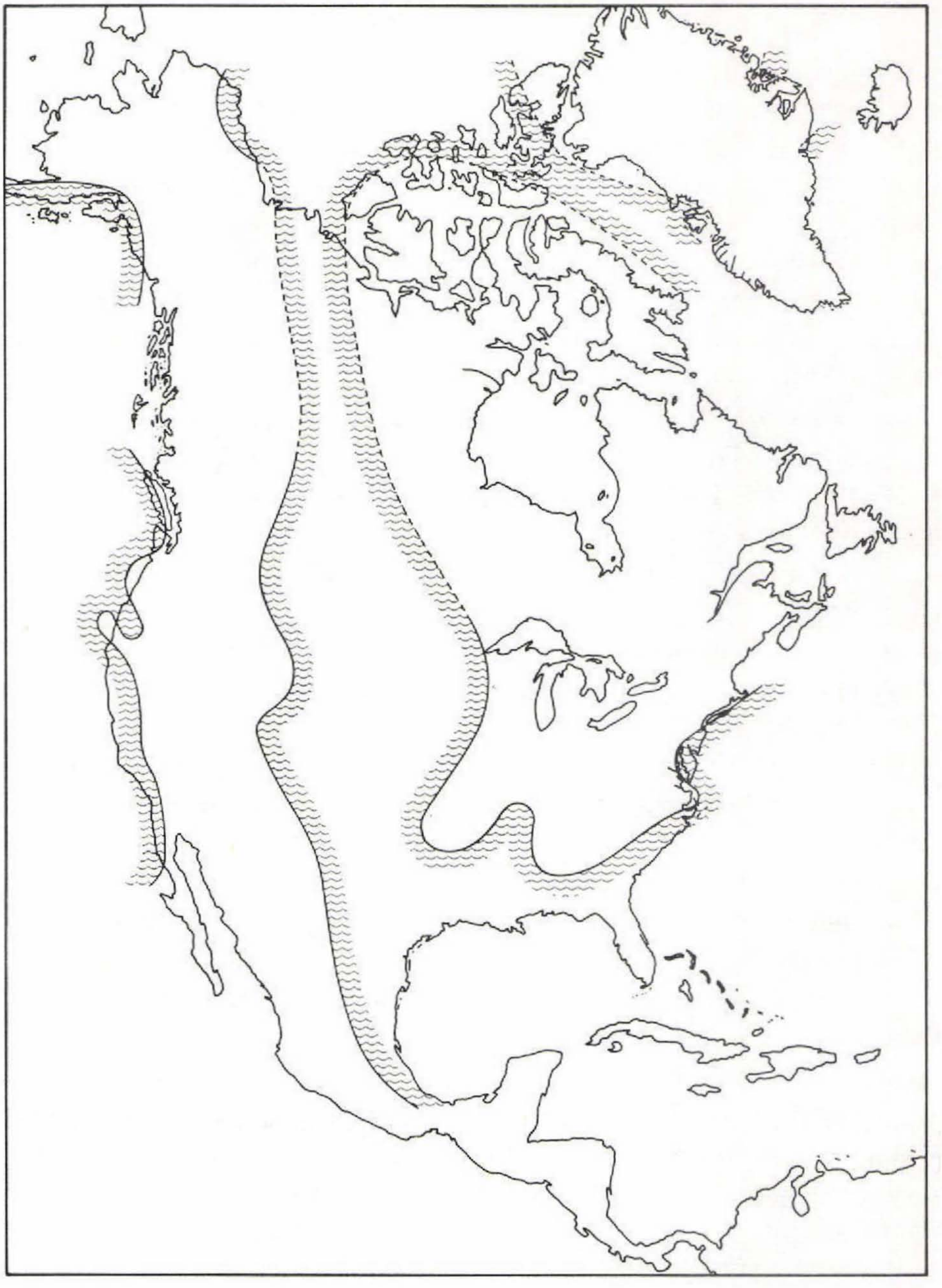

Fig. 2. Palaeogeographical map of North America and Greenland showing the boundaries of the Upper Cretaceous sea. (After Birkelund, 1965 and Gill and Cobban, 1966.)

The fact that there was a direct marine connection between the Sverdrup Basin and the West Greenland sedimentary basin during at least part of the period of sedimentation makes it relevant to take the Sverdrup Basin into consideration when discussing West Greenland. One significant pointer to be obtained from such a comparison is a suggestion of what rocks could be expected below the Cretaceous sediments in West Greenland away from the margin of the basin where the Cretaceous-Tertiary rocks rest directly on Precambrian rocks. As to the oil and gas prospects in the Sverdrup Basin, in a recent article in "The Oil and Gas Journal" (January 29, 1968, pp. 156-161) the Mesozoic and younger sediments in this basin are shown as being of potential interest for hydrocarbon accumulation. The map of the Arctic Islands (loc. cit., p. 158), shows occurrences of solid bitumen in the basin and the article mentions (p. 161) prospects for hidden oil reservoirs in the form of hidden bar and beach sand deposits.

However, although regional considerations serve to focus attention on the West Greenland basin, sufficient evidence is now available to discuss the basin on its own merits.

STRATIGRAPHY

A brief summary of the main features of the stratigraphy of the sedimentary sequence will be given in this section. Additional details on the sequence as a whole can be found in Rosenkrantz and Pulvertaft (in press); a review of the non-marine sediments can be found in B. E. Koch (1964).

Marine sediments

Marine sediments of Cretaceous age are found in Svartenhuk and substantial thicknesses of marine sediment of Cretaceous and Tertiary age are developed in north, central and south Nûgssuaq. The limits of the marine transgressions are shown in fig. 3. The various stratigraphic sections given in fig. 4 will help to give an impression of the development of both marine and non-marine sediments in Nûgssuaq.

Svartenhuk

In the Umîvik area west of Itsako marine Cretaceous rocks consisting mainly of dark, bituminous shales with subordinate sandstone bands and lenses form a sequence up to about 400 m thick underlying the Tertiary basalts. The sediments range from Upper Turonian to Lower Senonian and thus include the oldest marine sediments in West Greenland. North-west of Umîvik, in the area known as Simiútap kûa, there is a continuation of this marine sediment belt, and the beds here have yielded Upper Cretaceous belemnites (Birkelund, 1956, pp. 13-14). Although the non-marine sediments of Svartenhuk rest on Precambrian rocks, no base has been seen to the marine sediments, so the thickness given (400 m) is a minimum figure.

Nûgssuaq - north coast

Marine sediments are exposed along much of the coast section from Tuperssuartâ (west of the valley Itivdle) to Ikorfat in the east. Immediately east of Ikorfat a thinner sequence of marine Senonian and Danian beds is present above the non-marine Cretaceous beds and below the Tertiary basalts. It was only recently that Lower Danian beds were identified east of Ikorfat (A. Rosenkrantz, personal communication) and their discovery here has necessitated modification of the map by Rosenkrantz and Pulvertaft showing the limits of the marine transgressions (see fig. 3).

At Tuperssuartâ dark, bituminous shales with minor sandstone bands form a sequence about 300 m thick dipping westwards towards, and

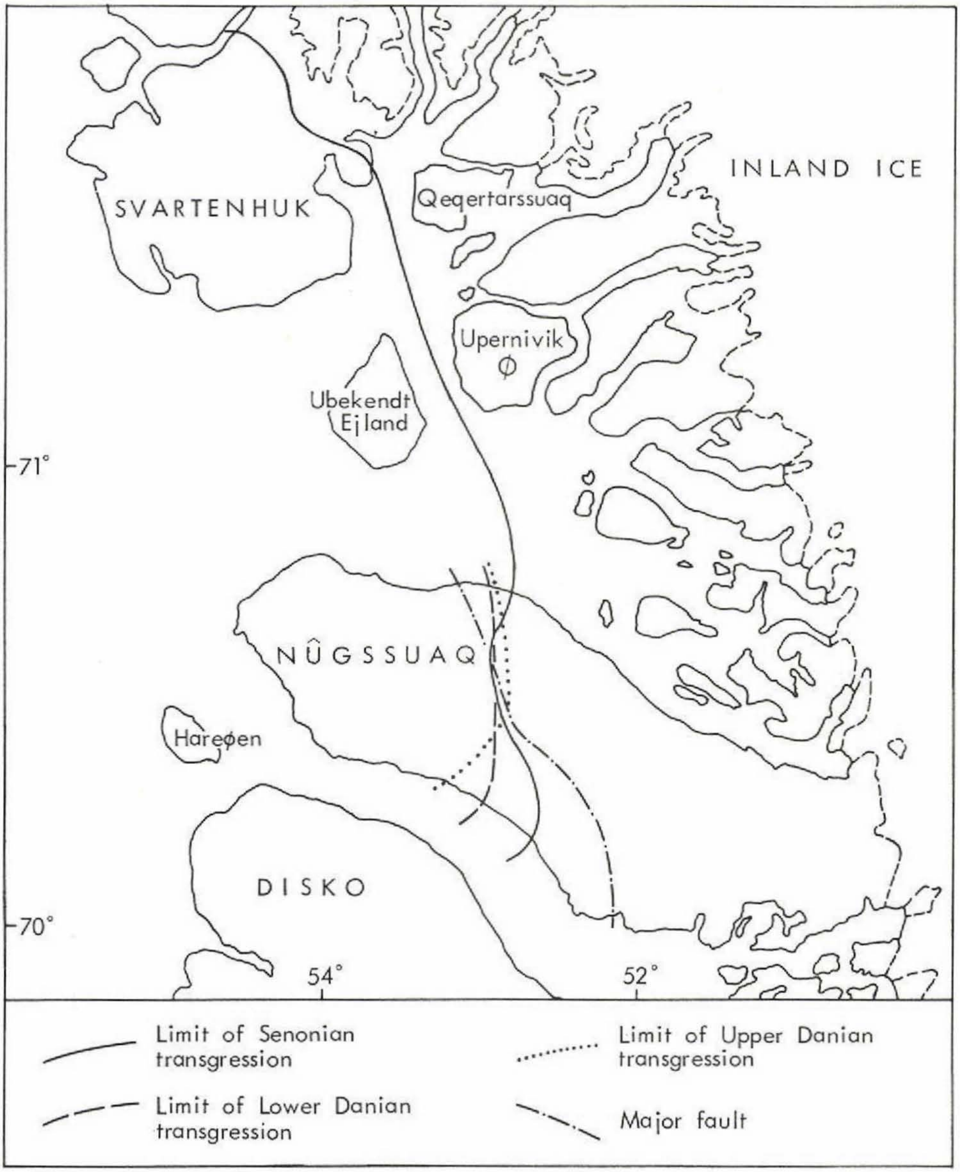

Fig. 3. Map showing the limits of marine transgressions in the West Greenland basin. (After Rosenkrantz and Pulvertaft, in press.)

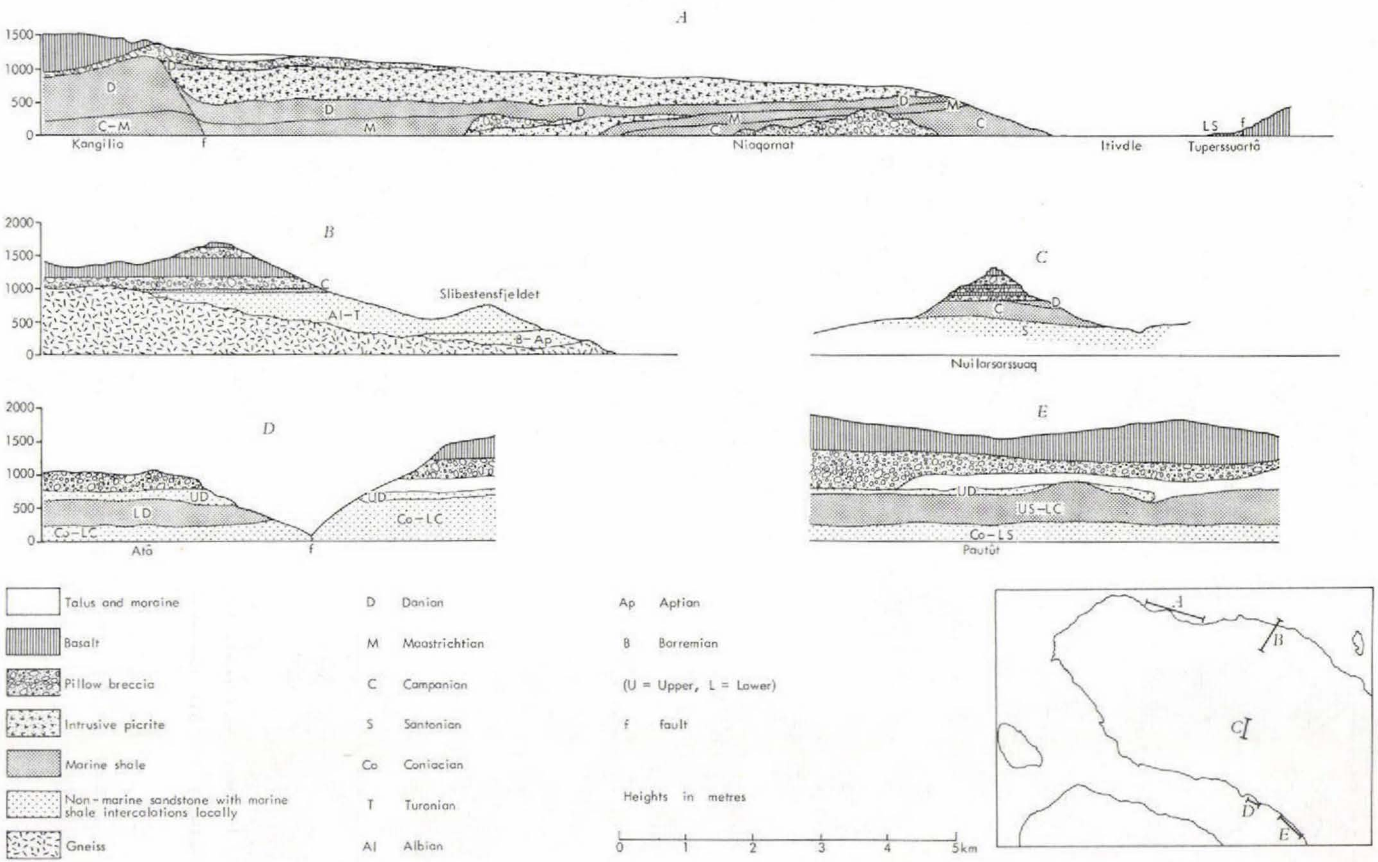

Fig. 4. Stratigraphic sections from various parts of Nûgssuaq. (Drawn by A. Rosenkrantz.)

in fault contact with, Tertiary basalts (see sketch by A. Rosenkrantz in Birkelund, 1965, p. 19). The lowest beds have yielded marine fossils of Lower Santonian age. No marine fossils have yet found in the highest part of the section. The base of the sequence is not exposed since the area to the east is occupied by a wide valley (Itivdle) filled with fluvioglacial deposits.

To the east of this valley the lowest beds are bituminous shales with sandstone bands. These have not yielded marine fossils but pass up into a sequence about 300 m thick consisting largely of dark, bituminous shales of Upper Campanian to Maastrichtian age. The maximum thickness of the Cretaceous beds in this area is about 500 m. The Cretaceous beds are overlain by Danian sediments. Farther along the coast to the east the Cretaceous-Tertiary boundary descends and in the valley of the Kangilia river a thick sequence of Tertiary beds is exposed. The boundary is an unconformity, and the Lower Danian Kangilia Formation commences with a conglomerate, which in places is up to 50 m thick. This is overlain by a thick sequence consisting mainly of black, bituminous shales. The Kangilia Formation has a maximum thickness of about 630 m (H. J. Hansen, personal communication). Intercalated in the upper part of the section are fossiliferous tuff layers of Lower Danian age, which give an age to the onset of volcanism in this area (Rosenkrantz, 1951, p. 158). To the east of Kangilia some 20 m of unfossiliferous sandstone is locally present between the black shales and the overlying volcanic rocks. The sandstone may be the lateral equivalent of the Agatdal Formation (Upper Danian) in central Nûgssuaq (A. Rosenkrantz, personal communication).

There is nowhere on the north coast where the entire known Cretaceous-Tertiary sequence is exposed in a continuous section, but it is nevertheless possible to make an estimate of what thickness of marine sediments could be present, either totally concealed below Tertiary basalts west of Itivdle or partly exposed and partly below sea level in the Kangilia area. The estimate is as follows:

Upper Danian	20 m
Lower Danian	630 m
Maastrichtian } Upper Campanian	500 m
- - - - - - - - - - - -	- - - - - -
not exposed	? m
- - - - - - - - - - - -	- - - - - -
Lower Santonian	300 m
Older than Lower Santonian	? m
Total	>1450 m

The thickness given for the Lower Santonian (300 m) is the total thickness of the section at Tuperssuartâ. It is recognized that the highest, unfossiliferous beds in this section may be younger than Lower Santonian. The thickness given for the Upper Campanian - Maastrichtian (500 m) is the maximum thickness of the Cretaceous beds exposed east of Itivdle. It should be noted, however, that the lowest, unfossiliferous beds could be older than Upper Campanian. To the total thickness given must be added an unknown thickness of Upper Santonian - Lower Campanian sediments which are either buried below, or faulted out in, the Itivdle valley, and sediments older than Lower Santonian which could be present at depth. Marine Coniacian sediments outcrop on the south coast of Nûgssuaq, and 400 m of marine Upper Turonian - Lower Senonian sediments outcrop in Svartenhuk, so it is reasonable to expect that there could be several hundred metres of older sediments below the Lower Santonian in northern Nûgssuaq. Against this must be set the fact that the Lower Danian beds are unusually thick in the Kangilia area. Nevertheless, it seems likely that there could be up to 2000 m of marine sediments on the north side of Nûgssuaq - and this estimate is based on sediments exposed in the basin.

Central Nûgssuaq

Cretaceous-Tertiary marine sediments are present for a considerable distance on both sides of the long valley Auvfarssuaq, which runs E-W through the centre of Nûgssuaq, and in the valley Agatdalen, which runs into the north side of Auvfarssuaq. The oldest beds found to date are of Lower Santonian age (Birkelund, 1965, pp. 16-17); the sediments range up to Upper Danian in age.

In central Nûgssuaq the Maastrichtian and the Upper Campanian are absent and the Lower Danian beds rest unconformably on Lower Campanian beds. The sequence Lower Santonian - Lower Campanian in this area is over 600 m thick. The sediments consist of sandstones alternating with black, bituminous shales, the proportion of shale increasing upwards. The first 400 m comprises largely non-marine sediments, and coal seams are common, but horizons with marine fossils are present.

The Lower Danian Kangilia Formation is of greatly reduced thickness in Agatdalen compared with the type locality on the north coast. In Agatdalen a conglomerate with abundant derived concretions, mainly of Maastrichtian age, in a shaly matrix containing Danian oysters and other pelecypods, forms the base of the formation (Birkelund, 1965, p. 18). The conglomerate, which is up to 5 m thick, is overlain by about 75 m of black, bituminous shale with concretions (A. Rosenkrantz, personal communication).

The upper Danian beds constitute the Agatdal Formation and rest unconformably on the Lower Danian beds. Rosenkrantz (in B. E. Koch, 1959, p. 75) recognizes three members of the formation at the type locality. The lowest member has a thickness of up to 50 m and consists of black shales with sandstone lenses; the middle member consists of a delta-like deposit of coarse sandstone, varying in thickness from 10 to 25 m; the highest member consists of alternating black shales and rather coarse fossiliferous tuffs and is up to 12 m thick. In parts of the area the Upper Danian succession commences with a coarse basal conglomerate. The Upper Danian varies greatly in thickness in this area, from 2 m near the southern entrance to Agatdalen to 60 m in the inner part of Agatdalen.

The maximum thickness of Cretaceous-Tertiary beds exposed in central Nûgssuaq is as follows:

Upper Danian		60 m
Lower Danian		80 m
Lower Campanian	}	
Upper Santonian	}	>600 m
Lower Santonian	}	
Total		>740 m

However, it must be emphasized that nowhere is the Precambrian basement exposed below the Cretaceous beds, so the true thickness of the sequence is unknown. Marine Coniacian beds are exposed on the south coast of Nûgssuaq and can well be present below the Lower Santonian beds in central Nûgssuaq. Marine Upper Turonian beds occur in Svartenhuk and could be present here at depth.

Nûgssuaq - south coast

West of the Itivdle valley beds of probable Lower Danian age, consisting of thinly interbedded black shales and sandstones, are exposed. The sediments have an exposed thickness of about 150 m; they are in fault contact with Tertiary basalts on the north and disappear under Quaternary deposits to the east and south.

Apart from two small sediment outcrops of unidentified age immediately south-east of Itivdle, the entire coast section for a distance of 26 km south-east from Itivdle consists of Tertiary volcanic rocks, with Quaternary deposits around the outlet of the Auvfarssuaq valley. Farther east, the volcanic rocks form the upper part of the long coast section as far as the Sarqaq valley, the lower part consisting of sediments. In the first stretch of this coast section, sediments of Coniacian age occur; these are thus the oldest marine sediments found to date in Nûgssuaq. The coast section is about 30 m high and the sediments dip gently east. At the top and bottom they consist of sandstones and shales of probable estuarine origin. The central part comprises dark, bituminous shales with Coniacian marine fossils (see Birkelund, 1965, pp. 14-16).

Still farther east the Cretaceous sediments, which range in age from Santonian to Campanian, consist in their lower part of sandstones, conglomerates and black shales of estuarine origin. The lowest beds are overlain by marine shales of Lower Campanian age, with intercalations of coal-bearing sandstone. The total thickness of the Cretaceous beds exposed is at least 700 m.

At Atâ the Cretaceous beds are overlain unconformably by marine Lower Danian beds (Kangilia Formation), consisting mainly of black, bituminous shales, with subordinate sandstone horizons, the sequence being about 300 m thick. The marine Lower Danian beds are overlain unconformably by non-marine Upper Danian beds, which consist of about 100 m of sandstones and conglomerates of fluviatile origin (Quikavsak Member of the Upper Atanikerdluk Formation - see B. E. Koch, 1959, p. 82).

The total thickness of beds exposed in this area, including the uppermost 100 m of non-marine deposits, is as follows:

Upper Danian	100 m
Lower Danian	300 m
Lower Campanian, Santonian, Coniacian	>700 m
Total	>1100 m

The base of the sedimentary sequence is not seen in this stretch of coast, so the total thickness of sediments present is not known.

Non-marine sediments

Thick sequences of sandstone and shale of non-marine origin form important parts of the sedimentary succession in West Greenland. The sediments range in age from Lower Cretaceous (Barremian-Aptian) to Upper Danian. In parts of the area there is evidence of lateral changes in depositional environment, since non-marine sediments have been observed to pass into marine sediments away from the old coastline. This is, of course, to be expected, but will have implications in the consideration of the offshore areas.

Svartenhuk

The Itsako peninsula on the east side of Svartenhuk contains about 1000 m of sediments, which are mainly of non-marine origin. In their lower part they are fluviatile-lacustrine deposits consisting of loose sand and sandstone with sandy shales and a little coal (Gry, in Rosenkrantz et al., 1942). These beds have yielded a Kome (Barremian-Aptian) flora. The upper part of the succession consists of shales with subordinate sandstone bands. On the south-western side of Itsako marine shales are present and have yielded Upper Cretaceous ammonites (Birkelund, 1965, p. 11). The highest shales have yielded a plant flora of early Tertiary age (K. Raunsgaard Pedersen, personal communication).

Non-marine sediments continue north-west of Itsako along the border of the Precambrian basement.

Qeqertarssuaq

Upper Cretaceous sediments are present on the west side of the island. According to Ødum and Koch (1955, p. 7), they alternate "between very fine-grained, almost silty, sandstone, and coarse conglomerates, showing cross-bedding and ripple-marks, and enclosing carbonized leaves and branches". The total thickness of sediments exposed is about 300 m.

Upernivik Ø

There are two areas of non-marine Cretaceous sediments on this island. The larger of the two (on the south-western end of the island) contains arkosic sandstones, sometimes pebbly, with intercalations of dark carbonaceous shales, the sequence exposed being over 1000 m thick. The beds here have yielded a plant flora known as the Upernivik Næs flora, which is of Albian-Turonian age.

A smaller area occurs on the west coast of the island and contains, in addition to sandstones, boulder conglomerates with boulders up to 2 m in length.

Nûgssuaq and Disko

The entire Cretaceous-Tertiary sequence of Disko and south-east Nûgssuaq (some 1500 m in thickness) is of non-marine origin and consists of arkosic to quartzose sandstones (sometimes pebbly), with dark, often carbonaceous, shales and silts. Coal seams are present and coal is at present mined at Qutdligssat on Disko. In some areas (e.g. Slibestensfjeldet, between Ikorfat and Kûk on the north coast of Nûgssuaq) sandstone predominates, while locally (e.g. due east of Ikorfat, and in part of the succession at Atanikerdluk and at Pautût, on the south coast of Nûgssuaq) shale predominates. The beds that form the Kome Formation on the north coast of Nûgssuaq have yielded a plant flora known as the Kome flora, which is of Barremian-Aptian age; the sediments here are thus amongst the oldest in the West Greenland basin. The beds at Atâ, on the south coast of Nûgssuaq, have yielded a plant flora (Atane flora) of Upper Turonian - Coniacian age, while at Pautût, also on the south coast, a flora of Upper Santonian - Lower Campanian age has been collected (Pautût flora). Plant floras of Danian age have been collected from beds at Atanikerdluk on the south coast.

Grønne Ejland

A small outcrop of thinly bedded dolomite was found by A. Escher (personal communication) in 1967 below a dolerite sill on the south side of the easternmost of the islands in the Grønne Ejland group. According to Olexcon International, The Hague, who examined the material, the rock is probably of non-marine origin and may be an altered freshwater calcarenite. No traces of fossils were found, so that it was not possible to determine the age of the rocks. However, there seems little doubt that they are of Cretaceous-Tertiary age, in which case they represent the southernmost occurrence of rocks of this age in West Greenland and confirm the suggestion made by Rosenkrantz and Pulvertaft (in press) that the basin extended at least this far south.

In addition to the sediments described above, non-marine sediments are found as horizons within the basalts of Svartenhuk, western Nûgssuaq, and Hareøen. In Svartenhuk the beds consist mainly of arkosic sandstone, with subordinate shale and a little coal. In Nûgssuaq and Hareøen the beds contain a large amount of pyroclastic material, but also contain some coal. Plant remains from these sediments show that the age is not younger than Eocene.

STRUCTURE

The West Greenland basin is a fault-bounded basin whose coastline was probably largely fault-determined at the onset of sedimentation (see Rosenkrantz and Pulvertaft, in press). It can be proved that faulting occurred during more than one period during the development of the basin; this fact is important not only in understanding the structural history of the basin but also from the point of view of what sediments could occur within the basin away from the old coastline.

In this discussion on the structure of the basin and in the assessment of its economic potentialities the basalts are dealt with in more detail than might appear necessary, considering the scope of the present paper. It has, however, been considered advisable to give this amount of detail, partly to give a better insight into the structure, but also to complete the information in case this should prove helpful for future exploration.

The map in fig. 1 shows the important fault system that limits the basin to the east. As pointed out by Rosenkrantz and Pulvertaft, both on Nûgssuaq and on Svartenhuk basalts overlap the faults and lie directly on the Precambrian rocks to the east, so that it is almost certain that Cretaceous sediments were never deposited to the east. The main fault system has probably determined the limits of most of the Tertiary sediments of Nûgssuaq as well, but at the northern end of the basin, in the Ingnerit area (see map), non-marine sediments of presumed Tertiary age are found north-east of one prominent fault associated with the main fault system, and in the fjord east of Ingnerit non-marine sediments of presumed Tertiary age extend for some distance inland, filling pockets in the Precambrian surface; there is no evidence that they are limited by faults (T.C.R. Pulvertaft, personal communication).

The Ikorfat fault, which is probably an offshoot of the limiting fault system, is expressed in sediments and in the overlying Tertiary basalts. It has been proved that 400 m of the total 900 m downthrow that displaces the Maastrichtian sediments took place before the deposition of the Tertiary basalts, probably largely between the Lower Danian and the Upper Danian, and the remaining 500 m after the deposition of the basalts. Nowhere west of this fault is the base of the sediments exposed. It is thus clear that if there have been earlier movements along this fault during the initial phases of deposition, or if a fault-determined coastline existed here at the commencement of deposition, there could be marine sediments present below sea level that are older than any exposed anywhere above sea level in Nûgssuaq - for example, marine Turonian sediments, as in Svartenhuk, or even older beds. In this connection it may be noted that in parts of the Canadian Arctic Archipelago there was essentially uninterrupted sedimentation from the Middle Pennsylvanian to the early Tertiary (Thorsteinsson and Tozer, 1960, p. 12).

Unconformities at several levels provide evidence of repeated instability in the basin. These are:

1) Unconformity between non-marine Albian-Turonian beds and non-marine Barremian-Aptian beds west of Kûk.
2) Unconformity at the base of the marine Lower Danian beds.
3) Unconformity at the base of marine and non-marine Upper Danian beds.
4) Unconformity in many places at the base of the Tertiary volcanic rocks.

Throughout much of the area the Cretaceous-Tertiary rocks are rather flat-lying, but some gently open warps are to be seen. These are probably not compressional structures but the result of uneven sagging connected with movements along fault zones. In southern Svartenhuk, western Nûgssuaq and western Disko the basalts are tilted. Rosenkrantz and Pulvertaft (in press) point out that this tilting is accompanied by an increase in the thickness of the lava pile (an increase in the number of flows, not a thickening of individual flows), and they consider the two features to be related.

In western Nûgssuaq this tilting occurs north-west of an important fault zone which can be seen in the Itivdle valley. The downthrow along this zone, which consists of a number of faults, is to the north-west, and is clearly considerable. At various places along this zone Cretaceous-Tertiary sediments can be seen faulted against basalts, and the lower basalts - the picritic basalts - can be seen faulted against the upper basalts - the plagioclase-porphyritic basalts.

The only part of the fault zone in which pillow breccia has been found is on the west side of the northern end of the Itivdle valley, where there are two small outcrops of breccia showing through Quaternary cover. The almost total absence of pillow breccia along the fault zone is surprising in view of the thick development of breccia east of the Itivdle valley. Since the movements along the fault zone have been very substantial, it could be that the breccia has been faulted out, but is present below the basalts west of the valley. If breccia is not present below the basalts here, it would indicate that the area due west of the valley was considerably higher than the area east of the valley during breccia deposition. V. Münther (personal communication) has suggested that there was an earlier downthrow to the south-east along the fault zone so that the north-western block was above the level of breccia deposition. Evidence exists in Svartenhuk that there has been reversal of the sense of movement on reactivation of one of the faults there (Rosenkrantz and Pulvertaft, in press, fig. 3 d), and if this did indeed take place along the Itivdle fault zone, it would of course have implications for what sediments might be expected north-west of the zone.

The north-western part of Nûgssuaq, west of Itivdle, has not only been subjected to tilting, but has also undergone block faulting on a considerable scale. This area is in contrast to Ubekendt Ejland, where Drever (1958, p. 200) states that the tilting of the basalts is not accompanied by major faulting or block displacements. The block faulting in north-west Nûgssuaq does not affect all the basalts. The highest basalts are almost undisturbed by faulting, but have dips ranging from 10° to 20° to the north-west on the south coast to 15° to 25° to the west on the north coast. In the belt between the highest basalts and the fault zone the fault pattern is complex and will require careful mapping if it has to be unravelled. Although many of the faults are visible on aerial photos, there are few markers that permit the amount of movements of the various blocks to be determined. However, a certain amount is known about this pattern. On the north coast the fault system includes antithetic faults, which have had considerable movement and have resulted in repetition of parts of the lowermost plagioclase-porphyritic basalts. On the south coast there are both antithetic faults and coast-parallel faults trending at right angles to the main fault zone.

The Itivdle fault zone can be traced to Hareøen, where it cuts basalts and downthrows to the north-west. South-east of the fault the basalts dip at 40° towards the fault. North-west of the fault the basalts show an anticlinal warp, the anticlinal axis being parallel to the fault. This warp is not regarded as being a compressional structure, but as the result of uneven sagging in connection with the fault movements.

The zone of tilting of the basalts in western Disko is not limited inland by one major fault zone as in Nûgssuaq; instead, the attitude of the basalts changes gradually from horizontal to subhorizontal in the eastern and central parts of the island to westward-dipping on the west side, dips of up to 25° being shown at the west coast. There are numerous N-S strike faults, and also oblique faults, in this zone of tilting.

Although it has not been mentioned previously in this paper, the intrusive picrite in Nûgssuaq (see Rosenkrantz and Pulvertaft, in press) is important in considering the structure of the peninsula. A large picrite intrusion has been emplaced, mainly between the pillow breccia and the underlying sediments, in an area east of the northern part of the Itivdle valley. Another body of picrite with identical appearance in the field was found during mapping in 1968 east of the southern entrance to this valley.

The picrite may have been emplaced at a fairly late stage, possibly simultaneously with the downfaulting of the block north-west of the Itivdle fault zone. As would be expected, it has deformed the pile of rocks into which it was emplaced and there is evidence suggesting a stoping of roof rocks down into the body.

PHENOMENA ASSOCIATED WITH THE BASIN

Burnt shales

The burnt shales of Nûgssuaq have attracted attention for a good many years, and it is therefore appropriate to discuss them in some detail. At many places along the north and south coasts of peninsula, slipped masses of bituminous shale have caught fire and at some places still burn from time to time. One slipped mass of shale on the north coast has been on fire on various occasions since 1933 (see fig. 5) and was seen smouldering periodically during the summer of 1968. Burnt shales are also known from two localities in the centre of the peninsula. At one locality they occur on the lower slopes of a mountain and may well have slipped, although this

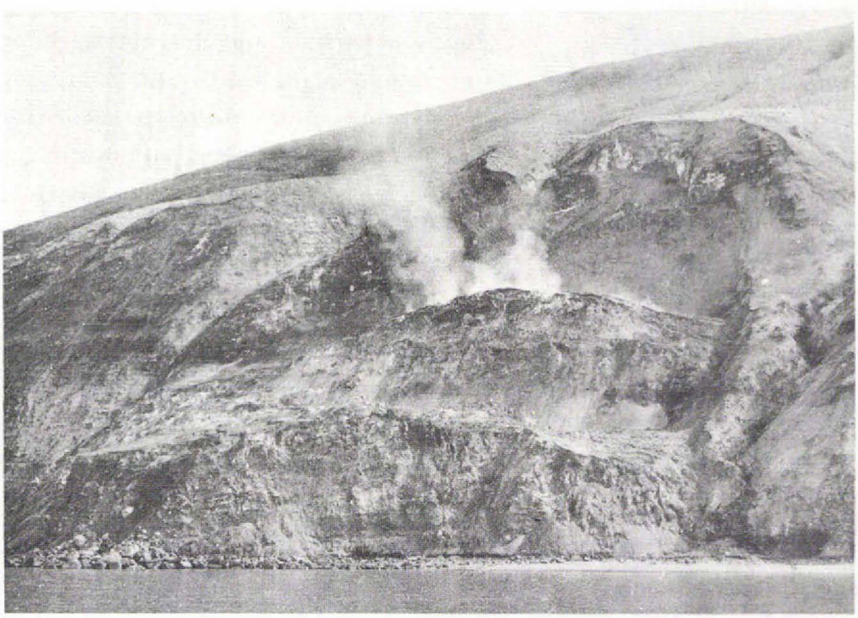

Fig. 5. Landslipped shales on fire, Pujôrtoq, north coast of Nûgssuaq, July 8, 1958. The lowest terrace comprises shales that slipped in 1932. (Photo: A. Rosenkrantz.)

has not been proved; at the other locality the position of the burnt shales does not suggest slip in the recent past, but the sediments are poorly exposed and it is not possible to state that the burnt shales are in situ. The localities where burnt shales occur are shown in a map by Rosenkrantz (1967a, p. 360).

The burnt shales are brick-red in colour and catch attention from a distance. It is quite probable that the process of slipping and combustion has gone on for a very long time. Rosenkrantz (1967b) presents evidence suggesting that burnt shales were seen by the Norsemen as long ago as 1300 A.D. He also mentions (loc. cit., p. 383) that during archaeological investigations at Ikorfat, on the north coast of Nûgssuaq, fragments of red shale, which had apparently been used for painting, were found amongst implements of Dorset age. The fragments could have come from an area of burnt shales at Saviarqat, west of Ikorfat, indicating that there was combustion in the shales in this area 2000 years ago.

In those parts of Nûgssuaq where the relations are clear, it can be seen that there is a definite connection between landslips and combustion: the combustion has taken place in slipped masses, while the bituminous shales that have not slipped have not caught fire. Rosenkrantz (1967b, pp. 381-82) has suggested that the combustible material in the shales catches fire either because of heat generated by the slipping or because of a content of pyrites. Recent chemical analyses by Olexcon International have shown that in one sample, 112953, which was collected only a few hundred metres from the burnt shales at Pujôrtoq, there is a very high content of elemental sulphur in one of the extracts; moreover, many of the rocks analyzed showed a high content of elemental sulphur in this extract. Elemental sulphur (in statu nascendi) is very unstable and will take part very readily in reactions. In the sample mentioned, the analytical results have already shown that sulphur has probably reacted with original hydrocarbons and partially destroyed these.

In trying to arrive at an explanation of why these shales have caught fire in places, there are two aspects to be taken into consideration: 1) their chemical composition and 2) their physical state. As to 1), the analyses have shown that these bituminous shales contain elemental sulphur and will ignite very readily in any case. As to 2), there can be no doubt that the process of slipping has something to do with the combustion of the shales. It is of interest to note that data are available on two of the slips on the north coast that enable something to be said about the interval that elapses between slipping and visible combustion. According to reports from the local inhabitants, the Pujôrtoq slip took place in 1932, but it was first in 1933 - a year later - that the slipped mass was seen to be burning. According to local accounts of another area of burnt shale, east of Niaqornat, a year also elapsed between slipping and visible combustion.

If heat developed by slipping were responsible for the shales catching fire it would seem difficult to explain why these combustible shales were first seen to be burning a year later, and in particular why the fire has not spread beyond the slip to the unslipped material. The writer considers that the slipping has caused some disintegration of the shales, thus permitting access of air and moisture and facilitating a spontaneous combustion. In this respect it is worth making a comparison with coal dumps, but it must be emphasized that this comparison is being made purely on the physical state of the material that catches fire. As far as chemical composition is concerned, the material is not the same. In one case the material is bituminous shale (and at Pujôrtoq a marine source rock - see later) while in the other case the material is coal of non-marine origin.

The phenomenon of spontaneous combustion in coal dumps is well known. Whether or not the coal in the dumps catches fire depends on various factors, but fragment size is important. Ungraded coal or fine coal of certain compositions is apparently prone to combustion, because of the large total surface area of the fragments exposed to air within the pile of coal; one way of reducing the risk is to build the dump up in layers and to roll each layer with a roller in order to compact it. The height of the dump is also critical: the higher the dump the greater the risk. The presence of moisture may also play a role. It would seem reasonable to compare these slipped masses of bituminous shale with dumps of ungraded coal, but, and this must be emphasized once more, only as far as the physical state of the material is concerned.

Naturally occurring burnt shales and clays are a phenomenon known from other parts of the world in sediments of various ages and types. In Trinidad the Pliocene Talparo and La Brea formations contain porcellanites, which are naturally burned and sintered lignitic clays and silts; the pyro-metamorphism is attributed to the spontaneous combustion of the lignite layers started by the heat of oxidation of pyrites (Suter, 1954, p. 43). According to Beeby Thompson (1950, pp. 248-249) bituminous Liassic or Kimmeridgian clays on the Yorkshire and Dorsetshire coasts of England yield a slight exudation of oil which occasionally ignites spontaneously, causing the surface of the cliffs to burn for a considerable time. Beeby Thompson also mentions occurrences in Barbados, the Mackenzie River district in Canada, the Athabasca district of Canada and the Santa Clara district of California. Mention can also be made of burning shales in the Middle East.

Mud volcanoes

Mud volcanoes are a common feature in the West Greenland basin, and have been observed in valley floors in Svartenhuk, Nûgssuaq and Disko. These mud volcanoes (see Rosenkrantz, 1940b, 1943; in Rosenkrantz et al, 1942 and in Kühnel, 1958) are built up of Quaternary deposits, and in those that are active, gas and water come up to the surface in a central crater. In addition to the active mud volcanoes, there are inactive mud volcanoes that still have their conical form and central crater preserved and must be presumed to have been active not long ago. Apart from these there are numerous small lakes whose water has a chemical composition similar to that of the active mud volcanoes. Some of these may be extinct mud volcanoes whose original conical form has been destroyed by erosion. On the other hand, there is one lake inland from Marrait kangigdlît on the south coast of Nûgssuaq that emits considerable quantities of gas at present, so much that the noise produced by the gas emission can be heard from some distance away (A. Rosenkrantz, personal communication), but the lake is not surrounded by a wall as the crater lakes of the typical mud volcanoes. This shows that gas and water eruptions through Quaternary deposits in Nûgssuaq do not necessarily produce a typical mud volcano.

Investigations have shown that in West Greenland mud volcanoes and lakes of the type referred to are only found in valleys believed to be underlain by Cretaceous-Tertiary sediments or by volcanic rocks presumed to be overlying these sediments, and are never found in valleys that are known to be underlain by Precambrian rocks (A. Rosenkrantz, personal communication). This is good evidence that the mud volcanoes in West Greenland are related to the Cretaceous-Tertiary sediments.

Some of the mud volcanoes and lakes genetically related to them are located in known fault zones, e.g. the mud volcanoes in the Itivdle valley and the lake mentioned in the preceding paragraph. However, since all the mud volcanoes and lakes of the type referred to are situated in Quaternary deposits, comparable relations with faults may exist for the others. In this connection it can be noted that in the Kûgánguaq valley in northern Disko there are several mud volcanoes occurring along a line; this is very suggestive of the presence of a fault or fracture at depth.

Professor Rosenkrantz has kindly supplied the writer with analyses of gas and water samples collected by him on various occasions from a large, currently active mud volcano, Qapiortoq kitdleq, in the Auvfarssuaq valley in central Nûgssuaq. The results of the gas analyses are given in table 1. They show that the gas consists mainly of methane. The content of noble gases in the "N_2" (nitrogen + noble gases) from the mud volcano is a little higher than it is in atmospheric "N_2". The content of argon is a little higher than in atmospheric "N_2", while the content of helium + neon is twice as high as it is in atmospheric "N_2". Helium was not determined separately. However, it may be noted that the natural gas of petroleum reservoirs often has a relatively high content of helium (Levorsen, 1967, p. 218), so that it may well be helium that is responsible for the relatively high content of helium + neon in the "N_2" from this mud volcano. The composition of the gas might be taken as indicating a connection with the bituminous shales. In this connection it may be noted that Aliev and Buniat-Zade (1968) mention that the average methane value of gas produced by mud volcanoes in the Kura region of the South Caspian basin of the USSR is 95 per cent. These writers also mention the constant presence of minute quantities of heavy hydrocarbons, carbon dioxide and, rarely, nitrogen. Further evidence in support of a connection with bituminous shales is provided by the fact that this mud volcano in Nûgssuaq has brought

Table 1

Analyses of Gas Samples from the Mud Volcano Qapiortoq kitdleq, Auvfarssuaq, Nûgssuaq (Volume %).

Year	1946	1947	1948
CO_2	3.5	2.2	2.6
O_2	0.4	0.2	0.0
CH_4	84.6	94.8	95.6
"N_2"	11.0	2.9	2.1
	99.5	100.1	100.3
	He + Ne = 0.00188% of total gas	He + Ne = 0.00087% of total gas	He + Ne = 0.00090% of total gas

"N_2" = nitrogen + noble gases

Small amounts of unsaturated hydrocarbons were found in all the samples, but these amounts were not determined.

Noble Gases (Earlier Analyses)

Sample no.	3	4	5
"N_2"	1.048 ml	2.850 ml	2.935 ml
Noble gases	13.84 μl	37.31 μl	38.58 μl
Noble gases in "N_2"	1.321 %	1.309 %	1.314 %
Noble gases in "N_2" in atmosphere			1.186 %

The "N" in the gas from the mud volcano contains a little more argon than, and twice as much helium + neon as, atmospheric "N_2".

Samples collected by A. Rosenkrantz. Analyses: Den Polytekniske Læreanstalts Kemiske Laboratorium. A.

small amounts of bitumen to the surface (A. Rosenkrantz, personal communication).

On the other hand, Rosenkrantz (1957) has already drawn attention to the fact that, in West Greenland, natural gas occurs in areas where the rocks consist of bituminous shales and sequences containing coal seams, so the possibility that the methane-rich gas could be coming from coal seams should not be overlooked. Coal seams are common in the non-marine sediments in Nûgssuaq.

The analysis of a water sample is given in table 2. Numerous other water samples collected from this mud volcano between 1939 and 1968 have been analysed. The results show that the variation from one year to another is insignificant. This analysis may therefore be considered to be representative for water from this mud volcano.

Professor Rosenkrantz considers (personal communication) that methane has reduced the original sulphate, which has been replaced by bicarbonate/carbonate, and that there has been exchange of Na^{+} ions for Ca^{++} and Mg^{++} ions.

In West Greenland these mud volcanoes are only found in Quaternary deposits in the floors of valleys. No gas-bearing springs with water of a similar chemical composition have been found in the hillsides flanking the valleys. It is of interest to note, however, that springs with a high sulphate content are common in the shale areas (Rosenkrantz, 1940b, p. 653). The composition of the water varies considerably from one spring to another, but it is characteristic of all of them that the sulphate content is very high. Analyses of two samples are given in table 2. The first sample was taken from a spring in shales at the locality Hamiteskløft on the north coast of Nûgssuaq (for location see Birkelund, 1965, plate 48). The second sample was collected at the same locality, from a small lake fed by the spring. The water from these springs is rich in radicals that are absent from, or poorly represented in, the water from Qapiortoq kitdleq and can be regarded as being in many respects chemically complementary to the water from this mud volcano.

The term "dyndvulkan" (mud volcano) was originally applied to these features in West Greenland by Rosenkrantz (1940a; 1940b); in a later paper (1943, p. 97) he drew parallels with mud volcanoes in the Baku region, Romania and Java. Amongst other areas where mud volcanoes

Table 2 Water Analyses (p.p.m.)

	I						II											
Source	Cl^-	SO_4^{--}	CO_3^{--}	HCO_3^-	NO_3^-	PO_4^{---}	Na^+	K^+	Ca^{++}	Mg^{++}	Fe^{++}	Fe^{+++}	Al^{+++}	Mn^{++}	NH_4^+	SiO_2	I+II	References
Qapiortoq kitdleq, Nûgssuaq, West Greenland	260	0.6	168	2,977	0	1.2	1,255	8.5	7.0	88	<0.1			0	0.15	37	4,764	1
Spring, Hamites-kløft, Nûgssuaq, West Greenland	<10	13,189			0	12	244	tr.	246	2,187	0	768	338			116	15,876	2
Lake, Hamites-kløft, Nûgssuaq, West Greenland	tr.	16,542			0	25	0 or tr. (Na + K)		163	1,140	0	3,350	698	66		104	17,845	3
Vestligst Vulkan I Tobiasdal, East Greenland	9.2	0.8		281	0		93 (calc.)		11	3.3	<0.2				0	6.0	398	4
Dyndvulkan IV Tobiasdal, East Greenland	22	250		641	0		113 (calc.)		26	123	<0.2				0	4.0	1,175	5
First Wall Creek Sand (Cretaceous) Wyoming, USA	240	-	92	3,050			1,372 (Na + K)		-	-							4,754	6
Miocene, Lagunillas, western Venezuela	89	-	120	5,263			2,003 (incl. K^+)		10	63							7,548	7
Sea water	19,350	2,690	150				11,000 (Na + K)		420	1,300							35,000	8

1. Sample collected by A. Rosenkrantz, 1961. Analysis: Danmarks Geologiske Undersøgelse.
2. " " " " , 1939. " " " "
3. " " " " , 1939. " " " "
4. " " " " , 1945. " " " "
5. " " " " , 1945. " " " "
6. Crawford, J.G., 1940, analysis no. 100.
7. Staff of Caribbean Petroleum Company, 1948, p. 557.
8. Dittmar, W. in Levorsen, A., 1967, p. 166.

occur, mention can be made of the Kura region of the South Caspian basin of the USSR (Aliev and Buniat-Zade, 1968), the Arakan coast of Burma, and Trinidad (Levorsen, 1967, pp. 22-23). According to Levorsen (pp. 19-20) most mud volcanoes are high-pressure gas seepages that carry with them water, mud, sand, fragments of rock, and occasionally oil; many of them are associated with anticlines, faults, or diapiric folds.

It may be asked whether the West Greenland mud volcanoes are, in fact, directly comparable to the mud volcanoes referred to in the preceding paragraph. Morphologically very similar features occur in East Greenland in valleys underlain by sedimentary rocks; these were originally termed "dyndvulkaner" by Noe-Nygaard and Rosenkrantz (1950, pp. 112-113). Müller (1959) undertook a later study of these features in East Greenland and referred to them as "pingos". He recognized, however, that the East Greenland occurrences must have a different origin from the pingos of the Canadian Arctic. He considers that in East Greenland, "pingos develop where sub- or intrapermafrost waters penetrate into the permafrostzone, forced up by hydrostatic pressure, with a relatively small temperature difference between this water and the frozen ground and at a low rate of flow. Within the upper part of the permafrost zone the uprising water produces a hydrolaccolith sensu stricto which, with further reduction of the temperature, will become the ice body. The crystallization pressure of this process together with the hydrostatic pressure will exceed the pressure and force of cohesion of the overlying layers of frozen or unfrozen clays, gravels, or even bedrock" (p. 116).

There are certain major differences between the occurrences described by Müller and the mud volcanoes in West Greenland. Whereas the gas from Qapiortoq kitdleq in Nûgssuaq is rich in methane, the gas sample collected by Müller from the "Gletscherpingo" in East Greenland has a composition close to that of air (loc. cit., p. 48). The water from the crater of Qapiortoq kitdleq is rich in Na^{+} and HCO_3^{-} radicals, while the content of Ca^{++} is low and SO_4^{--} is present as a trace only. The water from the "Quellpingo" and the "Gletscherpingo" in East Greenland (loc. cit., pp. 45 and 48) is a water with dissolved calcium carbonate and calcium sulphate. Analyses of precipitates associated with water coming from other craters in the area described by Müller show them to consist largely of calcium carbonate and calcium sulphate. Some of the effluent water is stated to contain iron hydroxide.

These waters and precipitates have a composition quite different from that of the water from Qapiortoq kitdleq, but have features in common with the water coming from springs in the shales in West Greenland. This water is, as mentioned rich in sulphates. Müller states (loc. cit., p. 48) that the water of the "Quellpingo" and the "Gletscherpingo" must come from shallower depths than the water from Qapiortoq kitdleq.

Another difference between the East Greenland occurrences and the West Greenland mud vulcanoes is the presence of outcropping, albeit deformed, sedimentary rocks in some of the East Greenland occurrences; mud volcanoes in West Greenland expose only unconsolidated material.

However, water with chemical affinities to the water from Qapiortoq kitdleq does occur in some places in East Greenland. Two previously unpublished analyses of water samples collected in 1945 by Professor Rosenkrantz in Tobiasdal are given in table 2. The first sample was collected from the crater of Vestligst Vulkan I. The analysis shows that that the total content of dissolved salts is much lower than in Qapiortoq kitdleq, but the water here is also an alkaline type, with virtually no sulphate and very little magnesium. Only Quaternary deposits were visible in the crater wall. The second sample was collected from the crater of Dyndvulkan IV. This shows that the water here contains a substantial amount of sulphate and magnesium in addition to sodium and bicarbonate. Bituminous shales of Cretaceous age are present in the wall of this crater and it is considered likely that the water is of mixed origin, part having come up from depth and part having come from the shales at surface. There are thus two types of water present in craters in East Greenland, whereas in West Greenland it is only the alkaline type that has been found in craters, the sulphate-bearing type being restricted to springs in the shales.

Müller finds no evidence to relate the East Greenland occurrences to bituminous shales, and the mechanism proposed by him to account for their origin is different from the mechanism proposed by Rosenkrantz to account for the mud volcanoes in West Greenland (gas pressure). It has been suggested by Rosenkrantz (personal communication) that, even though methane-rich gas is not now emerging from the craters in East Greenland, the presence in some of these of sulphate-poor water, relatively rich in bicarbonate, suggests that gas of this type has been present in the past and has brought about a reduction of the sulphate, and that it was the pressure of this gas that caused these features to form. The fact that methane-rich gas can come up in mud volcanoes in West Greenland under considerable pressure is clear from fig. 6.

Fig. 6. Water fountain caused by escape of gas in crater of mud volcano Qapiortoq kitdleq, Nûgssuaq. August 25, 1939. Matchbox on left gives scale. (Photo: B. Thomsen.)

The present writer has reviewed the evidence at some length because it may be important to oil exploration to know as much as possible about the genesis of these features. In some respects, i.e. the form, and the composition of the gas being emitted, the West Greenland occurrences are very similar to mud volcanoes elsewhere in the world.

More needs to be known about the processes responsible for the composition of the crater water and springs; analysis of fresh core material may throw light on this. The content of dissolved salts in the water from the Qapiortoq kitdleq mud volcano is too low for sea water and much too low for it to be a brine of the type normally found in oil fields;

moreover, the chemical composition is different; this is a strongly alkaline water. Nevertheless, the content of dissolved salts is relatively high. For comparison, two analyses of oil-field waters from the Cretaceous of Wyoming, USA (Crawford, 1940), and the Miocene of the Lagunillas field, western Venezuela (Staff of Caribbean Petroleum Company, 1948), are given in table 2. The composition of the water in these two analyses is very similar to the composition of the water from Qapiortoq kitdleq, the resemblance being closest for the Wyoming example. Crawford states (p. 1214) that all the oil-field waters of Wyoming have been considerably modified by the infiltration of surface water. In giving these analyses, it must be stated that no thorough study of published water analyses has been made; the two examples are given merely to show that some oil-field waters have a composition like that of the Qapiortoq kitdleq water. It is not inconceivable that the Qapiortoq kitdleq water could be formation water coming up from depth together with the gas. If this is so, the constant production of water and gas over the years might suggest that the formations at depth, at least in some places, have a reasonable permeability to water and gas. One thing is, however, certain: the gas in the West Greenland mud volcanoes is natural gas coming up from the Cretaceous-Tertiary sediments at depth.

As mentioned previously, there is probably a relation between the West Greenland mud volcanoes and faults. The location of the mud volcanoes in the floors of valleys only may be explainable in terms of permafrost. It is known that permafrost tends to be thinner below river valleys, partly because of factors such as heat transfer from runoff. It would thus be easier for gas and water under pressure to reach the surface in the valley floors than it would be above the valley floors, where the permafrost will be thicker and tend to form a more effective seal.

PART II

ECONOMIC APPRAISAL

INTRODUCTION

Four fundamental geological requirements must be met before an area can be said to be a potential producer of oil or gas:

1) The area must contain rocks in which oil or gas have been able to form - source rocks.
2) Suitable reservoir rocks must be present.
3) The oil or gas must have been able to migrate from the source rocks into the reservoir rocks.
4) Suitable traps must be present so that the oil or gas once having reached the reservoir rocks has not been able to escape from them.

Although much work remains to be done before it can be said that all these requirements can be fully satisfied in the West Greenland basin, it is possible to state that all four can be met to a greater or less degree.

Before such an area can be regarded as an economic producer of oil or gas a further condition must be fulfilled: the quantity of oil or gas that can be yielded by the area must be sufficient to cover the costs of finding, developing and selling the oil or gas. At this stage it is naturally impossible to state whether this condition can be fulfilled in the West Greenland basin. This can only be settled by drilling. However, some of the problems involved in exploration and exploitation work will be dealt with in this report.

SOURCE ROCKS

The presence of thick sections of dark shale in the Nûgssuaq peninsula has been known for a long time (Steenstrup, 1883), but Rosenkrantz (1940a, p. 125) was the first to recognize that bituminous shales formed an important part of the sedimentary sequence. Bituminous shales are found in north, central and south Nûgssuaq, in formations ranging in age from Coniacian to Upper Danian (see also Koch, 1959; Koch and Pedersen, 1960). Bituminous shales of Upper Cretaceous age also occur in Svartenhuk.

It was not previously known whether the bituminous shales of Nûgssuaq were true source rocks or shales of the "oil shale" type. Analyses undertaken by Olexcon International on samples collected during 1968 have established beyond doubt that the bituminous shales of Nûgssuaq include true source rocks. The analyses are included in the appendix. The geographical locations of the samples are shown in fig. 7 and their stratigraphic positions are shown in table 3.

All the samples were collected from near-surface outcrops, some with the use of explosives and some with the use of a pickaxe or hammer and chisel, but none from a depth greater than 1.2 m. Since the shales at surface and just below surface in the permafrost were weathered the samples were not as good as could have been wished for this sort of analysis. Under the circumstances the results obtained must be considered to be very encouraging.

Two of the samples proved to be definite source rocks. One of these (112953) is a shale of Upper Campanian or slightly older age collected from the north coast of Nûgssuaq a short distance to the west of the burnt shales at Pujôrtoq. The other sample (112966) is a shale of probable Lower Danian age from the south coast of Nûgssuaq, due west of the southern entrance to the Itivdle valley. The results of element analyses undertaken on these two samples support the results of the source-rock analyses.

Eleven samples have been classified as doubtful to weak source rocks for the present, pending analyses of fresh core material to elucidate the effects of weathering and the part played by elemental sulphur. The samples were collected from shales of various ages from Lower Santonian

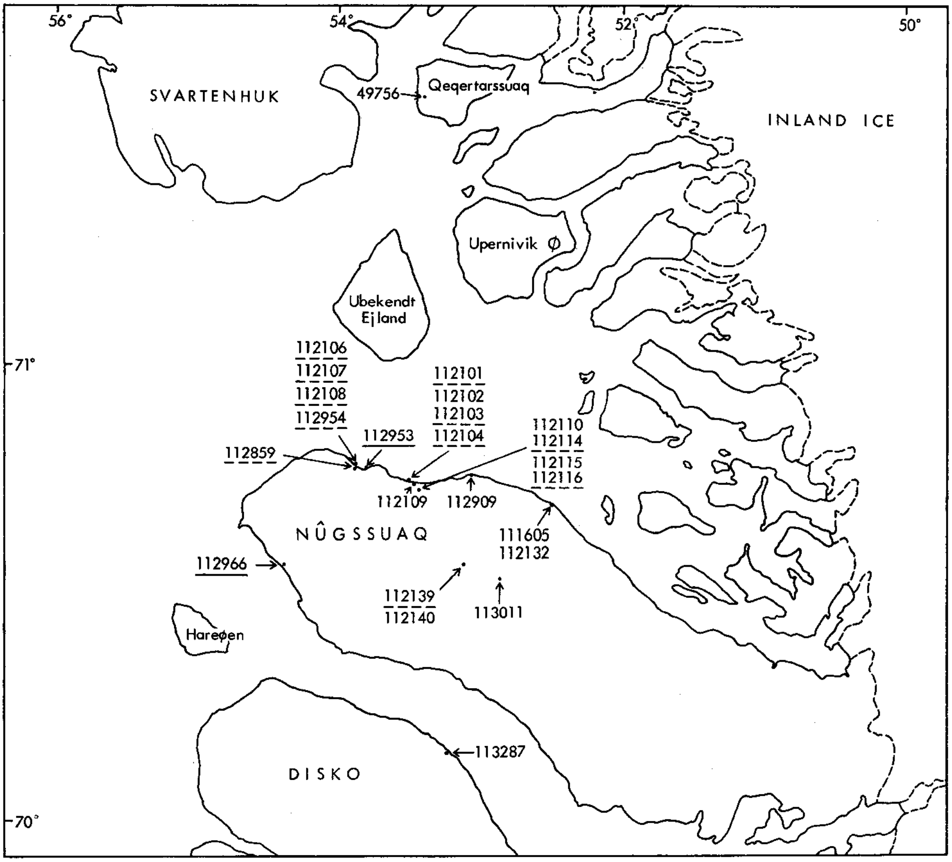

Fig. 7. Map showing locations of samples collected for source-rock analysis. Solid underlining: source rocks; broken underlining: samples classified as doubtful to weak source rocks pending further analyses; no underlining: negative samples. The location of the bitumen-impregnated sandstone in west Qeqertarssuaq (sample 49756) is shown.

Table 3 (opposite). Stratigraphic positions of the samples collected for source-rock analysis. Solid underlining = source rocks; broken underlining = samples classified as doubtful to weak source rocks pending further analysis; no underlining = negative samples. (Table drawn by A. Rosenkrantz.)

Table 3

Sample no.	Paleocene - Eocene	Pillow breccias and plateau basalts. Intrabasaltic Ivssorigsoq flora		
112139 112140 113011 113287 — ?	Upper Danian	Upper Atanikerdluk flora	Globoconusa daubjergensis - Tylocidaris - Latiarca - Stegoconcha - Venericor - Tylostoma - Creonella - Gilbertina - Ravniella	
			unconformity	
112110 112114 112115	Lower Danian		Echinocorys - Tylocidaris - Dendrophyllia candelabrum - Thyasira conradi - Palæocypraea aff. spirata - Ravniella - Cimomia - Hercoglossa	
			unconformity	
112116 112966 — ? 112109	Maastrichtian		Sagholinites - Neophylloceras - Discoscaphites wagei - Inoceramus fibrosus	
			Div. Discoscaphites - Diplomoceras sp. ?	
112101 — ? 112102 — ?	Upper Campanian		Hoploscaphites greenlandicus	
			Hoploscaphites ikorfatensis + div. Hoploscaphites - Pseudophylloceras	
112103 — ? 112104 — ? 112953 — ?	Lower Campanian	Pautût flora	Scaphites cobbani - Baculites obtusus - Pseudophyllites skoui	
			Haresiceras sp.	Inoceramus steenstrupi - group
112106 — ?	Upper Santonian		Baculites codyensis	
112107 — ? 112108 — ? 112859 — ? 112954 — ?	Lower Santonian		Clioscaphites aff. saxitonianus	
			Clioscaphites septentrionalis	
	Coniacian	Atane flora	Angiosperm pollen in increasing amounts	Scaphites ventricosus
				Scaphites preventricosus svartenhukensis - Inoceramus deformis
	Upper Turonian			Scaphites corvensis - Borisjakoceras ?
	Turonian - Cenomanian - Albian	Upernivik Næs flora		no marine deposits
			unconformity	
112909 111605 112132	Aptian - Barremian	Kome flora	No angiosperm pollen	no marine deposits
	Precambrian			

or slightly younger to Upper Danian, but excluding Maastrichtian, on the north coast of Nûgssuaq and in the Agatdal area in the centre of the peninsula.

Ten samples proved to be negative. Nine of these were of shales of Barremian-Aptian, Maastrichtian, Lower Danian and Upper Danian age from northern and central Nûgssuaq. Three of the nine were collected from horizons of non-marine Lower Cretaceous (Barremian-Aptian) shale on the north coast of Nûgssuaq. The tenth sample was collected from (?marine) shale of probable Danian age on the north coast of Disko.

Indirect evidence in support of the presence of source rocks is provided by the results of an element analysis of an outcrop sample of Upper Cretaceous sandstone with bitumen impregnation collected near the rim of the basin in the island of Qeqertassuaq and by the fact that one of the mud volcanoes in Nûgssuaq has brought small amounts of bitumen to the surface; whether the results of the gas and water analyses point to the presence of source rocks is still an open question. These features are discussed in detail later.

As pointed out by Levorsen (1967, p. 190), crude oil frequently has a relatively high content of vanadium and nickel. Two analyses of the vanadium content of bituminous shales from the Campanian of north Nûgssuaq were kindly supplied to the writer by Professor Rosenkrantz. The analyses were undertaken by R. Bøgvad, Kryolitselskabet Øresund A/S. The first sample was collected at Vestre Konglomeratkløft at Angnertuneq; it proved to contain 0.027 per cent V_2O_5. The second sample was collected from the locality known as "Amfiteater", west of Angnertuneq; it proved to contain 0.012 per cent V_2O_5.

RESERVOIR ROCKS

No specific study has yet been made of the sandstones of the area with the object of finding out whether, in the areas where source rocks or possible source rocks exist, the porosity and permeability would make them good reservoir rocks, so the remarks that follow are based on general knowledge of the sandstones in the basin.

Much of the non-marine sandstone in the area is friable and porous in surface outcrop, and there is no reason to believe that this would not apply at depth. The non-marine sandstones are often very thick. They would probably be very good reservoir rocks.

Sandstone bands associated with the marine shales vary in outcrop from friable, porous rocks to cemented rocks with a lower porosity. In the lowermost 400 m of the Cretaceous sequence in central Nûgssuaq, which is mostly of non-marine origin, but does have marine intercalations, many of the sandstone bands are friable and porous, and would probably form good reservoir rocks. On the other hand, some of the thin sandstone bands in marine shales (for example, Lower Santonian shales) on the north coast are compact, cemented rocks.

EVIDENCE OF MIGRATION OF FLUIDS

It has already been mentioned in an earlier section of the report that gas and alkaline water are produced by mud volcanoes in the West Greenland basin. It is probable that the gas is coming from the bituminous shales. Evidence was given in support of the idea that the water could be formation water coming up from depth together with the gas. The fact that one of the mud volcanoes has brought small amounts of bitumen to the surface is additional supporting evidence for a connection with the bituminous shales.

There have been reports from Greenlanders in the past of oil seepages in Nûgssuaq and Svartenhuk (see Rosenkrantz, in Rosenkrantz et al., 1942, p. 42; Rosenkrantz, 1962, p. 271), but investigations in these areas have not confirmed the presence of such seepages. The mud volcano Qapiortoq kitdleq has, however, brought small amounts of bitumen to the surface, as mentioned previously. During the summer of 1968 the writer examined sandstone outcrops close to major faults in Nûgssuaq, but no hydrocarbon impregnation was found.

During a visit to the western part of the island of Qeqertarssuaq in 1963 the writer discovered an outcrop of bitumen-impregnated brecciated sandstone about 700 m from the fault that separates the non-marine Upper Cretaceous sediments from the Precambrian metamorphic rocks (see fig. 8). The presence of bitumen in this type of lithology can only be explained as the result of migration of hydrocarbons; a lateral migration from marine rocks has to be assumed, unless source rocks are present at depth.

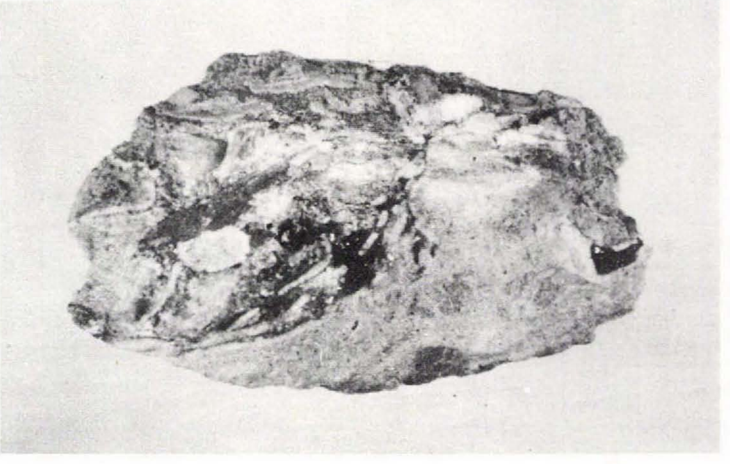

Fig. 8. Bitumen-impregnated sandstone from west Qeqertarssuaq. GGU sample no. 49756. About 2/3 natural size. (Photo: P. Nielsen.)

TRAPS

There are good possibilities for the presence of structural and stratigraphic traps below surface in the West Greenland basin.

Structural traps

As already mentioned, there is no evidence of compressional folds in this basin; such gentle folds as exist are probably gentle warps associated with movements along major faults. The presence of faults, however, gives possibilities of fault trapping.

In the north-western part of Nûgssuaq the tilting of the basalts in association with widespread and substantial block faulting immediately north-west of the fault zone running through the Itivdle valley makes the presence of fault traps in the sediments underlying the basalts highly likely. Detailed mapping of the basalts in this area will enable the major faults to be shown and it ought to be possible to calculate the displacements on many of these faults.

The tilting of the basalts in western Disko has also been accompanied by faulting, but it is not yet possible to say much about the effects of the fault movements. It is not known whether the sediments under the basalts of western Disko are marine or non-marine, but there should be good possibilities for fault traps being present in these sediments.

In both western Disko and north-west Nûgssuaq the direction of dip of the basalts is away from the old coastline, so that if the structure of the sediments follows that of the basalts it is possible that reservoir fluids have migrated updip from marine into non-marine sediments.

The discovery of bitumen in brecciated Upper Cretaceous sandstone due west of the faulted contact between the sediments and the Precambrian rocks in western Qeqertarssuaq means that the zone close to the limiting faults cannot be neglected in the search for fault traps.

In the area between Itivdle and Marrait kangigdlît on the south coast of Nûgssuaq a zone of repeated faulting affects pillow breccias and the lowest picritic lavas. The picritic lavas in the fault zone dip at angles of 15^{o} to 30^{o}. The cover of volcanic rocks may not be very thick here, and this area must be considered to be of interest.

Stratigraphic traps

Lateral variations in lithology are known on a regional scale in parts of the area, As an example, the Lower Santonian rocks can be mentioned. In the Auvfarssuaq valley in central Nûgssuaq, the Lower Santonian consists largely of sandstones, with some coal seams, but contains intercalations of marine shale. On the north coast, beds of the same age consist almost entirely of dark, bituminous shale, sandstone being of very minor importance.

If the tilted basalts of Svartenhuk, Ubekendt Ejland, north-western Nûgssuaq and western Disko are underlain by interfingering marine shales and sandstones, conditions would exist for the presence of primary stratigraphic traps.

Secondary stratigraphic traps may be present in connection with the unconformities mapped in the sedimentary column; since there is in places an unconformity at the base of the volcanic sequence, there are also possibilities of secondary traps being present in association with this unconformity.

POINTS OF IMPORTANCE TO FURTHER EXPLORATION

In the preceding pages attention has been paid to the four primary geological requirements that must be met before the area under discussion can be termed a potential producer of oil or gas. Because of a number of factors, some geological and some non-geological, the West Greenland basin will be difficult and costly to explore and develop; however, the expense of exploration in difficult areas of this type has not deterred exploration in the Canadian Arctic or northern Alaska. The first indications are encouraging and invite further exploration for oil and gas. The geological problems involved in this exploration will be considered first.

Cover rocks

One of the major problems facing exploration work in West Greenland is the fact that a considerable part of the area investigated is covered by Tertiary basalts. In some of the areas that would be considered on purely theoretical grounds to be amongst the most attractive areas for exploration drilling, the basalt cover is very thick. According to Rosenkrantz and Pulvertaft (in press), the total thickness of subaerial basalts extruded after the pillow breccias were laid down amounts to about 8 km, although it must be emphasized that thicknesses of this order are only to be found in the western part of the area, i. e. southern Svartenhuk, Ubekendt Ejland, north-western Nûgssuaq and western Disko.

In southern Svartenhuk, the pile has a thickness of many kilometres. Drever (1958, p. 200) states that the picritic lavas are about 5 km thick on Ubekendt Ejland. In north-western Nûgssuaq it is difficult to estimate the true thickness of basalts present because of the block faulting; however, a conservative estimate would be 5 km. The thickness of the basalts in western Disko must be of the same order.

There are indications that increasing thicknesses of basalt are accommodated by increasing dip (Rosenkrantz and Pulvertaft, in press). There is a reduction in dip of the basalts in the extreme north-western part of Nûgssuaq and in the extreme west of Svartenhuk. It is not inconceivable, therefore, that this reduction in dip could reflect a reduction of the total lava thickness in the offshore area. Furthermore, these authors mention that regional variations in the thickness of the lowest part of the lava pile have been observed in the western part of this area, the lowest lavas being much thicker in Ubekendt Ejland than to the north and south. It is therefore possible that the very considerable thicknesses of lava observed in the western part of the area investigated are not representative of the offshore areas to the north and south.

Quite clearly the areas where the maximum thickness of basalt is present must be considered to be excluded as areas of economic interest. However, the zone where the basalts start to become tilted must be considered to be of interest; in Nûgssuaq, for example, this is the area immediately north-west of the Itivdle valley, where the picritic lavas and the lowest plagioclase-porphyritic lavas form the surface outcrops.

It will be necessary at an early stage in the exploration to find out 1) the thickness of the basalt cover, 2) the thickness of the sedimentary column and 3) the internal structure of the sediments in this zone in Nûgssuaq. Normal geophysical techniques cannot be adopted because of the thick cover of basalt. However, it may be possible to develop a particular technique for obtaining information from below the basalt cover. The technique in mind is low-frequency refraction seismic survey. Some work has already been done elsewhere on developing instruments for this type of survey (see Jones and Dennison, 1955).

In many parts of Nûgssuaq east of the Itivdle valley the sediments are exposed below the basalt cover. Conventional geophysical surveys can be run in some of the valleys in this eastern part. In the area east of the southern entrance to Itivdle, on the south coast of Nûgssuaq, where there is repeated faulting affecting pillow breccia and the lowest picritic lavas, and in the area to the east of this, where the surface outcrop is pillow breccia, low-frequency refraction seismic surveys would be necessary for obtaining information from depth.

In conclusion, it could be noted that the presence of a thick cover of basalts as an overburden may have had a positive influence on the behaviour of the hydrocarbons.

Thickness of the sediments

It will be necessary at an early stage to obtain more information about the thickness of sediments present below surface in places that are accessible to the drill. A certain minimum thickness must be shown to be present if the area is to be considered attractive for exploration. At this stage it is only possible to give an estimate of the thickness of the sediments based on exposure in various parts of the area. For reasons explained earlier there may well be older sediments present at depth. It is only possible to state that in parts of Nûgssuaq the total thickness of marine sediments is at least 1500 m, and possibly 2000 m.

The Geological Survey of Greenland plans to send a geophysical party to Nûgssuaq during the summer of 1969. This party will undertake magnetometer surveys in the Itivdle valley and magnetometer and gravimeter surveys in the Auvfarssuaq valley. In this way it is hoped to obtain information about the thickness of the sediments and the configuration of the basement in these areas, and it may be possible to obtain some information on the structure of the sediments below the Auvfarssuaq valley.

Areas of interest onshore

With reference to the foregoing account, the following areas of interest onshore can be arrived at. The values listed comprise the areas of exposed marine and non-marine sediments and areas where it is considered that the basalt cover is not very thick. The figures are approximate.

Svartenhuk and Qeqertarssuaq:	800 km^2
Ubekendt Ejland and Upernivik Ø:	100 km^2
Nûgssuaq:	2800 km^2
Disko:	2300 km^2
Total	6000 km^2

Offshore area

The position of the 200 m isobath off the coast of West Greenland is shown in fig. 9. Although the latest bathymetric charts suggest that the continental shelf round much of Greenland extends as far as the 500 m isobath, the 200 m isobath is accepted here as the limit to the shelf for practical purposes at present. Thus defined, the shelf area adjoining the onshore part of the West Greenland basin extends westwards for a distance of 50 to 100 km, except for the area north-west of Nûgssuaq, where there is an embayment and the shelf area is therefore narrower. Immediately south of Egedesminde the shelf area extends about 100 km westwards, this distance decreasing gradually to the south to about 50 km off Kap Farvel.

Access

The various parts of the West Greenland basin are readily accessible by sea during the summer. However, from about Christmas until the end of May the sea is frozen over in most of this area and access by sea would require the use of icebreakers. Icebergs that have come from the numerous glaciers in this part of West Greenland can be encountered

Fig. 9. Map showing the position of the 200 m isobath off the west coast of Greenland.

throughout the area. Their distribution varies considerably from one area to another at any one time, but their presence represents an obstacle to offshore drilling in this part of West Greenland. However, it can be mentioned that in the offshore area to the south icebergs, particularly larger icebergs, are encountered much less frequently than in the area farther north. Pack ice coming from East Greenland is encountered in the southernmost part of the offshore area and pack ice from the Baffin Bay area can be encountered farther north, but it can be stated that the area between Holsteinsborg and Fiskenæsset is the area where pack ice is least likely to be encountered. The period from the end of July till the end of November is the most favourable in this area.

Good natural harbours are few and far between. In north-western Nûgssuaq the best natural harbour is at the abandoned settlement of Nûgssuaq on the extreme western end of the peninsula, where the dipping basalts extend seawards along the strike to form a series of skerries. This area is reasonably well protected from all except south-west storms, and if some of the channels were deepened and breakwaters built a reasonable anchorage could be made. It is possible to anchor at Marrait kangigdlît, farther east along the south coast, but this place is unprotected against north-west storms. Much farther to the east, there is a natural anchorage at Atanikerdluk, where ships seek shelter when it is impossible to anchor at Qutdligssat on the north coast of Disko.

There are no all-weather anchorages on the north coast of Nûgssuaq, but it is possible to anchor at Niaqornat, Qaersut (between Niaqornat and Kûk) and a few other places in calm weather.

Access to the interior parts of the various peninsulas and islands is difficult for a variety of reasons. First of all, most of the country is very rugged. The sides and floors of the valleys are lined with Quaternary deposits, and as this is a permafrost area, these deposits are subject to solifluction; this will introduce difficulties in maintaining roads. Moreover, the solifluction deposits are very soft in the early part of the summer and wheeled transport tends to sink in. However, the Survey maintains jeeps at Marrait kangigdlît on the south coast of Nûgssuaq, and it is possible to drive the 70 km into Agatdalen in August and early September. In summer the rivers of the area are often fast-flowing and deep, since they are fed by melt water from glaciers; the shallower rivers on the sides of Auvfarssuaq and Agatdalen can, however, be crossed by jeep in the late summer.

The relief around the anchorage at Nûgssuaq is not too extreme and it would probably be possible to make a landing strip for light aircraft here. From the area of the landing strip it would be possible to build a road across the hills to the scarp overlooking the Itivdle valley. It should also be possible to build a landing strip at Marrait kangigdlît and a road could be built from here westwards along the coast to Itivdle.

Acknowledgements

The writer would like to thank Professor A. Rosenkrantz for making so much information available for this report and for time spent in discussion of the contents. Thanks are also due to Professor T. Birkelund, Dr N. B. H. Stevens and to Messrs B. Eske Koch, K. Raunsgaard Pedersen and T. C. R. Pulvertaft for critical reading and discussion. Mrs. R. Larsen kindly assisted with some of the diagrams.

APPENDIX

RESULTS OF THE OIL SOURCE ROCK ANALYSIS OF SURFACE SAMPLES FROM WEST GREENLAND

N. B. H. Stevens

INTRODUCTION

Discussion on the analysis in general

Oil source rock and oil migration analysis is undertaken in order to determine the presence of commercial source rocks of petroleum and natural gas and to distinguish these source rocks from other types of bituminous rocks, such as the so-called oil shales and rocks containing secondary, migrated hydrocarbons.

The analysis is a microchemical analysis and comprises the determination of moisture, carbonate content and nitrogen content and extraction by two different solvents of a fixed composition, after the rocks have been ground to the same grain size.

This analysis has been developed as the result of research over the years. The analytical methods applied, the special apparatuses to carry out the analysis and the criteria for interpretation have been developed as a result of this research.

By starting the first analysis in an oil-bearing basin and by taking rock samples from a complete sedimentary sequence down to the basement, it was possible to be certain that the samples analysed included source rocks, and properties were noted which distinguished those rocks that were believed to be source rocks from the non-source rocks, including rocks with migrated hydrocarbons.

This led to the establishment of criteria, at least for the basin concerned, the preliminary conclusions having been confirmed by tracing the relationships on the basis of organic and inorganic components in all rocks analysed. Subsequently, the same analysis was applied to other basins and the results were confirmed by the same checks in some of the basins investigated. Meanwhile the analysis and the criteria for interpretation were refined, after the same analysis had been applied to a large number of samples of all types of bituminous rocks.

Since then, the analysis has been applied as a routine analysis of samples from many basins all over the world. The experience obtained in various basins is of course helpful, especially in the evaluation of prospects.

As source rock formation is a facies phenomenon, it is evident that for an evaluation of prospects, geological information in general and stratigraphic information in particular, including environments of deposition, are of great importance in selecting areas of varying interest. For instance, the presence of source rocks was often noted in beds formed when a transgression had been followed by a rather sudden regression.

This is only one item that illustrates the necessity of an integrated source rock and geological study; a detailed source rock analysis in a stratigraphic and lateral sense is necessary if the best evaluation in terms of areas of interest is to be obtained.

Discussion on the type of analysis

The determination of moisture is simply a routine part of the analysis which has to be carried out but has no significance for interpretation purposes, unless the moisture content is excessive or indicative of special circumstances.

The carbonate content has proved to have a relation with the nitrogen content, probably attributable to action by ions, and has therefore to be taken into account. All other analytical results, including the nitrogen content, are of prime importance for interpretation, the amounts as well as their ratios.

Two different solvents are used; each has a fixed composition, which is obviously necessary for comparison. One solvent mainly extracts hydrocarbons present in petroleum. This solvent gives extract A as indicated in the following table. The other solvent extracts other organic compounds, e.g. those related to higher plant remains, etc. The second solvent gives extract B.

Sometimes additional analyses are required or desired. For instance, it may sometimes be desirable to determine the sulphur content in the extract in order to find out the quantity of hydrocarbons left for interpretation purposes, especially if the sulphur content is high. This was done with the samples dealt with in this report. In some cases, depending on the environment of deposition, the determination of acidities yields desirable supporting evidence for the interpretation.

Finally, the term total organic carbon content should be explained. It has been proved by chemical analysis that the organic carbon content determined does not constitute the total organic carbon present in the rock analysed. In order to arrive at this, an average correction factor of 1.22 has been determined, which is fairly accurate for any sample analysed. In other words, in order to know the total amount of organic carbon present, the amount of organic carbon stated should be multiplied by 1.22. This total organic carbon content is of no specific importance, but should be mentioned as an overall comparative value.

23 surface rock samples from West Greenland were selected for oil source rock analysis, 22 from the Nûgssuaq peninsula and one (no. 113287) from the island of Disko. The sample numbers and ages are given in the table. Samples collected in the permafrost are marked with an asterisk. The stratigraphic positions of the samples are indicated in table 3 in the main report. From this it may be noted that the samples cannot be considered to be fully representative of the sedimentary sequence as a whole. Following the source rock analysis, an element analysis was carried out on two selected samples from Nûgssuaq and on another sample (no. 49756) with bitumen impregnation, which was collected from the west side of the island of Qeqertarssuaq.

ANALYTICAL RESULTS

The results of the analysis are tabulated below in weight percentages.

Sample	Age	Moist.	Carbonate	N	Org. C	Extr. A	Extr. B	S in A	Total org. C
112139*	U. Danian	4.28	10.4	0.14	4.36	0.14	0.039	91.0	5.32
112140*	"	3.51	15.6	0.14	4.30	0.26	0.46	89.4	5.25
113011	"	3.81	15.3	0.29	6.37	0.023	0.048	11.3	7.77
113287	Danian?	1.96	12.6	0.12	3.10	0.014	0.020	13.9	3.78
112110*	L. Danian	3.17	15.5	0.08	2.47	0.05	0.062	81.1	3.01
112114*	"	3.19	10.7	0.13	4.42	0.20	0.087	96.1	5.39
112115*	"	8.00	42.4	0.04	0.84	0.008	0.041	3.0	1.02
112116*	"	5.27	20.9	0.15	4.38	0.37	0.074	96.7	5.34
112966	L. Danian?	1.85	8.2	0.19	7.20	0.082	0.041	29.2	9.08
112109*	Maastrichtian	4.75	19.5	0.14	2.79	0.017	0.034	44.1	3.40
112101*	U. Campanian or slightly older	3.15	6.3	0.29	6.88	0.13	0.031	94.6	8.39
112102*	"	3.45	8.6	0.29	7.15	0.017	0.022	3.5	8.72
112103*	"	3.77	11.8	0.29	6.88	0.10	0.026	95.4	8.39
112104	"	2.48	8.7	0.34	7.79	0.09	0.063	79.2	9.50
112953	"	2.16	3.7	0.26	10.33	0.33	0.011	89.8	12.60
112859	L. Santonian or slightly younger	3.38	9.1	0.25	7.81	0.12	0.024	95.8	9.53
112954	"	2.19	2.6	0.20	6.08	0.14	0.009	98.2	7.42
112106	"	2.89	9.3	0.23	7.06	0.22	0.043	96.3	8.61
112107	"	2.29	3.5	0.24	6.47	0.27	0.029	96.4	7.89
112108	"	2.93	9.6	0.21	5.40	0.15	0.041	94.8	6.59
112909	Barremian-Aptian	0.98	14.0	0.08	4.39	0.008	0.018	0.0	5.36
111605	"	0.81	5.0	0.006	0.53	0.004	0.002	14.1	6.47
112132	"	1.30	3.1	0.02	1.74	0.009	0.033	23.8	2.12

An element analysis of the samples nos. 112953 and 112966 and of a brecciated sandstone sample with bitumen (no. 49756) of Upper Cretaceous age was subsequently carried out. For the analysis of the first two samples more rock material was used in order to provide a larger quantity of extract. The results are as follows (in percentages):

Sample	Age	C	H	S	Other
112966	L. Danian?	31.3	3.9	19.3	45.5
112953	U. Campanian or slightly older	3.4	not observed but < 0.2	96.4	-
49756	U. Cretaceous	87.7	8.7	< 0.2	3.4

INTERPRETATION OF THE ANALYTICAL RESULTS

Most of the samples show high nitrogen and organic carbon contents exceeding the limits below which samples do not qualify as source rocks. It is surprising that this holds for most samples of various ages, except for one Lower Danian sample and two Barremian-Aptian samples.

A further conspicuous aspect is the often very high sulphur content in extract A. However, although this is not common in source rocks, it is not exceptional, especially in surface samples and in core samples that have been exposed for some time.

Leaving the sulphur content out of consideration for the time being, the following samples do not qualify as source rocks, viz.: 113011, 113287, 112110, 112115, 112109, 112102, 112909, 111605 and 112132, since the extract values fall below the critical limits, whilst the ratios extract A/extract B are too low. For this last reason sample 112140 does not qualify either. Since the samples 112909, 111605 and 112132 represent non-marine rocks, only a negative result could be expected here.

The high sulphur content, which is an uncommon, although not exceptional, feature in source rocks presents an unexpected complication in the interpretation of surface rock samples, particularly as no fresh core sample material was available for comparison, since this elemental sulphur (in statu nascendi) is known to be highly sensitive, especially in the presence of oxygen as at the surface. The burning of the shales at many localities is probably initiated by spontaneous combustion of sulphur.

There is little doubt that the proportionally high sulphur content accounts for the destruction of a large part of the hydrocarbons originally present; the fact that in crude oils the sulphur percentage is only a fraction of the percentages found in the extracts from these samples supports this interpretation. Furthermore, the high organic carbon contents support this view. How far an increase of the sulphur content has been caused by secondary enrichment is hard to evaluate. Only analysis of fresh samples obtained by drilling at some depth where little or no action by, or addition of, sulphur may be assumed, can possibly give a better insight; it would be particularly desirable to have a continuous series of samples from the bottom to the top of the borehole.

However, at this stage it may be stated that the samples 112966 and 112953 represent oil source rocks, because, even when its sulphur content is taken into account, sample 112966 qualifies, as does sample 112953, though to a lesser degree, but the higher organic carbon content has been taken into consideration here. Furthermore, for the time being, until fresh core material is available to elucidate the effects of the sulphur, the remaining samples 112139, 112114, 112116, 112101, 112103, 112104, 112859, 112954, 112106, 112107 and 112108 are considered to range from doubtful to weak source rocks.

Comparing the samples collected in permafrost with those collected above the permafrost, there does not appear to be any difference in the results. This implies that the samples collected above the permafrost may previously have been below the permafrost.

Referring to the results of the element analysis, first of all it should be mentioned that the differences in the C/S ratio, if the present results are compared with those of the source rock analysis, have to be attributed to the fact that for the latter analysis a selected portion of the sample material was used, whereas for the element analysis more and other sample material was used to obtain more extract for the element analysis.

Sample 112953 shows a surprisingly low hydrogen content, which, however, can be explained as a result of chemical reactions whereby the sulphur has largely destroyed the original hydrocarbons. The high organic carbon content indicates this. The sample was collected near an occurrence of burnt shales.

The H/C ratio of sample 112966 suggests a hydrocarbon of a composition in between that of paraffinic and aromatic hydrocarbons. The H/C ratio of sample 49756 from west Qeqertarssuaq indicates a composition near to that of aromatic hydrocarbons. This sample is a brecciated sandstone impregnated with a black material. The analysis proved the presence of bitumen, whose presence in this type of lithology can only be explained as the result of migration of hydrocarbons; this provides indirect evidence of the presence of source rocks.

The composition of the bitumen in sample 49756 is in line with what is known from other areas, i.e. that hydrocarbons of an aromatic type are found in seepages or as impregnations, whereas paraffinic and other types are more usually found in the underlying source rocks forming part of the same sedimentary sequence. This sample 49756 was collected near the rim of the basin in west Qeqertarssuaq, about 700 m from the fault that forms the boundary between the non-marine Upper Cretaceous sediments and the Precambrian rocks to the east. Accordingly, a lateral migration from marine rocks has to be assumed, unless source rocks are present at depth.

COMMENTS

It was not previously known whether the bituminous rocks of the area included true source rocks. The analysis has established that true source rocks are present. This has obviously a definite bearing on the evaluation of the oil and gas prospects of the West Greenland area as well as of the adjoining areas. As becomes clear from the stratigraphic chart, it is only some horizons of the Cretaceous-Danian sequence that have been investigated, and only to a limited lateral extent.

Together with a detailed stratigraphic analysis a more detailed source rock analysis seems therefore required for a proper evaluation of prospects; this should include a continuous series of core samples, so that the part played by the sulphur can be established. It would also be advisable to carry out source rock analysis on samples of Lower Palaeozoic age from the occurrence near Sukkertoppen, south of the West Greenland basin.

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