GEOLOGY and HYDROCARBON POTENTIAL of
THE JAN MAYEN RIDGE
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Authors:
Karl Gunnarsson,
NEA, Reykjavik
Morten Sand,
NPD, Stavanger
Steinar T. Gudlaugsson,
Dept. of Geology,
Univ. of Oslo

Oljedirektoratet
Norwegian Petroleum Directorate
OD-89-91

Orkustofnun
National Energy Authority, Iceland
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ABSTRACT/EXECUTIVE SUMMARY

In 1981 Iceland and Norway agreed upon the partition of the continental shelf in the area between Iceland and Jan Mayen. A joint project of geological mapping of the sub-sea resources of the Jan Mayen Ridge was included in the agreement. This mapping has been executed in close cooperation between Orkustofnun (National Energy Authority - Iceland) and Oljedirektoratet (Norwegian Petroleum Directorate). This report describes the work done, and gives an interpretation of the geological history of the area, including an evaluation of the hydrocarbon-potential. The work has concentrated on the acquisition of seismic data, and the interpretation of these data integrated with other existing geophysical and geological information.

Important conclusions drawn are:

- Reflections from pre-Tertiary strata are locally observed. These may represent Mesozoic sediments that could satisfy the basic conditions for hydrocarbon-generation and accumulation, but they could also partly be basaltic lavas with no hydrocarbon potential. There is no information available about the lithology of these rocks except by comparison with the geologically related areas of East Greenland and the Norwegian shelf.

- The Tertiary history, which is dominated by the plate tectonic opening of the Norwegian-Greenland Sea, is outlined in some detail. Both the tectonics and the sedimentation of the area can now be considered fairly well known. The Tertiary sediments are not likely to satisfy the conditions necessary to form hydrocarbon accumulations. For a better evaluation of this, more information on vertical movements and heat-flow at the ridge through time is needed. Information about the lithology of the early Tertiary sediments is also lacking, source-levels may be present, and stratigraphic traps caused by facies changes
may possibly occur.

- In general the hydrocarbon-potential of the area must be considered low - but all geological conditions necessary for hydrocarbon generation could be present - so at the existing level of knowledge it can not be ruled out.

- Production of possible hydrocarbons can not be expected in the near future because of the deep waters, remoteness and harsh weather conditions of the area.

- The interest of the oil-companies is for the time being low. The seismic data acquired were offered for sale to relevant companies in late 1987, but have until now only been bought by Statoil.

Concluding the report is a set of recommendations. Some further activity in the area is advised. Different levels of activity in terms of cost are defined. Continued interpretation of the existing dataset is the minimum option. Acquisition of more seismic data, shallow drilling and ultimately a deep bore-hole are escalating possibilities. Lack of lithological information from drilling presently makes it impossible to give a final answer to the question of the hydrocarbon-potential of the area, so drilling is the logical next step from a geological point of view. We present for discussion different arrangements for the continued exploration: whether to continue with exclusive governmental work, or to try to obtain participation from oil-companies by opening of the area for geophysical data acquisition or by awarding production licenses in the area.
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1 INTRODUCTION

1.1 PROJECT DESCRIPTION

In 1981 an agreement (included as Appendix 1) was reached between the governments of Iceland and Norway delimiting the continental shelf between Iceland and Jan Mayen. The agreement implies Norwegian acceptance of the Icelandic 200 nautical mile economic zone and continental margin in the area (Fig.1.1). In addition to this clear definition of the national boundaries, the agreement defines a subsea area to be explored by the two nations in company (Fig.1.1). This area is delimited by latitudes N60° - N70°35' and longitudes W10°30' - W6°30'. It covers a total of 45 470 km², of which 32 750 km² is in the Norwegian sector, and 12 720 km² in the Icelandic sector. The two parties also have specified rights to shares in possible hydrocarbon-production from the national subareas of this defined common interest subground. The agreement stipulated a joint survey program, to carry out a systematic geological mapping of the area. For this purpose a geophysical survey with emphasis on acquisition of multi-channel seismic reflection data was considered the most appropriate starting point. The survey was planned and executed in close cooperation between representatives of the relevant governmental bodies: the National Energy Authority (NEA) of Iceland, and the Norwegian Petroleum Directorate (NPD). The acquired dataset was to be considered common Icelandic/Norwegian property and treated confidentially. The Norwegian government was to carry the cost of acquisition and processing of the data. Possible profits from the sales of the data were to be split between the two parties, after costs had been covered. Funds for the acquisition, processing and interpretation of the data have been provided from 1985 and onwards.

This report contains a short description of the acquisition and processing of the geophysical data acquired during the
project. The main part is a description of the geology of the Jan Mayen microcontinent, including an evaluation of its hydrocarbon potential. Also included is a short description of follow-up projects in progress, continuing the regional geological mapping of the area, and recommendations for future exploration activities in the area.
Fig. 1.1. Bathymetry and political boundaries in the Norwegian-Greenland Sea. Approximate continental shelf boundaries are shown with broken lines. Location of the Icelandic-Norwegian treaty area on the Jan Mayen Ridge stippled. Bathymetry from Perry et al (1980).
1.2 THE JAN MAYEN RIDGE 1985 SEISMIC SURVEY

1.2.1 DATA ACQUISITION

A survey plan was set up by NPD and NEA early 1985. In anticipation of weather and technical problems lines on three priority-levels were planned, totalling some 5000 km. Most lines were planned with normal 7-8 seconds recording time and shot-intervals of 25 m. Some lines with 15 seconds recording time and shot-intervals of 50 m were included in order to increase the understanding of basement-structure and the deeper crust. A number of seismic companies were invited to submit bids for the acquisition of data according to this plan which was incorporated into NPD's total data-acquisition programme for the season. It was decided to use GECO's vessel Malene Østervold for the survey.

The survey lasted from July 17 to August 31, with a break in the period 13-18 August for crew-change and shooting of a proprietary survey for NEA north of Iceland. A total of 4236 profile-km were shot, out of which 247 km were reshot because of faulty control of shot intervals. Figs. 1.2 and 1.3 and App. 4a show the location of the lines.

The navigation used during the survey was primarily LORAN-C, backed up by GPS and Transit satellite navigation when available. The seismic equipment included an airgun-array with a total volume of 3564 cubic inches, a 3 km long 120 channel streamer, and a DFS-V recording system. A more thorough description of the acquisition parameters is given in Appendix 2.

Gravity and magnetics were recorded during the whole survey. A Lacoste-Romberg gravimeter was used. The recovery of gravimetric measurements was 100 %. Magnetics were recorded with a Geometrics G801 instrument. It did not function during shooting of lines 19, 20, 21 and 22.
Fig. 1.2 Geophysical survey grid on the Jan Mayen Ridge acquired by NPD and NEA in 1985, and by NPD in 1979. Bathymetry from Richardson et al. (1981).
Sonobuoy station

Multichannel seismic reflection lines:

- recording time 15s
- recording time 6-8s

Fig. 1.3 Seismic reflection grid and sonobuoys acquired on the Jan Mayen Ridge by NEA and NPD in 1985, and by NPD in 1979.
Of 44 sonobuoys that were deployed for refraction seismic registration during the survey, 38 worked satisfactorily. They were all recorded both in analog and digital form. Their location is shown in Fig. 1.3 (App. 4a).

The Final Field Operation Report from GECO, and the Supervision Report from the hired client's representative (Delph Management Ltd), are both available, and give full information on technical equipment, and on the daily operations.

1.2.2 DATA PROCESSING

Seismics

The seismic companies were invited to submit bids for processing of the acquired seismic data. After evaluation of prices, six companies were invited to do processing tests on the data-set. Based on the results, GECO A/S, Sandvika, was awarded the processing contract. An initial timeschedule for the processing agreed on by both parties was set up in February 1986. According to the schedule the work was to be completed in September 1986. GECO proved to be unable to comply with the schedule, causing delay also of the interpretation of the data. Delivery of the final seismic sections took place in October 1987.

The objective of the processing was to obtain good overall data-quality. No specific horizons or levels were optimized at the cost of others. Suppression of multiples was the most difficult problem to cope with. FK-multiple attenuation and weighted stack proved necessary. For noise-reduction and data-reduction nmo-corrected summation of every two adjacent traces in the shot gathers was carried out. Remnant noise was attenuated with a post-stack FK-filter. Seismic data from the area acquired and processed by NPD in 1979 were post-stack reprocessed to make them more comparable with the 1985-vintage data.
Generally the final data-set is of good quality, giving better resolution and penetration than earlier seismic investigations in the area.

Appendix 2 gives a description of the processing sequence. The available Processing Report gives full information on tests and evaluations during the processing.

**Gravity/Magnetics**

The gravimetric and magnetic data were processed by GECO A/S. No specific problems arose during the processing. Digital recordings at a temporary landbase (Tjørnnes) in northern Iceland were used as a control of the variability of the magnetic field. The data were all integrated with the dataset acquired by NPD in the area in 1979. The final product consists of profiles in horizontal scale 1:50.000, plotted to match the migrated seismic sections (in 1/2 scale), and maps (contoured and annotated) in scales 1:500.000 and 1:250.000 of waterdepth, free-air-anomalies, Bouguer-anomalies and magnetic anomalies.

**1.2.3 SALES OF DATA**

All data have been offered for sale to relevant companies/institutions. The offer includes filtered and migrated seismic sections in full, half and squashed scales, together with gravity/magnetics profiles and maps. Both 1979 and 1985 vintages are included in the sales. In order to keep the companies entry costs relatively low the data-set was divided into two parts. The basic package, intended to give a regional overview of the area, consists of 1800 profile-km and is priced at NOK 995.000,-. The other package contains the rest of the data, 2800 profile-km, priced at NOK 1.450.000,-. The letter offering the data for sale is included as Appendix 3. Till October 1989 only Statoil has bought the basic package.
2 GEOLOGY OF THE JAN MAYEN RIDGE

2.1 BACKGROUND

2.1.1 PHYSIOGRAPHY OF THE JAN MAYEN RIDGE

The Jan Mayen Ridge (JMR) is a bathymetric ridge complex extending southwards from the Jan Mayen island (Fig. 2.1). The ridge complex is thought to be composed mainly of continental crust, but can be transitional in nature where it is broken up and subsided. We also loosely use the term JMR to denote this geological entity, the Jan Mayen microcontinent.

The ridge can be divided into two main structural elements, a northern and a southern part. The northern part, here referred to as the North Ridge, is a prominent flat-topped ridge that extends southwards from the young volcanic island Jan Mayen. Water-depth over the top of the North Ridge increase towards the south, and is close to 1000 m over much of its southern half. This ridge is terminated by a NE-SW trending depression, the Jan Mayen Trough. Oceanographers often use the term Jan Mayen Ridge for this northern ridge only.

To the south of the trough is a complex of minor ridges, that becomes subdued and indistinct towards the south. This part of the ridge is referred to as the Southern Ridge Complex. The ridges rise up to 1000 m depth from the surrounding plain that is some 1500 to 2000 m deep. These ridges gradually disappear to the south, and are buried in young sediments and lava as Iceland is approached.

On the east side of the JMR is the Norway Basin, about 3500 m deep, extending to the continental margin of Norway. The area to the west of the ridge is generally called the
FIG. 2.1 Bathymetry of the Jan Mayen Ridge (from Richardson et al. 1981)

DSDP sites shown by dots and numbers.
Iceland Plateau, and is considerably shallower than the eastern basin, typically some 1500 m deep. The area just west of the North Ridge forms a distinct flat-bottomed depression, called the Jan Mayen Basin, with depths just exceeding 2000 m. The Iceland Plateau terminates to the west at the active spreading ridge called Kolbeinsey Ridge, but some writers use the term Iceland Plateau for a wider area extending westwards to the continental shelf of Greenland and including also the southern JMR area.

2.1.2 EARLIER GEOPHYSICAL INVESTIGATIONS

The Jan Mayen Ridge has been rather extensively studied compared to the rest of the North-east Atlantic. The academic interest in this area has been truly multinational. American, German, Soviet, French, British and Norwegian institutions and universities, have conducted surveys and experiments in the area. In the early phase of investigation, considerable amounts of single channel seismic data were acquired, together with magnetic and gravity data (see e.g. Johnson and Heezen, 1967, Talwani and Eldholm, 1977, Grønlie and Talwani, 1978). Especially the cruises of the Vema and Conrad from the Lamont-Doherty Geological Observatory contributed a great deal to the understanding of the area.

The second phase of investigation of the JMR and the surrounding ocean basins consisted principally of a number of regional surveys, using the multi-channel seismic reflection method. The multi-channel cruises or projects that have included the JMR are (Fig 2.2):

- Cepan 1 Cruise 1975: A cruise by French institutions, also referred to as the CNEXO-data (Gairaud et al. 1978). A considerable amount of fair quality data in and around the entire JMR area. Includes magnetics.
- University of Bergen 1978 survey: A cruise of the Håkon Mosby, mainly on the northernmost part of the JMR (see Sundvor et al, 1979).
- Conrad 1978 cruise(C2114): A project of the Lamont-Doherty Geological Observatory. This cruise included an expanding spread seismic experiment on the northern JMR. (See Olafsson, 1983, and Johansen et al, 1988)
- NPD 1979 survey: A reconnaissance survey of the North Ridge. This survey was the first step by the NPD to investigate the area by the seismic reflection method (see Eggen, 1984)
- NPD-NEA 1985 survey: The Norwegian-Icelandic survey which forms the main database for this report.
- University of Oslo 1987 survey: A cruise of Håkon Mosby, concentrated on areas east of JMR, but with two profiles located on the eastern part of the North Ridge.

Surveys in the area using other methods than multi-channel seismics are:

- Project Magnet Aeromagnetic survey: This large scale survey by the US Naval Oceanographic Office of the entire Iceland Plateau includes the southern and western parts of the JMR area. Line spacing are 5.5 and 11 km (see Vogt et al., 1980).
- NPD aeromagnetic survey 1976: Commissioned by the NPD and carried out by Compagnie Generale de Geophysique. Consists of a 5 by 15 km grid on the main JMR, totalling 11 620 km. (See Navrestad and Jørgensen, 1979).
- University of Hamburg, 1984 (Arktis II/5): A seismic refraction study of the JMR, employing ocean bottom seismometers and explosives (Weigel et al. 1986)

- University of Hamburg, 1987: A continuation of the 1984 project based on use of ocean bottom seismometers.

- IFP 1987 survey: Institut Francais du Petrole carried out a seismic refraction study. A series of Expanding Spread Profiles were measured, to obtain better understanding of the crustal structure by velocity observations. The data are being interpreted at the University of Oslo.

The earlier data represented a combined data base of considerable quantity. It was anyway evident that the uneven distribution of lines and variable and often unsatisfactory quality of the data required a systematic reflection survey of the most likely hydrocarbon exploration area. This was the basis for the NPD-NEA survey in 1985.

2.1.3 RESULTS OF DSDP-DRILLING

The only boreholes on Jan Mayen Ridge and its vicinities were drilled during leg 38 of the Deep Sea Drilling Project (DSDP) in 1974 (Talwani, Udintsev et al. 1976). 18 holes were drilled in the Norwegian-Greenland seas, of which 5 holes, numbered 346-350, were drilled at or near the Jan Mayen Ridge (Figs 2.1 and 2.6). Sites 346, 347 and 349 were drilled on the North Ridge, site 350 was drilled in the Southern Ridge Complex, and site 348 on oceanic crust on the Iceland Plateau. Table 2.1 lists the positions, waterdepths and penetration of the boreholes.
Fig. 2.2 Multichannel seismic reflection and refraction data acquired on the Jan Mayen Ridge by academic institutions 1975-87
Table 2.1: DSDP boreholes in the Jan Mayen Ridge area drilled during leg 38 in 1974.

<table>
<thead>
<tr>
<th>Hole</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water-depth</th>
<th>Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deg Min</td>
<td>Deg Min</td>
<td>(m)</td>
<td>(m)</td>
</tr>
<tr>
<td>346</td>
<td>69 53.35N</td>
<td>08 41.14W</td>
<td>732</td>
<td>187</td>
</tr>
<tr>
<td>347</td>
<td>69 52.31N</td>
<td>08 41.80W</td>
<td>745</td>
<td>190</td>
</tr>
<tr>
<td>348</td>
<td>68 30.18N</td>
<td>12 27.72W</td>
<td>1763</td>
<td>544</td>
</tr>
<tr>
<td>349</td>
<td>69 12.41N</td>
<td>08 05.80W</td>
<td>915</td>
<td>320</td>
</tr>
<tr>
<td>350</td>
<td>67 03.34N</td>
<td>08 17.68W</td>
<td>1275</td>
<td>388</td>
</tr>
</tbody>
</table>

The lithologies and inferred ages of the penetrated rocks are summarized in Fig 2.3. Holes 347 and 348 are not included because they were respectively drilled very close to hole 346, and relatively distant from the Jan Mayen Ridge. Hole 348 penetrated 527 m of sediments, before bottoming in basalts. The sediments were mainly mudstones, partly sandy mudstones containing mainly cold-water fauna. Age determinations show Pleistocene at the top, to the Miocene/Oligocene transition at the bottom. The age of the tholeiitic basalts seems to confirm this age for the creation of the basaltic basement. Hole 350 at the southeastern rim of the Jan Mayen area also bottomed in basalts after penetrating 346 m of mainly mudstones and sandy mudstones. A relatively thin Pleistocene-Miocene section is underlain by Oligocene and Late Eocene sediments, with well developed turbidites towards the base. The basalts bottoming the hole were normal tholeiites with an indicated age of 40-44 m.y. - in accordance with the paleontological dating of the overlying sediments.

The three holes drilled on the North Ridge proper (346, 347 and 349) have important common traits. They were (unintentionally) all drilled shortly west of a main down to the west normal fault, and thus not optimally positioned
to reach as deep stratigraphic levels as was technically feasible (Fig 2.4). Accordingly they all penetrate only sediments of a Pleistocene - Late Eocene age, and encountered a main unconformity at depth about 120 m below seabottom. The top sediments of the holes 346 (347 was drilled close to 346) and 349 are of Pleistocene/Pliocene age, and have "glacial" origin, containing supposedly icerafted material. A second unit, of Middle Miocene - Late Oligocene age is identified. Its main lithologies are muds and sandy muds with occasional layers of volcanic ash. Below the main unconformity at 120 m depth Late Eocene sediments are found, consisting of bioturbated mudstones and sandy mudstones. In lower parts turbidites are abundant.

In hole 346 the sandcontents of the lower unit is generally about 30%. Above it sandcontents are generally below 20%. In hole 349 an interval right above the main unconformity has sandcontents above 50%. So has an interval at about 150 m depth. All other samples show sandcontents below 20% in this hole. In hole 350 relatively few measurements of sandcontents was done, giving results in the interval 0.5-35% sand (Cameron 1978).

Additionally some analyses of the organic geochemistry of the cores from DSDP leg 38 have been done. These are reported on in chapter 3.1.1.
Fig 2.3  Lithostratigraphy of DSDP-sites 346, 349 and 350.
Fig 2.4 Interpretation of a part of seismic line JM-32-85, through DSDP site 349, showing stratigraphic correlation.
2.1.4 PLATE TECTONICS AND GEOLOGICAL REVIEW

Previous studies of the area have concluded that the Jan Mayen Ridge is likely to be a microcontinent. The Jan Mayen island and its immediate surroundings is supposed to be of volcanic origin created by extrusion of abnormal amounts of volcanic material, while most of the ridge is believed to be of continental origin, split off and isolated by the intricate opening history of the Norwegian-Greenland sea. This is based partly on the geophysical properties of the ridge (see e.g. Myhre et al. 1984): Gravity modelling on traverses across the ridge indicates relatively light material in the ridge, the ridge and its immediate surroundings are magnetically relatively quiet, and seismic refraction studies give velocity profiles similar to measurements made on the East Greenland and Norwegian margins. Studies of the Tertiary plate tectonic history of the area also support the assumption that the Jan Mayen Ridge is a microcontinent. The basic pattern of spreading history affecting the JMR was already established by Johnson and Heezen (1967). Talwani and Eldholm (1977) established a comprehensive model for the opening of the entire Norwegian-Greenland Sea, that has later only been modified or challenged in regard to details.

The initial opening of the Norwegian-Greenland sea took place east of the Jan Mayen Ridge about the time of the transition Paleocene/Eocene, probably at the time of the reverse magnetic epoch between the normal anomalies 24 and 25. This age is about 57 Ma according to the time scale of Berggren et al. (1985), which is consistently used in this report. After a phase of normal parallel spreading until the time of anomaly 22 (52 Ma) according to Skogseid and Eldholm (1987) or anomaly 20 (45 Ma) according to Nunns (1983a), during which the Jan Mayen Ridge only existed as the outermost part of the continental margin of East-Greenland, a phase of irregular spreading began. A new rift or spreading axis was activated west of the Ridge, and
sliced it off from the Greenland margin, while the older axis to the east (the Aegir Axis) remained active. Figure 2.5 illustrates the spreading history.

When these two rifts had formed east and west of the JMR, a small crustal plate consisting of the Jan Mayen microcontinent and the attached western half of the oceanic crust of the Norway Basin, began to rotate counterclockwise, causing spreading rates in the Norway Basin to be greater in the north than the south. This phase of two spreading axes continued until the time of anomaly 7 (26 Ma). Evidence for this period is found in the Norway basin, where the magnetic anomalies show a fan-shaped pattern, widening out to the north. Rigid plate geometry demands a similar fan-shaped pattern to the west, opening up to the south, to compensate for this irregularity. Such anomalies have not been observed, and the area formed by this spreading is not well defined. It is assumed that the

Figure 2.5 (see next page)
Reconstruction in four stages of the opening of the NE-Atlantic in the vicinity of the Jan Mayen Ridge (modified and simplified from Nunns 1983a). a) At the time of the beginning of anomaly 24 (56 Ma), which is the oldest detectable magnetic anomaly between Greenland and Europe. Spreading began shortly before this time. b) End of anomaly 20 time (45 Ma). At this time the spreading on the Aegir axis in the Norway Basin, originally normal, had developed into fan shaped spreading, complementary spreading was beginning between Greenland and the Jan Mayen Ridge. This led to counterclockwise rotation of the Jan Mayen microcontinent away from Greenland. c) End of anomaly 7 time (26 Ma). Spreading in the Norway Basin is finally extinct, and regular spreading being established on the Kolbeinsey Ridge west of the Jan Mayen Ridge. d) Present. Note that anomaly 5 (10 Ma) is indicated on the Kolbeinsey and Reykjanes Ridges.
mode of spreading in this area did not give rise to identifiable anomalies. Talwani and Eldholm (1977) point to parts of the Southern Ridge Complex. Nunns (1983 a,b) considers that the complementary spreading took place to the west of the ridge. Larsen (1988) expresses a similar view, and suggests a northwards propagation of the Kolbeinsey Ridge spreading axis over a period of time, together with a parallel termination of spreading on the Aegir Ridge. Crustal extension in the Jan Mayen Ridge area could also have taken up some of the spreading, but this is less well understood.

This abnormal phase ended when spreading ceased in the Norway basin, and only the western spreading axis remained active. According to Talwani and Eldholm (1977) this happened at the time of anomaly 7 (25 Ma), when a now extinct spreading axis, the Iceland Plateau Axis, took over all spreading activity, until a further westward jump of the axis initiated the now active Kolbeinsey Ridge. Vogt et al. (1980) are of the opinion that this intermediate axis did not occur but that the Kolbeinsey Ridge has been active from the start. The above mentioned variations in opinion of the detailed spreading history of these oceans do not lead to basically different models for the tectonic history of the JMR.

A geological map of the area (Fig 2.6) shows the areas of assumed continental origin surrounded on all sides by oceanic crust of varying age. On both sides of the ridge are strips of crust that are of uncertain composition. Interpreted seismic lines (Fig 2.7) show typical cross-sections of the Ridge in two locations. The North Ridge has a characteristic cross-section, tilted down to the east, and with distinctly asymmetric flanks. The eastern flank is only mildly affected by faulting, and the Tertiary sedimentary wedge and the acoustic basement bear witness of progressive eastward tilting. The western flank of the ridge is by contrast formed by extensive normal faulting,
where the movement is down on the western side. Bathymetric maps and seismic sections show a complex pattern of fault blocks that have subsided to varying degree into the Jan Mayen Basin.

The ridges of the Southern Ridge complex (Fig 2.7) are mostly NNE-trending, partially surrounded by the flatlying opaque basement reflector of the western volcanic region, which is found in structurally low areas. Many attempts have been made to unravel the structural complexities of this part of JMR. Talwani and Eldholm (1977) recognized 6 ridges, partially on the basis of gravity anomalies, and denoted them as R1-R6. They considered some of them to be continental in origin, but the SE-corner of the area to be oceanic.

Horizon O (Fig. 2.7) represents a reflector at the base of the Tertiary sedimentary succession that is supposed to be composed of lava extruded shortly before the ocean-basin started to form. It was opaque on all vintages of seismic data up to the NPD 1979-survey (Eggen 1984), so previous authors have not discussed the pre-Paleocene/Eocene history of the ridge based on seismic reflection data.

2.1.5 THE CONJUGATE MARGINS

The post-Caledonian history of the area between Greenland and Norway is generally speaking characterized by tension. A rifting process was initiated in Late Carboniferous/Early Permian and ended with seafloor-spreading and the creation of a deep ocean basin - the Norwegian-Greenland Sea - in Early Eocene. The accompanying faulting and vertical movements have created lateral facies changes and hiatus/erosional phases that are not known in detail. As we have no direct observations of pre-Paleocene/Eocene lithology
Fig 2.6 Geological map of the Jan Mayen Ridge area. From Richardson et al. (1981). An interpretation of profiles CEPA-75-108 & 129 is shown in Fig. 2.7.
Fig. 2.7 - Interpreted seismic profiles CEPA-75-108 and 129 crossing the North Ridge (JMR) and the Southern Ridge Complex. Profile locations in figures 2.2 and 2.6. The sediment lithologies and ages are based on drilling at DSDP Sites 346, and 349 on the North Ridge. (Nunns 1983b, modified from Gairaud et al 1978).
lithology in the area between Haltenbanken and East-Greenland the best we can do is to assume a sedimentary sequence with parallels to the flanking shelf- and on-shore sediments.

Palinspastic reconstructions show the pre-rift position of the Jan Mayen microcontinent. There are slight differences in the positioning suggested by different authors, but the general picture is agreed upon (Figs. 2.5 and 2.8).

On the Greenland side (for a geological review see e.g. Surlyk et al. 1981, 1984 and 1986, and Larsen 1984) the microcontinent was lined up along the Blosseville Coast and Liverpool Land. On the Blosseville coast early Tertiary subaerial lavas of thickness up to several km cover a thin, patchy layer of sediments of Late Cretaceous/Paleocene age resting upon Precambrian basement. Liverpool Land is a horst containing Precambrian rocks, lying just seaward of an extensive area of the post-Caledonian Jameson Land basin, containing Devonian-Cretaceous sedimentary rocks. This basin continues further north along the Greenland coast (Fig 2.8). Larsen (1984) interprets seismic data offshore Liverpool Land, and concludes that fault-blocks of Mesozoic or older age underlie large accumulations of Tertiary sediments.

On the Norwegian side (for a geological review see e.g. Bøen et al. 1984, Brekke and Riis 1987, Bukovics et al. 1984 and Skogseid and Eldholm 1989) the microcontinent was bordered to the north by the Jan Mayen Fracture Zone and Voring Basin, to the east by the Faeroe-Shetland Escarpment and the Møre Basin. Both these neighbouring basins were subjected to large-scale Cretaceous subsidence. Sediments have been mapped in patches on the Norwegian mainland (Devonian basins in Western Norway), and on Andøya, while extensive mapping offshore based on seismics and borehole information, has uncovered that the shelf is totally covered with post-Caledonian sediments (Fig 2.8). Very
little is known about the pre-Early Triassic stratigraphy on this part of the Norwegian shelf.

This results in three basic alternatives for the lithostratigraphy of the pre-opening rocks at the Jan Mayen Ridge:

1) a thick Paleocene, mainly volcanic, deposit as on the Biosseville Coast
2) thick deposits of Cretaceous age as on the outer parts of the Norwegian shelf
3) mainly a Jurassic and Triassic sequence with a stratigraphy comparable to the inner parts of the conjugate margins.

The seismic reflectivity and velocity structure of the deeper parts of the ridge established in this study indicates that at least parts of the ridge contain a pre-Cretaceous sedimentary section. It is however impossible to predict with any certainty the lithologic column below the Early Tertiary basalt. The stratigraphy and main tectonic phases of the relevant parts of the conjugate margins are shown in Fig 2.9, to indicate probable pre-Tertiary sediments, and thereby source/reservoir combinations that could be found on the JM-microcontinent.
Figure 2.8 Pre-drift location of the Jan Mayen Ridge relative to Greenland and Norway. Onshore geology and structural elements offshore shown schematically.
Generalized lithostratigraphic columns for the Haltenbanken area offshore Mid-Norway and Jameson Land in Central East Greenland. Major tectonic events and potential source and reservoir levels are indicated.

1) Dalland, Worsley & Ofstad, 1988
2) Surlyk, Piasci & Rolle, 1986
3) Brekke & Ris, 1987
2.2 TECTONIC PHASES

The short outline of the tectonic history of the Jan Mayen Ridge presented here, is based on the new results obtained in this study integrated with earlier results.

In Late Paleozoic and Mesozoic times, the Jan Mayen Ridge was located in the western part of the regional system of post-Caledonian rift basins between Greenland and Norway (Fig. 2.8). The ridge was established as a separate structural entity in the Tertiary as a result of two main tectonic events (Figs. 2.5 and 2.10):

1) The opening of the Norway Basin in the earliest Eocene, when the ridge still remained as a part of the Greenland continental margin, and

2) The separation of the ridge from Greenland through rifting and formation of a new spreading centre on the Greenland margin in the period from middle Eocene to the end of Oligocene.

Both events led to the formation of a passive rifted margin (Figs. 2.11 and 2.12). In the first event, a volcanic margin was formed on the eastern side of the ridge. In the second, a blockfaulted margin, to a lesser degree affected by volcanism, was formed on its western side. As the margins developed, each went through a rift phase, characterized by crustal extension, magmatism and initial isostatic adjustment, followed by breakup and a drift phase characterized by thermal subsidence and sediment loading. Because of the short time interval between the two events, the thermal structure and vertical movements resulting from the first event were strongly modulated by the second event.

The syn- and post-opening history may be divided into four phases of tectonic development by rift onset and breakup at
the two margins (Figs. 2.10 and 2.19)

First rift phase

The eastern volcanic margin was formed as the continent rifted on the Greenland side of the wide Jurassic/Cretaceous rift. There is remarkably little evidence for brittle deformation of the upper crust in this phase. The extension, which was accompanied by uplift and regional tilting, was apparently concentrated on a few widely spaced faults. The late rift and early drift stages were accompanied by the emplacement of basaltic dike swarms and subaerial eruption of a voluminous suite of basaltic lavaflows which now covers the ridge.

First drift phase

Breakup was followed by parallel seafloor spreading on the Aegir axis, and thermal subsidence of the margin and the spreading centre beneath sea level as the Norway Basin was formed. Sediments derived from Greenland accumulated at the margin and a paleo-shelfedge was built from the west.

Second rift phase

The western block-faulted margin was formed when a new rift, contemporaneous with the later stages of the Aegir Axis spreading centre, opened from the Iceland hotspot into the Greenland margin and gradually separated the ridge from Greenland. The Jan Mayen microplate was partly rotated anticlockwise and partly deformed between the competing spreading centres. The rifting process broke the earlier continental margin into a complex of rotated fault blocks. Magmatic activity was renewed and a sill complex was emplaced beneath the slope of the eastern margin.
Fig.2.10 Stratigraphy and tectonism at the Jan Mayen Ridge. The chart shows the correlation between phases of seafloor spreading in the Norway Basin and on the Iceland Plateau, tectonic phases at the Jan Mayen Ridge, and the main seismic stratigraphic markers.
As the incipient rift subsided, sediment input to the ridge from the Greenland side was shut off. Parts of the eastern rift flank, which now constitutes the JMR, were uplifted above sea level and eroded extensively. Shortlived submarine fans developed on both flanks of the ridge in response to sediment supply from its exposed top. As the local provenance areas were submerged some time prior to breakup west of the ridge, the ridge complex became sediment starved. At breakup, the basin plains west of the ridge, which lay several hundred meters below sea level, were covered with flatlying basalts. These were either emplaced as voluminous lava flows or as an extensive complex of sills just beneath the seafloor.

Second drift phase

After breakup the JMR continued to subside, driven by cooling and thermal contraction. Sedimentation became increasingly pelagic, but due to the steep slopes created in the second rift phase, gravity flow of sediments continued onto the basin plains from both the eastern and the western slope.
2.3 STRUCTURE

2.3.1 STRUCTURAL STYLE

The Jan Mayen Ridge is a sliver of continental crust bounded by passive rifted margins on both sides. The two margins are markedly different from a structural viewpoint (Figs. 2.11 and 2.12).

The ridge structure is illustrated with a structural map (Fig. 2.13, App. 4B), an isochrone map of reflector Purple, which marks the top of the extrusives covering the ridge (Fig. 2.14, App. 4C), an isopach map of total sediment thickness above the reflector (Fig. 2.15, App. 4F) and a series of interpreted seismic sections (Figs. 2.16 and 2.17, Apps. 5A and 5B).

The eastern margin exhibits few fault defined structures. Pre-opening strata are uniformly tilted or monoclinally flexured towards the Norway Basin. An extensive cover of volcanic extrusives is found west of the oldest seafloor spreading anomaly. A well developed morphological rise is present along the entire margin.

The western margin is characterized by normal faults with large throw down to the west that divide the margin into structural highs and rift basins arranged en echelon. A complex of sills or submarine lava flows covers most of the basins and masks the transition to normal oceanic crust on the Iceland Plateau. The margin is sediment starved and lacks a morphological rise.

Because of the proximity of the lines of breakup of the two margins, the structures formed at the eastern margin are partly overprinted by the structures formed at the western margin. The combination of eastwards tilting and flexuring of the eastern margin with down-to-the-west normal faulting
Geological provinces:

1. Oceanic crust in the Norway Basin
2. Eastern volcanic province
3. Eastern margin continental crust
4. Western margin continental crust
5. Western volcanic province
6. Oceanic crust on the Iceland Plateau

Figure 2.11 Main geological provinces and structural features of the Jan Mayen Ridge. Bar shows location of generalized cross section in fig 2.12.
Fig 2.12 Generalized cross section of the Jan Mayen Ridge.
Location in fig 2.11.
Fig 2.13 Main structural and volcanic features of the JMR.
Fig 2.14 Isochrone map reflector Purple
Fig 2.15  Isopach map of total sediment thickness above reflector Purple
and eastwards rotation of faultblocks at the western margin, imparts a fundamental asymmetry to the cross-sectional geometry of the ridge.

The complex of faultblocks that make up the ridge defines a structural axis with a northerly trend. There are systematic changes in structure from north to south along this axis. The width of the passive margin doublet, as defined by the oldest seafloor spreading anomalies on both sides of the ridge, increases towards the south. This is also true of the depth to the top of the ridge, the degree of fragmentation into faultblocks and the amount of structural overlap between the two margins.

An abrupt change in the orientation of the structural fabric of the ridge occurs at a prominent bend in the ridge at 6915N. North of the bend, the average strike of faults and geological units is about N7W, whereas south of the bend it is N23E.

Figure 2.16 (see next page)
Line drawings of four seismic dip lines (JM-4-, -10-, -12- and -17-85) across the Jan Mayen Ridge. Location of lines shown on index map.

Figure 2.17 (two pages ahead)
Line drawing of a composite seismic strike line (composed of lines JM-25-, 1226- and 326-85) along the eastern flank of the Jan Mayen Ridge. Location of line shown on index map, Fig. 2.16.
2.3.2 THE EASTERN MARGIN

The most striking characteristic of the eastern margin is the presence of an extensive complex of igneous rocks at a shallow structural level, comprising both volcanic rocks and intrusives (Figs. 2.11, 2.12, 2.13, 2.16, 2.17 and 2.18, Apps 4B, 5A and 5B). The volcanics overlie continental pre-opening rocks as a thin layer which thickens towards the continent-ocean boundary and merges with oceanic crust in the Norway Basin. The presence of a well developed sequence of seaward dipping and diverging reflectors beneath a smooth and extensive volcanic basement places the margin within the class of volcanic margins.

Talwani et al. (1983) divided the Norwegian volcanic margin into four structural zones: Zone I of inner lava flows, landward of the Voring and Færøy-Shetland Escarpments; zone II, a subhorizontally stratified volcanic high seaward of the escarpments; zone III of seaward dipping reflectors; and zone IV of oceanic basement. This zonation has since been shown to characterize many other volcanic margins. Skogseid and Eldholm (1987) identified zones II, III and IV at the eastern margin of the Jan Mayen Ridge, but zone I and the corresponding escarpment were apparently lacking. They tentatively divided zone III into two subzones, IIIA and IIIB, on the basis of differences in cross-sectional geometry. The present study confirms this structural zonation (Fig. 2.18). The identification in the new data of an extensive complex of dikes and sills associated with the seaward dipping reflector sequence and continental crust beneath its inner part sheds further light on the structure and evolution of the margin.
Fig 2.18  Structure of the volcanic megasequence at the eastern margin of the North Ridge.
Zone II

A zone of high-standing continental crust, largely unaffected by faulting in the first rift phase, uplifted and tilted eastwards in the second rift phase, is present in a narrow strip along the central axis of the North Ridge. Beneath a thin layer of plateau basalts, continuous with the sequence of seaward dipping reflectors in zone III, a stratified sequence of sediments, possibly containing some volcanics, overlies continental basement. The zone continues into the Southern Ridge Complex broken by the system of normal faults formed in the second rift phase.

Zone IV

Oceanic crust in the Norway Basin extends some distance to the west of the oldest seafloor spreading anomaly at the eastern margin, anomaly 24b. A number of fracture zones are present, the main ones being, from north to south, the Western, Eastern and Central Jan Mayen Fracture Zones and the Norway Basin Fracture Zone (Fig. 2.13, App. 4B). Adjacent to the margin the basement surface is generally only slightly hummocky and much smoother than normal oceanic basement. An exception is the area north of the Central Jan Mayen Fracture Zone, where the basement is highly fractured and uneven.

Zone III

The main geological units in this zone are the sequence of seaward dipping reflectors, subsided continental crust beneath the inner part of the sequence, and a complex of intrusives (Fig. 2.18).

Seaward dipping reflectors have been mapped in a 20-40 km
wide zone beneath the slope of the eastern margin from 68N to 7025N, and may continue further south. In a transect across the margin, systematic changes in the cross-sectional geometry of the volcanic sequence define two juxtaposed and partly overlapping wedge-shaped units, the inner and the outer wedge. The inner wedge, closer to the ridge, has an overall divergent reflector pattern. The outer wedge marks a transition to a more offlapping pattern. It is characterized by a subhorizontally stratified top layer that oversteps the inner wedge upslope and terminates at westfacing escarpments.

Continental crust continues some distance from zone II eastwards into zone III beneath the sequence of seaward dipping reflectors.

A complex of intrusives is present within zone III along the margin. A series of west-dipping reflector segments, interpreted as a dike swarm, crosscuts the stratification of the inner wedge as well as the underlying continental rocks. A number of short horizontal high-amplitude reflectors, interpreted as sills, are found within the post-opening sediments.

Structural changes along the margin

The two main structural trends characteristic for the Jan Mayen Ridge as a whole are clearly evident at the eastern margin. North of the Norway Basin Fracture Zone, the dipping reflector sequence and underlying continental units have a northerly strike. Both the fracture zones and the seafloor spreading anomalies in the Norway Basin make an oblique angle with the margin trend and the isochrons are displaced sinistrally across the fracture zones. Thus, the initial oceanic rift was left-stepping at this part of the margin. There is evidence that the geometry was inherited from the continental rift in that two clear offsets are
observed in the margin landward of the oldest seafloor spreading anomalies. The Transverse Ridge, an east-west oriented structural high beneath the slope (Fig. 2.13, App. 4B), offsets the dipping reflector sequence and associated escarpments and intrusives left-laterally by some 20 km. It lies in direct continuation of the southern strand of the Central Jan Mayen Fracture Zone, and probably corresponds to a short shear margin segment. A similar shear segment may be present further north.

South of the Norway Basin Fracture Zone, the margin strikes east of north in a direction more parallel with the seafloor spreading anomalies. It is divided into two structural segments by Rift "A" west of DSDP site 350 (Figs. 2.1, 2.11 and 2.13). A continuous sequence of seaward dipping reflectors is present beneath the flank of the easternmost faultblocks north of the rift. With the available data we cannot determine whether the sequence continues southward across the rift. If it does and is found at the flank of the easternmost fault blocks, as indicated by Pelton (1985), this implies a structural offset in the margin at the northern termination of the rift at the time of opening of the Norway Basin. The rift itself was formed in the second rift phase, but cannot have created such an offset because faulting of the required magnitude is lacking on the eastern margin north of the rift. Alternatively, the dipping reflector sequence was broken by faulting in the second rift phase and now lies partly within the rift.

The Jan Mayen Trough reaches the outer continental margin, but there is no apparent offset in the dipping reflector sequence across its mouth.
Rift phase structures

A remarkable feature of the eastern margin is the lack of prominent rift structures associated with the first rift phase. Along most of the margin pre-opening strata are traceable, without apparent faulting or syntectonic sedimentary features, a horizontal distance of approximately 10 km beneath the inner wedge (Fig. 2.18).

Tectonic overprint

Tectonic overprint by the second rift phase is recognized along the entire eastern margin in the form of uplift of the eastern ridge flank and emplacement of the sill complex within the post-opening sediments. The eastwards tilting of the outer continental margin is in places taken up by a flexure or west-facing normal faults at the base of the slope. The faultblock bounded by the reverse fault on the southeastern corner of the North Ridge and the Transverse Ridge are apparently compressional structures resulting from the second rift phase.

2.3.3 THE WESTERN MARGIN

Despite its position at the edge of a narrow microcontinent, the western margin (Figs. 2.11, 2.12, 2.13, and 2.16, Apps. 4B and 5A) is in many respects a typical block faulted passive margin. Due to the thin sedimentary cover, the rift structures are unusually well imaged. Three structural zones are recognized in a transect from east to west across the margin: A terrain of blockfaulted continental crust, deep rift basins covered by flatlying sills or lavas and oceanic crust on the Iceland Plateau dated by seafloor spreading anomalies.
Blockfaulted terrain

The width of the blockfaulted terrain increases from 50 km at 70°N to more than 100 km at 67°40'N. With few exceptions, the larger normal faults exhibit downthrow to the west and divide the microcontinent into a complex of eastwards rotated fault blocks. The dimensions of the blocks, as measured by cross-strike bedlengths within the hanging walls, range from a few hundred meters to approximately 15 km. On the larger blocks throw on the boundary faults reaches 1.5-2 km and stratal dips up to 10 degrees have been measured.

The crustal extension that caused the fault system divided the western margin into a series of faulted ridges separated by rift basins (Fig. 2.13): The Jan Mayen Basin; the North Ridge; the Jan Mayen Trough; and a complex of faultblocks, the Southern Ridges, divided by Rift "A" west of DSDP site 350. This is reflected in the bathymetry (Fig. 2.1).

The North Ridge is a 50 km wide block, structurally coherent from the island of Jan Mayen a distance of 300 km towards the south. The block is asymmetric in cross-section, flat-topped, with an eastwards tilted eastern flank and a steep faulted western flank. The high-standing central part was uplifted and truncated by erosion in the second rift phase but only to a minor degree affected by faulting. The ridge is bounded on the west by a listric master fault zone (Fig. 2.11, 2.13, 2.16, Apps 4B and 5A) which separates the main ridge block from the blockfaulted terrain further west. The fault zone is composed of two main segments which intersect at an angle of 30 degrees at the ridge bend. The faults sole out in the Jan Mayen Basin beneath a series of fault blocks forming a listric fan in the hanging wall. At the northern segment, the fan consists
of a few narrow ridges, whereas a wider terrace of larger fault blocks is present at the southern segment. Nearly all the fault planes dip to the west except furthest to the north where a system of antithetic faults has resulted in a grabenlike geometry (Fig. 2.16, App. 5A line JM-4-85).

Although there are strong similarities in structural style between the Southern Ridge Complex and the North Ridge, there are also some important differences. In the Southern Ridge Complex, the blockfaulted terrain reaches into zone III of the eastern margin and a single master fault zone bounding it on the east is lacking. Instead, several narrow fault blocks on the outer continental margin are bounded by shorter left stepping normal faults. Generally, the faults are steep and planar as deep down as they are imaged and direct evidence of sole faults is lacking. The relatively uniform width, rotation and depth to the top of the faultblocks, shows that a near horizontal shear zone must exist at depth, either as one or more discrete decollement surfaces or a zone of ductile deformation.

Along the entire western margin, abrupt lateral offsets of faultblocks (Figs. 2.11 and 2.23, App. 4H) are commonly observed showing that transversely oriented structural discontinuities exist within the fault system. The seismic grid spacing and the paucity of strike lines is such that none of the inferred discontinuities between individual blocks are imaged directly, but at about 6745N a number of small faultblocks with discordant strikes define a broad east-west trending zone linking the northern tip of the unnamed rift with the southern end of the Jan Mayen Trough (Fig. 2.11). The zone is interpreted as a zone of accommodation transferring extension towards the west.

Thus, many of the fundamental structural characteristics of extensional terrains in continental crust are found at the western margin of the Jan Mayen Ridge. Compressional structures formed coevally with the extensional structures
add another dimension to this picture. The clearest examples are found as tectonic overprint on the eastern margin. On the southeastern corner of the North Ridge, a 65 km long NNE striking fault with a near vertical faultplane and maximum throw to the west of some 600 m marks the western boundary of a large faultblock (Figs. 2.13 and 2.16, App. 4B and 5A). This fault and similar steep faults in zone III south of the Jan Mayen Trough were interpreted by Skogseid and Eldholm (1987) as a system of dextral strike slip faults. We find no indications of a significant strike-slip component and interpret them as reverse faults. In either case a compressional regime is indicated. The Transverse Ridge further north, the elongated domal uplift on trend with the southern strand of the Central Jan Mayen Fracture Zone, is another feature belonging to the same phase of structuring and indicating compression. Two small thrust faults are observed immediately south of the Transverse ridge.

Rift basins

The rift basins are elongated, oriented along the prevailing structural trends with their longitudinal axes arranged en echelon and their northern tips shifted successively towards the north and west. A flatlying opaque reflector covers the largest basins and masks the underlying structure. The fact that they widen towards the south and apparently coalesce indicates that they are rift arms protruding from a larger rift system in the south. At their northern end, where the opaque reflector is absent and the deep structure can be studied, they are seen to be faulted troughs structured in the same style as the higher-standing terrain with eastwards rotated faultblocks bounded by westvergent normal faults and occasional antithetic faults.
Igneous complex

The opaque reflector covering the rift basins is flatlying at a depth of 0.4-0.6 s twt beneath the basin plains. In cross-section it is composed of numerous horizontal segments at slightly different stratigraphic levels giving it a stepped character. Detailed analysis has shown the reflector to represent the top of a sill complex or a series of submarine lava flows. The reflector is completely opaque except at the edges close to the ridge where on a few lines the continental rocks of the blockfaulted terrain are traceable a short distance underneath it. On line JM-8-85, sedimentary layers continue below the reflector halfway across the Jan Mayen Basin to an isolated fault block (the Middle Axis) rising above the basin plains (Fig. 2.13, App. 4B). The implication is that a considerable part of the basins masked by the reflector may be underlain by continental crust.

Oceanic crust

Magnetic seafloor spreading anomalies on the Iceland Plateau show that oceanic crust is present immediately west of the Jan Mayen Basin. The oldest anomaly identified with certainty on the Iceland Plateau is anomaly 6C, but there is some indication of anomaly 7 (Vogt et al., 1980). Oceanic basement on the plateau is characterized by a smooth opaque reflector (Eldholm and Windish, 1974; Talwani and Eldholm, 1977; Olafsson, 1983) not much different in character from the igneous marker covering the rift basins to the east.

North of about 69N, the Jan Mayen Basin is separated from the magnetically lineated oceanic basement on the Iceland Plateau by an eastfacing scarp. The oceanic crust immediately west of the scarp is composed of a suite of subbasement layers beneath a strongly reflective upper
surface. The layered basement has an interval velocity in its upper part of 4 km/s twt derived from CDP stacks and is interpreted to consist of a sequence of submarine lava flows. South of 69N, the igneous marker covering the rift basins can be traced onto oceanic crust on the Iceland Plateau without marked discontinuity or change in character.
2.4 STRATIGRAPHY

2.4.1 Stratigraphic framework

The cross-sectional images of the Jan Mayen Ridge provided by the new seismic reflection data (Figs. 2.16 and 2.17, Apps. 5A and 5B) contain wealth of new geological information. Sixteen geological units, ranging from continental and oceanic basement to sedimentary and volcanic layers and igneous intrusives, were studied in order to unravel the structure and history of the ridge.

The stratigraphic framework proposed here is based mainly on seismic analysis. It is illustrated with the generalized cross-section in Fig. 2.12 and a schematic crustal column (Table 2.2). The section runs through a type locality on the southeastern corner of the ridge where the stratigraphy is exceptionally complete.

A top basement surface divides the crustal column into continental basement rocks and a cover of volcanic and sedimentary strata.

Continental basement

Beneath the basement surface, the crust is divided into two units on the basis of a difference in reflectivity.

The lower unit is characterized by horizontal reflectors observed in an average depth range of 5.5-6.5 s twt beneath the North Ridge and parts of the Southern Ridge Complex (unit 1, Table 2.2 and Fig. 2.12). On lines registered to more than 7 s twt there is an apparent lowering of reflectivity below this unit.
<table>
<thead>
<tr>
<th>Stratigraphic marker</th>
<th>Geological unit</th>
<th>Mega-sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seafloor</td>
<td>Hemipelagic and pelagic sediments (15)</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>oceanic basement (16)</td>
<td></td>
</tr>
<tr>
<td>Pink</td>
<td>Breakup marker 2</td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td>Syn-rift megasequence locally derived; divided by several rift-related unconformities. Early syn-rift (10), (11), late syn-rift (12), (13), sill complex (14)</td>
<td>(3)</td>
</tr>
<tr>
<td>Turquoise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>Rift unconformity 2</td>
<td>(2)</td>
</tr>
<tr>
<td></td>
<td>Post-opening sedimentary sequence derived from Greenland (8), sill complex (9)</td>
<td></td>
</tr>
<tr>
<td>Purple</td>
<td>Breakup marker 1</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>Volcanic megasequence with seaward dipping reflectors (5), dike complex (6), oceanic basement (7)</td>
<td></td>
</tr>
<tr>
<td>Orange</td>
<td>Rift unconformity 1</td>
<td></td>
</tr>
<tr>
<td>Brown</td>
<td></td>
<td></td>
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<tr>
<td>Top basement</td>
<td></td>
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<tr>
<td></td>
<td>Continental basement rocks, non-reflective (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reflective deep crustal layer (1)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2 Main seismic stratigraphic markers and geological unit
The upper unit (unit 2) is characterized by low reflectivity. The occurrence of a few reflections in some cases gives the impression of weak layering, but in general it is difficult to discriminate between real reflections and artifact. Because strong reflections are returned from below the unit, the lowering in reflectivity is interpreted to be real.

An integrated analysis of the available geological and geophysical data back up the interpretation of the basement rocks as being continental in origin.

Cover strata

The volcano-sedimentary cover is divided into a lower series of pre-opening strata and an upper series of syn- and post-opening strata by reflector Orange. The reflector is interpreted to mark the onset of the rift phase which led to breakup of the continent between Norway and Greenland and the opening of the Norwegian-Greenland Sea.

Lower series

At the type locality on the southeastern corner of the North Ridge, the lower series occurs as a thick and well-stratified sedimentary succession on an upthrust faultblock bounded on the west by a prominent reverse fault (Figs. 2.11 and 2.12). The series is bounded at its base by a narrow band of strong reflections from the top of the less reflective basement beneath and has a maximum thickness of about 2.5 s twt. A marked unconformity, Reflector Brown, divides it into two sequences (units 3 and 4). Outside the type locality, a distinct basal reflector is observed only sporadically. An estimated average thickness ranging from 0.4 to 1.2 s twt therefore represents a minimum.
Upper series

A major result of the stratigraphic analysis of the upper series is the identification of the rift onset and breakup markers of the two rift phases: Reflectors Orange, Purple, Red and Pink divide the series into four megasequences corresponding to the major phases in the plate tectonic evolution of the ridge (Fig. 2.10).

Reflector Orange represents an unconformity at the base of the eastern margin volcanics. Beneath the inner wedge of dipping reflectors the unconformity is clearly erosional and truncates the underlying lower series strata. Signs of synrift sedimentation or emplacement of volcanic extrusives are apparently lacking in the lower series. It therefore probably consists of pre-rift sediments and reflector Orange marks the onset of rifting at the eastern margin.

The Orange-Purple megasequence (unit 5) spans the volcanic megasequence emplaced at the Greenland margin during the rift and early drift phase. It includes the sequence of seaward dipping reflectors and the thin volcanic layer extending upslope from it and is interpreted to consist mainly of subaerial basaltic lava flows.

Reflector Purple defines the top of the volcanic megasequence. It is an amalgamation of surfaces which young towards the ocean and merge with oceanic basement. At the outer wedge, the youngest volcanic subsequences below it are time-equivalent with the lower part of the Purple-Red megasequence. Ridgeward of the outer wedge, where the reflector marks the top of basalts which flooded the continent, it is close to being a chronostratigraphic boundary and is interpreted to correlate with or slightly post-date breakup.

The dike complex (unit 6) observed within the volcanic
megasequence, the underlying lower series sediments and the continental basement, is interpreted to have been emplaced contemporaneously with the dipping reflector sequence.

The Purple-Red megasequence (unit 8) is the sequence of drift phase sediments deposited on the Greenland margin and in the Norway Basin after breakup and prior to the onset of the second rift phase. It records thermal subsidence of the margin and the initial development of a shelfedge facing the Norway Basin.

The Red-Pink megasequence is the synrift sequence deposited during the second rift phase when the ridge was separated from the Greenland margin. Reflector Red represents the onset of uplift and faulting associated with this phase. Reflectors Yellow, Turquoise and Blue divide the megasequence into four depositional sequences (units 10 to 13) recording different stages in the development of the rift. The uppermost sequence, Blue-Pink, post-dates the main phase of faulting and represents a period of thermal subsidence prior to breakup.

The sill complex (unit 9) is largely confined to the Purple-Red megasequence. A few sills are observed within the abovelying sequence. It is interpreted to have been emplaced in the second rift phase.

The Pink-seafloor megasequence of sediments deposited during the second drift phase (unit 15) continues onto oceanic basement west of the ridge and thus post-dates breakup. Analysis of reflector Green, the opaque reflector which covers the rift basins west of the ridge, shows that the emplacement of the complex of sills or lavaflows it represents (unit 14) was approximately coeval with breakup and with the formation of Reflector Pink. Since reflector Green is composed of a number of reflector segments at slightly different stratigraphic levels it is not a chronostratigraphic boundary. Reflector Pink is
therefore taken as the breakup marker.

Mapping of stratigraphic boundaries

The regional stratigraphic framework was established by extending the stratigraphy of the type locality to other parts of the ridge. In order to establish regional correlations, reflectors Purple, Red and Blue, being the most easily correlateable reflectors, were mapped first. We are confident of the interpretation of these sequence boundaries along most of the eastern margin, less so on the western margin. Once the regional correlations were established, the other markers (Top basement, Brown, Orange, Yellow, Turquoise, Green and Pink) were introduced and mapped more locally in an effort to understand structuring and sedimentation at the ridge.

A major difficulty was the general lack of continuous stratigraphic ties between the different subprovinces of the ridge due to fault zones, masking by igneous rock suites and erosional truncation. On the eastern slope, part of the post-opening sedimentary cover is composed of a multitude of laterally restricted local depositional units, and stratigraphic boundaries are in many cases difficult to follow along strike. The western margin is structurally complex and few effective longitudinal tie-lines exist. Out of several possible correlations, the one that minimizes structural complexity and leads to a simple and plausible history of tectonism and sedimentation has been chosen.

Isochrone maps of reflectors Purple, Red and Blue (Figs. 2.14, 2.20, 2.22, Apps. 4C, 4D and 4E respectively) and isopach maps of the intervals Purple-Red, Red-Blue and Blue-seafloor (Figs. 2.21, 2.23, 2.24, Apps. 4G, 4H and 4I respectively) illustrate the stratigraphy of the sedimentary cover. A total sediment isopach is shown in Figure 2.15 (App. 4F). The maps do not cover parts of the
structurally complicated western margin. Reflector Blue was chosen instead of the slightly younger reflector Pink, because it can be mapped over a far larger part of the ridge. As a result the two upper stratigraphic intervals presented as isopachs do not correspond exactly to megasequences.

2.4.2 AGE CALIBRATION

The new stratigraphic framework provides a relative chronology of events and enables a more accurate analysis of structure, tectonics and depositional systems than previously possible. An absolute age calibration of the framework is essential for further studies. Some of the stratigraphic markers may be dated with the help of seismic ties to biostratigraphically dated markers in the DSDP holes. Downlap of post-opening sequences on dated oceanic basement provides important additional constraints. For the older part of the succession, however, tentative ages must be assigned on the basis of correlations with the geology of the conjugate margins.

Basement

Reconstructions of the plate movements that took place between Greenland and Norway in Late Paleozoic, Mesozoic and Cenozoic times (Ziegler, 1989) show that the Jan Mayen Ridge must have been part of the province of Caledonian deformation, irrespective of the magnitude of the Devonian Arctic-North Atlantic megashear movements along the axis of the Caledonides. We can therefore safely assume that the continental basement beneath the ridge is Caledonian in age.
Lower series

The reconstructions also show that the ridge has been juxtaposed with the East Greenland sedimentary basin (Figs. 2.5 and 2.8) from Carboniferous times at least. We therefore anticipate strong similarities between the pre-opening sedimentary successions of the East Greenland basin and the Jan Mayen Ridge.

Because of the large thickness of the lower series, comparisons with the thick Jameson Land succession (Fig. 2.9; Surlyk et al., 1981, 1984; Ziegler, 1989, his Fig.50) are particularly relevant. Elements of the stratigraphy of the lower series which might be used to establish correlations between the two successions, are mainly the unconformities, associated phases of faulting and stratigraphic thicknesses of subunits. For two reasons, such correlations are difficult to establish:

1) The East Greenland basin was affected by a number of tectonic phases in Late Paleozoic and Mesozoic times (Surlyk et al., 1981). Most of the resulting unconformities are subtle and not identifiable on the basis of geometry alone.

2) The Jameson Land basin is separated from the shelf by a coastparallel basement high, Liverpool Land, which was active during several of these phases (Surlyk et al., 1981). The North Ridge probably constituted a separate fault block with potentially different history of vertical movements. Sequence thicknesses and gaps in the stratigraphic record may therefore differ between the two successions.

Thus, correlation of unconformities is non-unique and relative thickness of subsequences is not a reliable criterion on which correlations can be based.
Reflector Brown is a prominent reflector and represents an erosional unconformity caused by a tilting of the fault block at the type locality. Assuming that the reflector represents one of the strong late Mesozoic tectonic phases and noting the strong reflection coefficient, we suggest that the reflector corresponds to the base Cretaceous unconformity above the Jurassic sandstones. It follows that a part of the Cretaceous and Paleocene succession, missing in Jameson Land, but preserved as scattered remnants to the north and south, is preserved at the ridge. This may be explained by the large uplift and erosion which affected the East Greenland margin in late Tertiary times.

Upper series

The volcanic megasequence at the Jan Mayen Ridge exhibits strong stratigraphic and structural similarities with the volcanic sequences observed on the Norwegian and Greenland volcanic margins. The dipping reflector sequence at the Outer Vøring Plateau was drilled during ODP leg 104 and found to have been erupted mainly in the period of reverse magnetic polarity between anomalies 24 and 25, the youngest and possibly the oldest subsequences belonging to the periods of normal polarity above and below. This corresponds to an age of approximately 56-59 Ma. On the basis of a temporal correlation of the main igneous and pyroclastic units in the North Atlantic Volcanic Province (Eldholm et al., 1989), a similar age is indicated for the other dipping reflector sequences observed on the conjugate margins.

More direct evidence for the age of the volcanic megasequence at the Jan Mayen Ridge comes from its relation to the oldest seafloor spreading anomalies in the Norway Basin and a correlation with the Blosseville Coast plateau basalts of East Greenland. According to our interpretation, the second rift phase split the East Greenland volcanic margin along a breakup line which left zone III and part of
zone II on the Jan Mayen side. The volcanic megasequence at
the ridge was originally continuous with the Blosseville
Coast plateau basalts. Age constraints may therefore be
obtained from the exposed basalts in Greenland.

Biostratigraphic ages constrain the eruption of the
Blosseville Coast lavas to the time period from 55 to 59
Ma. Combined with the fact that the entire sequence is
reversely magnetized, this indicates emplacement during the
period of reverse magnetic polarity between anomalies 24
and 25. But, due to erosion, the upper part of the
Blosseville sequence is missing. On the Jan Mayen Ridge,
the volcanic sequence escaped erosion. Ridgeward of the
outer wedge, reflector Purple is a conformable
chronostratic surface marking a shift from continent-
flooding plateau basalts to younger and more restricted
sequences at the outer wedge. It probably corresponds to
the uneroded top of the Blosseville lavas. Because the
dipping reflectors lie ridgeward of anomaly 24B, this inner
surface of reflector Purple probably predates the anomaly,
but normal polarity of the top layer of the outer wedge
cannot be excluded. Thus, the Orange-Purple megasequence
probably spans the time period from 59-56 Ma.

Age constraints on reflector Blue are provided by seismic
ties to the DSDP holes 345, 347 and 349 (Talwani and
Udintsev et al., 1976). The holes are located on the
western part of the North Ridge and bottom out beneath the
reflector. It represents an angular unconformity separating
late Eocene sediments below from a condensed sequence of
late Oligocene to Pliocene sediments above. Thus, a hiatus
of at least 7 Ma from 37 Ma (anomaly 15) to 30 Ma (anomaly
10) is present in this strongly eroded area. The boundary
becomes conformable in the basins on both sides of the
ridge and the hiatus associated with the reflector is
probably much smaller.

The seismic lines crossing these sites show that, due to
ambiguous correlations across fault zones, it is uncertain whether reflector Red was reached. They do show, however, that at least a part of the late Eocene section found in the holes overlies reflector Red. The reflector is therefore late Eocene or older. It was traced on several lines to its point of downlap onto oceanic crust in the Norway Basin. This point is not well determined, but occurs within a strip of seafloor defined by anomalies 20 to 22. Assuming that the basement was covered by sediments soon after its formation, which seems likely in view of the small width of the ocean basin at that time and the high rate of sediment input to the eastern margin, this gives an age of 45-52 Ma corresponding to the middle Eocene or the end of early Eocene.

Reflector Pink is defined on the western flank of the North Ridge. It cannot be followed across the boundary faults onto the flat top of the ridge where holes 346, 347 and 349 are sited, but age constraints are obtained from hole 348 and the reflector's relation to oceanic basement west of the ridge. The hole is sited on the Iceland Plateau and penetrates a relatively continuous sequence of sediments ranging in age from Pleistocene to early Miocene. An uncertain Oligocene age at the bottom of the hole is in conflict with the siting of the hole at anomaly 6A and must be rejected. Line L-DGO 206, which runs from site 348 to the North Ridge, shows that the sedimentary sequence can be followed from the site across anomaly 6C (24 Ma, Oligocene/Miocene boundary) into the Jan Mayen basin where it is continuous with the sequence above reflector Pink in the Jan Mayen Basin. This indicates that the reflector predates Miocene. In Sections 2.5.6 and 2.5.7 we present arguments for the correlation of reflector Pink with breakup at approximately anomaly 7 (26 Ma, late Oligocene).

None of the new lines cross DSDP-site 350 in the Southern Ridges. Due to steep stratal dips at the site, navigational inaccuracy and poor quality of the older lines
it has not proved possible to utilize the results from this hole for age calibration of the stratigraphy.

With the age constraints imposed by the available data, the reflectors Orange, Purple, Red and Pink, divide the upper series into four megasequences corresponding to the major plate tectonic phases in the Tertiary development of the ridge (Fig.2.19, App. 5C).
Fig 2.19 Evolution of the Jan Mayen Ridge.
2.5 ANALYSIS OF THE COVER STRATA

2.5.1 LOWER SERIES: PRE-OPENING PHASE

Overall geometry

The stratified series observed beneath the volcanics at the type locality (Fig. 2.16, App. 5A, line JM-12-85; Fig. 2.17, App. 5B, lines JM-25- and 1226-85) reaches a thickness of about 2.5 s twt, corresponding to some 4-5 km. The series is identified with certainty and mappable only on the fault block east of the prominent reverse fault on the North Ridge. It exhibits internal reflectors with good or fair continuity defining uniform parallel or gently diverging layering. The whole series is tilted towards the Norway basin and dips beneath the inner wedge of dipping reflectors.

When the displacement is restored on the reverse fault, the abovelying volcanic layer can be traced across it without apparent change in thickness. None of the lower series strata observed east of the fault can be identified to the west of it, and they may be entirely lacking there. Yet, there is some layering west of the fault, so their presence cannot be excluded.

Lower boundary

The band of reflectors plunging eastward from 5 to 6.5 s twt on line JM-12 and southward in a similar depth range on lines JM-25 and 1226, defines the base of the series and the top of the continental basement.
Upper boundary

Reflector Orange forms the upper boundary of the series and defines the base of the overlying volcanic megasequence. The boundary was mapped as a continuous reflector in a small region around the type locality on the southeastern part of the North Ridge. In zone II the boundary is conformable. In zone III, the following stratigraphic relations are observed:

1) The boundary marks a change from subparallel layering below to eastwards divergent within the abovelying inner wedge.

2) Reflectors in the wedge are in some cases observed to onlap the boundary updip.

3) The uppermost layers beneath the wedge thin in the downdip direction. On several lines this is clearly due to erosional truncation at the boundary.

Continuous mapping of reflector Orange outside this region proved difficult. Extension to the regions further north and south along the eastern margin is therefore based on correlation between dip lines, using the criteria above.

Subsequences

Reflector Brown divides the lower series into two sequences. Centrally on the fault block, the reflector represents a nearly conformable boundary. Towards the north, the underlying beds are truncated by the unconformity. This is also seen near the western edge of the fault block.
Tectonism and sedimentation

The parallel layering and good continuity of the internal reflectors, indicates a marine platform or basin margin sedimentary sequence. But continental sediments may also be present, and within the uppermost part of the series, the presence of volcanic layers cannot be excluded.

Reflector Brown and the associated erosional unconformity indicate slight tilting of the faultblock to the southeast. The uniform parallel stratification in the lower part of the Brown-Orange sequence indicates that these movements were followed by a period of stability. The uppermost part of the lower series thins downdip mainly as a result of erosional truncation at reflector Orange caused by uplift of the outer margin. A small part of the apparent downdip thinning may admittedly be caused by syntectonic depositional thickening towards the fault, but internal layering that might be used to determine this component is lacking.

Thus, the stratal geometry of the lower series differs markedly from the geometry expected if all or part of it was deposited in response to rifting at the eastern margin. The most reasonable interpretation is that the series predates the rifting. Alternatively, if all or part of the series was deposited during the rift phase which led to the opening of the Norway basin, the boundary faults of the rift must have been located well to the west of the reverse fault, but we do not consider this very likely.
2.5.2 MEGASEQUENCE 1: OPENING VOLCANISM

The megasequence spans the volcanic rock suite at the eastern margin and its westward extension across the ridge as a thin layer. A description of the overall geometry was given in Section 2.3.2 and is illustrated in Figure 2.18.

Upper boundary

Reflector Purple (Figs. 2.14 and 2.18, App. 4C) is the strong reflector marking the top of the volcanics. Detailed studies show that the reflector is composed of several surfaces at slightly different stratigraphic levels. As a first approximation, a division can be made into

1) a smooth surface defining the top of the volcanic megasequence over the ridge, including the inner wedge, and

2) a time-transgressive basinward-younging surface further downslope on the eastern margin. It is slightly rougher, continuous with the oceanic basement in the Norway Basin and oversteps the older surface upslope.

The two surfaces will be referred to as volcanic basement surfaces 1 and 2 respectively. The transition between the two occurs at the non-fault related westward facing escarpments along the eastern margin (Fig. 2.13, App. 4B), where basement surface 2 steps down to meet basement surface 1.

The reflector is a lithostratigraphic boundary separating volcanic rocks below from sedimentary rocks above. Basement surface 1, which forms the top of the inner wedge and the thin layer continuing upslope from it, is a relatively conformable boundary separating laterally extensive layers above and below. At the western escarpment there is a
transition to an increasingly offlapping reflector pattern in the sequence below. Thus, basement surface 1 is probably close to being a chronostratigraphic boundary, whereas basement surface 2 becomes increasingly younger basinward. Since basement surface 1 can often be traced some distance underneath basement surface 2, the latter in fact defines the top of a volcanic subsequence, time-equivalent with the lower part of the underlying sedimentary sequence. However, because of the marked difference in lithology and genesis, this subsequence is considered to be a part of the volcanic Orange-Purple megasequence. When reflector Purple is used in a time stratigraphic sense, its age is defined to be that of basement surface 1.

Stratigraphy of the dipping reflector sequence

In a typical cross-section orthogonal to the margin, the reflector pattern divides the sequence into basinward dipping and thickening subsequences that either pinch out in the updip direction or converge to a certain point before becoming parallel. The bounding surfaces are either planar or arcuate and convex upward in cross section. The subsequences build two basic types of sequence geometries, divergent and offlapping. In a divergent sequence, the subsequences are arranged in a vertical stack with the points of pinchout or maximum convergence approximately in the same location, referred to as the apex. The average dips decrease upwards from reflector to reflector, and the upper surface is close to being an isochrone. In an offlapping sequence, the subsequences are arranged in an oceanward prograding stack. No apex develops because of the successive oceanward shift of the pinchout points. The whole sequence, therefore, exhibits a general pattern of offlap from a relatively even, oceanward younging upper surface.
Inner wedge

The inner wedge exhibits an overall divergent reflector pattern. Both divergent-planar and divergent-arcuate geometries occur. A composite form with an arcuate lower part and a planar upper part is commonly observed. Second order departures from the regular divergent reflector pattern of the inner wedge are common enough to constitute a systematic shift in the westward extent of the subsequences from the bottom to the top of the wedge. The lower subsequences often onlap the basal surface of the wedge and pinch out before reaching the apex. The main body of the wedge does not pinch out in the updip direction. Some part of it at least, converges updip only to a certain degree at the apex, where it turns parallel and continues westward across the ridge as a thin layer. This layer can be followed to the western margin, where it is downfaulted at the boundary faults. At the top of the wedge there is an eastward shift and usually a change to an offlapping pattern associated with the transition to the outer wedge.

Outer wedge and escarpments

The cross-sectional geometry of the outer wedge is less regular than that of the inner wedge. Data quality and data coverage are also poorer. Overprinting by sills sometimes obscures the internal structure. Nevertheless, a distinct outer wedge is recognized on the basis of one or more of the following criteria:

1) A transition from a fanshaped to an offlapping pattern

2) Increased dips compared to the top layers of the inner wedge

3) A subhorizontal layer on top of the wedge rising above the upper surface of the inner wedge and overstepping it in the updip direction
The top layer thins updip as it oversteps the inner wedge. The thinning is the result of downstepping of the upper surface at the escarpments and other less prominent scarp.
The western escarpment marks the updip termination of the top layer of the outer wedge and is a rather subtle feature. The eastern escarpment is more prominent, especially south of the CJMFZ, where it is developed as a scarp reaching a height of several hundred meters. North of the CJMFZ, it is more subdued and resembles a wedge-like pinchout.

East of the eastern escarpment, the top layer of the outer wedge attains an average maximum height above the top of the inner wedge of 1.3 km. Its structure varies from subhorizontally stratified to irregular or opaque. The escarpment itself also varies in structure. Two basic forms are recognized: A steeply sloping surface onlapped by sediments; and a featheredge caused by the updip termination of horizontal reflectors interfingering with sedimentary layers. On some profiles, both forms are present. In neither case is there any sign of faulting or erosion. The escarpments therefore are depositional features.

East of the northern termination of the Jan Mayen Trough, several mound-like structures have been observed within the top layer of the outer wedge, just east of the eastern escarpment. The mounds are 7-8.5 km across and rise 900-1300 m from a horizontal base. They exhibit upward convex tops and internal reflectors that downlap the base.

Thin layer

The thin volcanic layer extending upslope from the inner wedge is characterized by high amplitude reflectors, smooth and continuous in the upper part. The thickness of the
layer is not well determined due to the uncertainty in the picking of the base (reflector Orange), but is estimated to be 380 ms twt on the average, corresponding to approximately 750 m. Although belonging to basement surface type 1, the top of the layer is not an entirely consistent chronostratigraphic surface. On the southern part of the North Ridge, it lies at a higher stratigraphic level than in the region immediately to the north and east. It steps down to the lower level at a northeast-facing scarp, some 400 m high, observed on several lines.

Depositional features and environment

The volcanic nature of the megasequence follows from the close stratigraphic and structural similarity with the volcanic sequences confirmed by drilling at other volcanic margins and the correlation with the plateau basalts at the East Greenland margin. Several stratigraphic and morphological features of the megasequence itself indicate a volcanic origin and provide further insights into the mode of emplacement.

A general feature of the dipping reflector sequence is basinward transition from a fanshaped to an offlapping pattern. Commonly, the thin upper edge of a subsequence oversteps the adjacent inner subsequence (or subsequences) and rises above it to form a local step at its updip termination. This is observed on different spatial scales, the escarpments associated with the outer wedge being just such a phenomenon on a large scale.

Onlapping and offlapping patterns are common in sedimentary sequences. Oceanward shift of onlap produces updip overstepping subsequences. Updip overstepping sometimes occurs also within overall offlapping sequences. But, updip facing scarps are produced in neither case, at least not in terrigenous clastic sediments. In the sedimentary
environment of the Norwegian-Greenland Sea, the combination of an overall offlapping sequence with occasional updip overstepping of individual subsequences terminating at well defined scarps is thus incompatible with a sedimentary origin, and strongly indicates a basinward retreating volcanic source. In this context, the westfacing escarpments associated with the outer wedge must be interpreted as being formed by lava flows, and the mounds observed within the top layer of the outer wedge find an explanation as volcanoes.

Lava flows, whether subaerial or submarine, have limited flow lengths and are bounded by marginal scarps. Flow lengths are generally much larger on land than beneath the sea due to lower cooling rates on land. Lavas flowing from land into the ocean or a lake are quickly quenched at the shoreline and a steep front often develops.

A basaltic volcanic zone that subsides beneath sea level will go through three distinct phases of volcanism. Above sea level, non-explosive volcanism will result in a layered stack of areally extensive lava flows. As the zone becomes submerged, the erupted magma will be torn apart in steam explosions and laterally restricted pyroclastic mounds will be formed together with extensive but relatively thin ash layers. Eventually, a critical depth is reached (several hundred m) at which the hydrostatic pressure prevents steam explosions and lavas will flow again as relatively restricted sheet or pillow flows.

A change from subaerial to submarine volcanism took place at the eastern margin as Norway Basin gradually opened. The transition from inner to the outer wedge is interpreted to record this event. The irregular layering of the top layer of the outer wedge, the increase in roughness associated with the transition from basement surface 1 to basement surface 2 and the formation of the escarpments are best explained as being caused by a decrease in lava flow
lengths due to the submergence of the volcanic zone or the development of a marginal sea between the volcanic zone and the continent. It is possible that an increase in volcanic production could have caused the updip overstepping of the top layer and the formation of a flow front, but this should not by itself have resulted in more irregular layering or sharply defined composite escarpments.

Alternative explanations are less feasible. A chemical control would imply increasing silica content with time, which can be rejected as an overall trend in the transition to the formation of oceanic crust. A fall in eruption temperature large enough to alter the flow lengths and morphology of the lavas seems unlikely. A change in the surface gradient resulting from differential subsidence could restrict lava flows but would not lead to the formation of escarpments.

The northeast facing escarpment on the North Ridge (Fig.2.13, App. 4B) is a well defined scarp limiting an extensive uniformly layered extrusive unit of nearly constant thickness. The strata above and below the unit show no signs of erosion or faulting and the scarp is therefore depositional in origin. In view of its thickness of 400 m, the unit is clearly composed of multiple flows. It seems that no possible mechanism, other than quenching at a shoreline, could cause the abrupt termination of multiple subaerial lava flows in exactly the same position, producing a sharply defined scarp. This implies early subsidence of the margin and supports the interpretation of the west-facing escarpments as being caused by submergence.
2.5.3 INTRUSIVES AT THE EASTERN MARGIN

The two sets of reflectors interpreted as intrusives are found along the entire eastern margin. The areal distribution of the sill complex is shown in Figures 2.11 and 2.13 (App. 4B).

Sills

The reflectors interpreted as sills are short reflector segments observed within the sedimentary sequence above reflector Purple. They are single-reflector bright-spots with sharp edges that give rise to diffractions on unmigrated sections. Although most are subhorizontal and conformable with the sedimentary layering, some are clearly discordant. Commonly, the sedimentary strata above the reflectors are uplifted. There are cases where the strata are uplifted as a block with step-like margins exactly coincident with the position of the reflector edges, and the affected section has a well-defined upper boundary above which there is no deformation. These characteristics identify the reflector segments as sills.

South of the Transverse Ridge, the sills are mostly found near the escarpments, which define the transition to the outer wedge. North of this ridge, they are more widely distributed. Most are found within the Purple-Red megasequence, but a few are found within the overlying Red-Pink megasequence. They tend to cluster at certain stratigraphic levels, commonly at a level corresponding to the top of the outer wedge.

The most precise indicator of their relative age is the uppermost stratigraphic level of sediments deformed by the sills, which consistently gives an age corresponding to reflector Red or the lower half of the Red-Blue sequence,
except for a few sills at the northern termination of the Jan Mayen Trough, which are emplaced at the level of reflector Blue.

Dikes

The reflectors interpreted as dikes are found at the inner wedge, where they dip westward orthogonally to the margin and crosscut the stratification of the volcanic megasequence as well as the underlying strata. They occur as sets of closely spaced short reflector segments with an average dip of 25 degrees. Generally, the reflectors do not offset the bedding, but minor offsets may be present in a few cases. The reflectors are dimmer and fewer in number above reflector Orange than beneath it.

Possible interpretations of the reflectors are metamorphic layering, faults or dikes. Metamorphic layering is not expected to generate a number of closely spaced reflectors. Closely spaced small-offset faults could explain the geometry, but should by themselves neither generate such strong reflections nor brighten beneath reflector Orange. A dike swarm could have the observed geometry and would be expected to give rise to more prominent reflections within the sediments below reflector Orange than in the basaltic sequence above. Thus, a dike swarm seems to be the most satisfactory interpretation. It has the added attraction of providing feeder dikes for the extrusives of the inner wedge. The emplacement of the dikes could be controlled by fractures or minor faults.

The upper boundary of the dike swarm is diffuse, but almost invariably lies within the Orange-Purple megasequence. In rare cases, dikes are observed to intrude the sediments just above reflector Purple. The stratigraphic level of the upper edge of individual dikes provides a constraint on their maximum possible age. It ranges from pre-Orange to approximately Purple. The most reasonable interpretation is
that their emplacement was coeval with the formation of the inner wedge, although a younger age cannot be entirely excluded.

2.5.4 MEGASEQUENCE 2: FIRST DRIFT PHASE

The Purple-Red megasequence is the post-rift sedimentary sequence deposited on the Greenland continental margin and in the Norway Basin following the opening of the Norwegian-Greenland Sea. It comprises all sediments deposited between breakup and the onset of significant rifting on the Greenland margin.

Overall geometry

The sequence was disrupted post-depositionally by extensional faulting in the second rift phase. It is preserved, tilted to the east, along the eastern margin and on the fault blocks of the western margin. It is relatively uniform in thickness, but depocentres are present beneath both the eastern and the western slopes (Figs. 2.16 and 2.21, Apps. 5A and 4G). It can be followed to the edge of the westernmost fault blocks. Eastwards it thins into the Norway Basin. The upper boundary downlaps oceanic basement, whereas the lower part of the sequence interfingers with the volcanic top layer of the outer wedge.

Upper boundary

Reflector Red is a prominent unconformity marking a change in the pattern of sedimentation. Over most of the ridge it is relatively conformable with the underlying sequence. At the base of the overlying sequence, a downslope thinning wedge of sediments downlaps the reflector towards the Norway Basin. At the northern end of the Jan Mayen Trough,
the boundary is clearly erosive in character. The slope sediments are truncated at the boundary, which is in turn overlain by a marine onlap sequence interpreted as a canyon fill.

Sequence description

Systematic changes in external and internal geometry show that two main depositional settings are present: shelf and slope. The shelf sequence is found over much of the central and western part of the ridge complex. It exhibits regular parallel layering. Continuation of the sequence onto the fault blocks of the present western margin is often ambiguous due to the non-unique correlations across the boundary faults. The simplest consistent interpretation of the sequence in this western area (Fig. 2.16, App. 5A) result in its continuation to the western edge of the complex of fault blocks without large variations in thickness. Nevertheless some differential subsidence is indicated along the western margin. The subsidence seems to be controlled by initial movements on some of the faults that developed into the fault complex at the western margin in the second rift phase.

A change to a gently diverging and converging reflector pattern on the eastern margin, together with the occurrence of progradational clinoforms, indicates the initial formation of a shelfedge and slope facing the Norway Basin. On the lower slope off the central part of the North Ridge, the external form, as well as the internal structure of the uppermost depositional sequences, indicates the presence of a large submarine fan.
Fig 2.20 Isochrone map of reflector Red
Fig 2.21  Isopach map of the Purple - Red megasequence
Tectonism and sedimentation

During the early drift phase, when the sequence was being deposited, Norway Basin gradually opened and deepened and the Greenland continental margin subsided beneath sea level. Evidence for the marine conditions at the base of the sequence comes from the northeast facing volcanic scarp on the North Ridge, mapped at the level of reflector Purple and interpreted as being caused by the quenching of lava flows at a shoreline. This indicates that the outer continental margin subsided below sea level soon after breakup and that most of the sequence consists of marine sediments. The lower part sequence was deposited coevally with extensive volcanism at the outer wedge of dipping reflectors in the Norway Basin.

A shelfedge was formed on the eastern margin of the Jan Mayen Ridge. The geometry of the sequence indicates abundant sediment supply to the margin from an eastern source and implies erosion of an uplifted provenance area in the Greenland hinterland.

Vertical aggradation of the shelf and outbuilding of the slope, evident along the entire eastern margin, indicates that, as the Norway Basin gradually opened and subsided, the growth in the space available to accomodate sediments beneath erosional base level outpaced sediment supply to the margin. Subsidence of the margin was probably thermally driven at this stage and mostly flexural in character. Yet, there are clear signs of some faulting within the interval. A rift basin was probably initiated on the shelf, but did not develop to become a significant sediment trap, because sediment supply to the eastern slope continued throughout the Purple-Red interval at a high rate. On the southern part of the North Ridge and on the the Transverse Ridge, there are indications of an event in the middle part of the sequence of much reduced vertical aggradation of the shelf.
contemporaneously with continued outbuilding of the slope. This can be explained by a relative fall in sea level and may be caused by the phase of extension indicated by the faulting.

2.5.5 MEGASEQUENCE 3: SECOND RIFT PHASE

The Red-Pink megasequence is the syn-rift sequence deposited during the second rift phase when the ridge was being separated from the Greenland margin.

Overall geometry

The sequence has an irregular geometry and exhibits a variety of depositional forms related to tectonic movements. The internal unconformities Yellow, Turquoise and Blue divide it into four subsequences which record different stages in the development of the rift along the western margin. The upper boundary of the sequence, reflector Pink, interpreted to mark breakup on the western margin, has not been identified with certainty on the eastern margin. An isopach map was therefore constructed for the Red-Blue interval (Fig. 2.23, App. 4H).

Sequence description

Sequence Red-Yellow exhibits variable thickness. South of the Transverse Ridge it defines a wedge of sediments downlapping reflector Red on the upper slope and thinning markedly into the Norway Basin. Although some faulting is associated with reflector Red, the sequence pre-dates most of the fault movements at the western margin.
Reflector Yellow is a tectonic unconformity marking the onset of the main phase of faulting and sequence Yellow-Turquoise spans the earliest sediments deposited syntectonically in response to this phase. On the eastern margin it forms the uppermost part of the downlap sequence, whereas on the western margin it defines restricted steep fans at some of the boundary faults.

Sequence Turquoise-Blue exhibits large thickness variations as a result of differential subsidence and syntectonic sedimentation. On the western margin, the sequence fills the rift basins and half-grabens. On the eastern margin, two different sequence morphologies are observed. South of the Transverse Ridge, the sequence is thin on the slope, but it thickens into the ocean basin at the foot of the slope. North of the ridge there is a thick stack of evenly layered sediments.

Reflector Blue (Fig. 2.22, App. 4E) is a marked unconformity over the entire ridge. It is truncated at some of the major boundary faults at the western margin, because of minor fault movements or erosion post-dating the reflector, but it clearly post-dates the main phase of faulting. On the North Ridge the reflector represents a prominent angular unconformity caused by uplift and erosion, which is estimated to have removed up to 1000-1500 m of sediments. On the western margin, it can be traced underneath the edge of the igneous marker, reflector Green.

Sequence Blue-Pink records the final infilling of the rift basins at the western margin and levelling of the seafloor to a plain.
Tectonism and sedimentation

Contemporaneously with the development of the rift on the Greenland shelf, the Jan Mayen Ridge, which formed the eastern rift flank on the outer continental margin, was fragmented into rift basins and faulted ridges. This was accompanied by the emplacement of sills at the eastern margin. The larger fault blocks were uplifted and tilted eastwards. The North Ridge was uplifted above sea level and eroded extensively. Following the main phase of faulting, thermal subsidence set in over the whole ridge complex prior to breakup, and the North Ridge was submerged.

The pattern of sedimentation underwent radical changes during the deposition of the sequence as a result of faulting and differential vertical movements. Four phases of sedimentation are discernible, corresponding to the four depositional sequences.

The sediments deposited in the first phase (sequence Red-Yellow) record mild uplift and tilting of the faultblocks which formed the eastern rift flank, coevally with subsidence of the rift basins. The basins began trapping sediments and, as a result, sediments deposited on the slope towards the Norway basin were increasingly derived from the eastern rift flank. South of the Transverse Ridge, a basinward thinning and downlapping wedge was deposited on the upper slope. A prominent submarine canyon was formed at the mouth of the Jan Mayen Trough, probably as a result of the steepening of the slope. A thin sheet of sediments deposited on the eastern margin north of the Transverse Ridge indicates that the uplift and tilting was less marked there.

In the second phase (Yellow-Turquoise), the rift basins on the western margin started to subside rapidly. Eastwards rotation of the larger fault blocks caused their western edges to be further uplifted coevally with subsidence of
the intervening half grabens. The North Ridge rose above sea level, but none of the fault blocks in the Southern Ridge Complex were exposed. At the same time as the North Ridge was established as a strongly eroded local provenance area, the deepening rift at the western margin began to trap all sediments derived from the Greenland side. On the eastern margin, south of the Transverse Ridge, the slope steepened and to a larger degree the sediments were carried into the basin and deposited as submarine fans. North of the Transverse Ridge, a downlap wedge was deposited. The wedge is similar to the wedge deposited south of the ridge in the first phase and its presence indicates that the uplift of the North Ridge propagated northwards.

At the onset of the third phase (Turquoise-Blue), the rift basins were already established and many faults had become inactive. Yet, extensional movements continued on many of the major faults. There is clear evidence that the tectonic regime acquired a coexisting component of compression. Uplift and the rate of erosion culminated on the North Ridge and a large amount of sediments was shed into the surrounding basins. On the western margin the sediments were transported by turbidity currents into the rift where they accumulated as a stratified fan complex filling in the many grabens and half grabens. On the eastern margin, the sedimentation was dominated by massflow down the eastern slope. Different depositional regimes continued to exist on either side of the Transverse Ridge. South of the ridge, overlapping fans initially built a slope front fill. Towards the end of the phase, the sediment input to the slope reached a near- catastrophic rate. A number of transversely oriented channels were formed as turbidity currents eroded into the sediments deposited earlier as a slope front fill. Between the closely spaced channels some sediment was deposited on overlapping levees, but most of it was carried further into the basin where coalescing fans built a sedimentary apron on the rise and filled an emerging depocentre at the mouth of the Jan Mayen Trough.
North of the Transverse Ridge, the slope was wider and much gentler than further south. The sediments eroded from the exposed top of the ridge accumulated as a thick and well stratified stack of turbidites. At the end of the phase, the top of the sequence was exposed to subaerial erosion and a large canyon was carved into it by turbidity currents carrying sediments deeper into the Norway Basin.

In the last phase (Blue-Pink), fault movements ceased and thermal subsidence set in over the whole ridge complex. The rift basins of the western margin were levelled to a plain by sediments derived from the unstable western slopes.

2.5.6 INTRUSIVES AT THE WESTERN MARGIN

At an average depth of 350-500 m below the seafloor, an extensive flatlying high-amplitude reflector, reflector Green, covers the major rift basins at the western margin and masks the underlying structure. No real energy is returned from below the reflector except at its northern and eastern edge in the Jan Mayen Basin.

Description

In cross section (Fig. 2.16, App. 5A) the reflector is composed of a number of segments with sharply defined edges. The individual reflector segments are straight and horizontal and range in length from 1-25 km. The grid of reflection lines available is too coarse to define the planform of their edges.

Normally the reflection signature is just one cycle, but in a number of cases several cycles are observed, indicating some internal structure. In at least two cases a clear
double reflection is observed from the same segment. Although individual segments are straight and horizontal, they are not smooth on a horizontal scale of hundreds of meters.

The areal extent of the reflector appears to be controlled by the bathymetric relief at the western margin, which in turn reflects the underlying structure. The reflector covers the Jan Mayen Basin, the Jan Mayen Trough, part of Rift "A" west of DSDP site 350 and the region to the southwest of these basins. The total areal extent within the study area is approximately 12 000 km² (Fig. 2.13, App. 4B).

In each basin the larger reflector segments form extensive flats with a well defined average depth level. Few segments are found shallower than 100 ms twt (90 m) above this level. Short deeperly segments are common, the maximum offset being 300 ms (250 m). The average depth to the reflector ranges from 3.5 s twt in the Jan Mayen Basin to 3.2 s twt in the Jan Mayen Trough and in Rift "A". In view of the large area covered by the reflector, this depth range (corresponding to some 250 m) is remarkably narrow.

In the major rift basins, the reflector's boundary is an easily mappable sharp edge, which either abuts against the raised tectonic relief or terminates abruptly on the basin plain. At the western flank of the North Ridge, sedimentary layers and faults in the listric fault complex are occasionally traceable a few km beneath the reflector's edge.

West and southwest of the Jan Mayen Basin, the Iceland Plateau is covered by a smooth and opaque basement reflector (Eldholm and Windish, 1974; Eldholm and Talwani, 1977; Olafsson, 1983). Although it is somewhat more rugged and in places tilted by faulting, this reflector is similar in appearance to reflector Green. It was reached by DSDP
hole 348, sited at anomaly 6A, and found to be basalt, probably a sill (Talwani, Udintsev et al., 1976).

North of approximately 69N, reflector Green terminates against the northerly striking basement high, which marks the western structural boundary of the Jan Mayen Basin and coincides roughly with the oldest seafloor spreading anomaly identified on the Iceland Plateau.

South of 69N, the Jan Mayen Basin lacks a structural boundary to the southwest and reflector Green can be followed onto undisputable oceanic crust on the Iceland Plateau where it merges with the opaque basement horizon without other discontinuity than the characteristic stepping. The only observable difference is that the opaque horizon on the Iceland Plateau is somewhat more irregular than reflector Green and the extensive flats defined by the latter in the rift basins are lacking. As the opaque reflector is followed towards Iceland it shallows by upward stepping, but retains its high reflectivity.

Stratigraphic position

Constraints on the age and origin of reflector Green are provided by its stratigraphic position within the sedimentary succession. Individual reflector segments lie at different stratigraphic levels but are conformable with the sedimentary succession. This follows from observations between the two edges of different segments, where a horizontally layered sequence is observed from above the edges down to the intervening segment at deeper level. Commonly, the two edges are joined by a sedimentary interface at exactly the same level. In the Jan Mayen Basin, reflector Blue dips underneath its eastern edge of reflector Green and reflector Pink continues into the basin within the sedimentary sequence above it. At the northern end of the Jan Mayen Trough, reflector Green lies 300 ms
twt above reflector Blue. In the eastern part of the Jan Mayen Basin, reflector Pink typically lies some 100 ms twt above reflector Green, but merges with it in the central and western part of the basin. The stratigraphic position of reflector Green is therefore high within the late rift sequence above reflector Blue, a major part being at the level of reflector Pink.

Origin and emplacement

Reflector Green is interpreted as being igneous in nature. A sedimentary origin is not supported by the data. The fact that the reflector is areaally restricted to the basin plains of the western margin and yet covers them only partially, excludes pelagic deposits and airborne ash. A sediment mass transport mechanism may explain the areal configuration, but the large reflection coefficient rules out most such deposits. Although submarine debris flows and slides are commonly highly reflective and structureless, they leave scars on the slope from which they derive. No large scars are observed on the western margin. A gas hydrate layer would not generate such a strong reflection. Thus, we are left with submarine lava flows or sills, an interpretation strongly supported by the reflector's lateral association with and similar appearance to the opaque reflector on the Iceland Plateau.

Reflector Green defines a horizontal surface high within the postrift basin fill sequence of the western margin. The basin plains must have been nearly horizontal at the time of its emplacement. Significant fault related subsidence of the basins with respect to the ridges, post-dating reflector Green, can be excluded. Any later component of differential thermal subsidence should have flexured or tilted the reflector. This appears unlikely in view of the present horizontal attitude of the reflector over the large area it covers. Because of the smoothness of the erosional
surface defined by reflector Blue on the North Ridge and lack of erosional channels at its edge, sea level cannot have fallen significantly below the top of the ridge. Thus, most of the present day level difference between the basin plains and ridges had already been established when the igneous complex was emplaced. A reconstruction to the time of emplacement of reflector Green indicates that water depths above the basin plains were of the order of 1000 m and implies a submarine origin for the layered volcanic basement at the western margin of the Jan Mayen Basin.

An examination of the sedimentary layering above the reflector does not yield a single unambiguous case of a step being caused by faulting. In one case, where the reflector is transparent, a prominent offset can be shown to be unrelated to faulting. However, up to a level just above reflector Pink, the sediments above reflector Green are commonly raised above individual segments and slightly stepped or kinked over the edges. This phenomenon needs not be explained by faulting, alternative interpretations being uplift by sill intrusion or differential compaction over sills or lava flows.

Although it is possible that the reflector's characteristic stepping was caused by tectonic disruption of a previously level and continuous surface, it is unlikely that the igneous complex represented by the reflector was derived from a single point or fissure source. The mechanics of horizontal submarine and subterranean magma transport make the possibility of a single source covering an area of more than 12 000 km² highly unlikely. Therefore, reflector Green is interpreted as being caused by locally derived igneous units, either sills or submarine lava flows, imbedded at different stratigraphic levels within the sedimentary sequence. It follows that overlap between the individual segments should be common, reflector Green representing only the upper surface of the complex. The fact that no gaps in the surface are found at the edges of different
segments indicates that this is the case.

There appears to be no unique way of discriminating between sills and lava flows with the available data. Sill complexes on the Norwegian Margin, in the Rockall Trough and on the eastern margin of the Jan Mayen Ridge all show examples of discordant sills. Large flats at approximately constant depth level, such as those defined by reflector Green are lacking, strongly indicating a different emplacement setting for this reflector. The narrow depth range to the reflector can be explained by emplacement at a horizontal surface where the magma pressure suddenly fell below the prevailing hydrostatic or lithostatic pressure. This in turn indicates emplacement at or just below seafloor where the pressure gradient is steepest. Additional evidence for emplacement close to the seafloor comes from the overlying megasequence.

The igneous nature of reflector Green, its areal distribution, similarity to the Iceland Plateau opaque horizon and lack of structural offset between the two reflectors at anomaly 7 south of 69N indicate that it formed at breakup west of the ridge, but this cannot be proven by seismic stratigraphic means.

2.5.7 MEGASEQUENCE 4: SECOND DRIFT PHASE

The sedimentary sequence above reflector Pink was deposited in the second drift phase when seafloor spreading was established on the Iceland Plateau.

Reflector Pink is defined on the western slopes of the North Ridge, where in places it defines submarine erosional channels. The overlying sequence pinches out in the updip direction where the slope is steepest just beneath the flat top of the ridge, but its presence there cannot be
excluded. The sequence steps onto oceanic basement on the Iceland Plateau and therefore post-dates breakup, but because reflector Pink merges with reflector Green in the western part of the Jan Mayen Basin, this may not apply to the whole sequence. A thin unit at the base may be masked by reflector Green and possibly pre-date the oldest oceanic crust.

Assuming that reflector Green was emplaced just before or at breakup, the part of the sequence above reflector Pink which continues onto oceanic basement may be stripped away to reveal the situation at breakup (Fig 2.19, App. 5C). This shows that reflector Green lay at the seafloor in the western part of the Jan Mayen Basin and just beneath it further east and that reflector Pink was formed approximately at the same time.

The sediments in the sequence above reflector Pink, seem to have been derived from the slopes at the western margin. This may be explained by the steepness of the slopes which probably rendered them unstable. In the upper part of the sequence, the sediments are expected to become increasingly pelagic. A minimum estimate of this component is provided by the thickness of the thin layer covering the top of the North Ridge.

The stratigraphic position of reflector Pink at the eastern margin, indicated on Figure 2.12, is only tentative because firm ties from the western margin are lacking.
Fig 2.24 Isopach map of the sequence above reflector Blue
3 HYDROCARBON RESOURCE POTENTIAL OF THE JAN MAYEN RIDGE

Two main sedimentary sequences on the Jan Mayen Ridge should be investigated for possible hydrocarbon generation and accumulation, the Tertiary post-rift sediments and the older sediments below the early Tertiary basalts. The post-rift sediments are transparent and easily detectable by seismic reflection methods. Some information about their nature is available from the DSDP-boreholes on the ridge and in other locations in the Norwegian-Greenland Sea, boreholes on the Norwegian shelf and a few onshore localities on Greenland. Their hydrocarbon generating potential must be considered uncertain, as is indicated by the discussion of relevant data below.

Estimation of the potential of the sediments below the basalts is hampered by lack of samples from these strata. Our knowledge of their distribution, thickness and stratigraphy is limited. The conjugate margins of the Jan Mayen microcontinent, the Møre margin of Norway and the central East Greenland margin, were adjacent to the microcontinent in pre-rift times and were part of the same sedimentary environment. In absence of any direct information on the hydrocarbon potential of the Jan Mayen area, a comparison with the results of hydrocarbon prospecting on these conjugate margins is of great interest (cf. chapter 2.1.5)
3.1 POTENTIAL SOURCE ROCKS

3.1.1 TERTIARY POST-RIFT SOURCE ROCKS

Results from organic geochemical studies of cores from leg 38 of the Deep Sea Drilling Project generally indicate that the Tertiary sediments of the Norwegian-Greenland Sea have little hydrocarbon potential (Kvenvolden, 1976). The only positive opinion is expressed by Erdman and Schorno (1976). Based on analysis of 5 samples from sites 346 and 349 they found total organic contents (TOC) in the range .18 % - 1.04%. They conclude that the sediments in general are relatively rich in organic carbon, including marine organic matter that could be favorable for oil generation. Oil genesis in the samples they studied was however at a very early stage. The source rock characteristics of partly the same cores were measured by Hood et al. (1976). They found slightly higher TOC-values, highest effective carbon contents not exceeding 0.22%, and the same low maturation level as the previous authors. Their conclusion is however that it is doubtful whether the sediments contain enough hydrocarbon-generating material to be considered potential source-rocks.

Dillon et al. (1986) have recently reviewed the resource potential of the western North-Atlantic basin, i.e. the deep sea basin east of North America. This environment is possibly comparable to the Norway Basin and the Jan Mayen Ridge area, and general conclusions could be applicable to both areas. No evidence is found of Tertiary beds so rich in organic material, that they could be considered as source beds.

A cautionary note is appropriate here, as the Tertiary sediments have not been fully sampled yet. According to a paleogeographical study of the Norwegian-Greenland Seas by Grønlie et al. (1979), the opening ocean basins were restricted to the south by the emergent Iceland-Faeroe
Ridge until in Middle Miocene time (about 13 Ma), and a full opening towards the north, the Arctic Sea, formed at anomaly 13 time (36 Ma). During the time of restricted water exchange the conditions in these relatively narrow and shallow ocean basins (Norway, Lofoten and Greenland Basins) could have led to stagnation (reducing conditions) and accumulation of organic matter in the sediments. The study indicates that the boreholes of the Deep Sea Drilling Project in the Norwegian-Greenland Sea did not penetrate these deep basinal sediments that accumulated in the first phase of the formation of the sea-floor (Eocene time). These early Tertiary sediments, that are e.g. found below the lowermost eastern slopes of the Jan Mayen Ridge, could therefore possibly be source rocks.

3.1.2 SOURCE ROCKS IN PRE-RIFT STRATA

The seismic detection of sedimentary layers of presumable Mesozoic and Paleozoic age below the early Tertiary basalts, generally improves the hydrocarbon potential of the Jan Mayen area. These strata are most clearly imaged in the south-eastern part of the North Ridge, under the eastern flank (Figs. 2.12, 2.16, 3.1, 3.3, Appendix 5). No direct information is available about the lithology of these pre-rift continental sediments, so we can only assume that the sediments of the Jan Mayen Ridge are similar to those found on the continental margins on both sides of the ocean (Figs. 2.8 and 2.9). On both margins sediments of all lithologies required for hydrocarbon accumulation are known, from Upper Permian to Lower Cretaceous age (Fig. 2.9). Upper Jurassic shales and Middle Jurassic sandstones are the most prolific combination of source and reservoir rock. Although the geophysical data indicate the existence of pre-rift sediments under the JMR, we see no way to assess which part of the Mesozoic or Paleozoic sequence is present. Drilling will be needed to get this information.
The Jan Mayen Ridge remained as part of the Greenland continental margin during the first phase of seafloor spreading in the Norwegian-Greenland Sea, and its geological history is probably closer to that of Greenland than of Norway. A commercial group has carried out some prospecting, including acquisition of seismic reflection data, on Jameson Land. So far no exact information is available about the results, but drilling is evaluated, so there are positive indications. In their evaluation of the hydrocarbon potential of this basin, Surlyk et al. (1984) point to a major sequence of black shales, which occur throughout the basin and are of Upper Permian age. These shales are rich in organic matter, and would be a good source rock for oil, given the appropriate maturity. The exposed sediments are generally on the immature side, but over-mature where locally affected by Tertiary volcanic intrusions. Listed as other possible source-beds (Surlyk et al. 1986) are the Graaklint beds of the Middle Triassic Gipsdalen Fm., the lowermost Jurassic Kap Stuart Fm. with some coals interbedded with shales and sands, and a laterally consistent shale unit of Middle Jurassic age, the Sortehat member of the Vardekløft Fm.. Upper Jurassic shales are the most promising source rocks, except for their lack of maturation as they are found at shallow depth. These Jurassic formations are the equivalent of the very productive Kimmeridgian formations of the North Sea, and would be very promising if they are also found offshore buried at greater depth.

It appears that the source rocks of Jameson Land are generally not mature for peak oil production, except possibly a part of the Permian shales. If a similar sedimentary sequence is present in the Jan Mayen Ridge, such problems would be less serious. The greater overburden of Tertiary basalts and sediments should have led to a higher temperature regime and more advanced maturation of organic matter. In the following section on maturation modelling, an attempt is made to estimate these effects.
3.1.3 SAMPLING AND ANALYSIS OF HYDROCARBONS

The only optimistic reports of sampling and analysis of gases in shallow cores in the Jan Mayen area are from a cruise of the Soviet research ship Akademik Kurchatov, that investigated the Jan Mayen area in 1971 and 1973. These investigations included an analysis of gases in a few bottom cores. Traces of hydrocarbons were found in samples from water depths of about 1200 to 1500 m in the southern area, that included methane and heavier hydrocarbons. These results were interpreted by the Soviet scientists as indications of deep hydrocarbon sources of possible economic importance (Geodekyan et al., 1980). In general, a correlation was observed between thickness of sediments and amounts of hydrocarbons in shallow cores in the seas north and northeast of Iceland. The results of the measurements were handed over to Orkustofnun, and Oljedirektoratet was later asked to give their opinion (See letter by Egil Bergsager, Oljedirektoratet, to Gudmundur Palmason, Orkustofnun, E/b/10, 16.2.,81, including appendix by SSE). This analysis indicated that the amount of gas was not exceptionally high and could well have had its source in shallow low-temperature chemical or biochemical processes, and that the composition and distribution with depth did not indicate migration of gas from deep sources.

3.1.4 HYDROCARBON MATURATION MODELLING

Methods have been developed to estimate the degree of maturation of organic material in sediments. Many parameters must be known to do these calculations with some degree of accuracy. The dominant parameter is however the temperature-history of the various layers - which is dependent on subsidence and depth of burial on one hand, and heat flow and temperature gradient on the other. Such
modelling has been attempted at relevant positions on the JMR to get some idea about the level of maturation. Our results are only approximate, as the constraints are not known in any detail. The method used is based on kerogen maturation as described by Tissot and Welte (1978), and Waples (1980). The methods are calibrated to data from wells on the Norwegian shelf. Also for sediment conductivity and porosity-changes through compaction/decompaction, Norwegian well-data have been used for calibration of the computer-modelling.

The accuracy of our calculations is limited by the lack of a reliable subsidence history, and the insufficient knowledge of heat flow through time. The only available measurements of heat flow in the area are reported by Sundvor and Myhre (1987), who measured the temperature gradient and conductivity in the upper few meters below sea-bottom. They found the heat flow today to be about 85 mW/m² just west of the JMR, and about 65-70mW/m² on top of the ridge and on the eastern flank. The early- and mid-Tertiary rifting episodes were certainly associated with higher heat flow, which have affected all possible source levels. Post-rift intrusions (sills) are also observed. Their effect is expected to have been to increase the maturation locally, but regional effects can not be ruled out, especially on the lower eastern flank of the ridge. The level of maturation is strongly influenced by the highest temperature experienced - so the heat pulses will have had a large impact on maturation in the area. The fact that the area previously has experienced higher heat-flow, supposedly has a generally negative effect on the present effective expulsion of hydrocarbons from mature source-rock, since lowering of temperature tends to reduce the expulsion efficiency.

In order to account for the uncertainties in the heat flow history two heat flow models have been used, a low heat flow case assuming 70 mW/m² from the deposition, and a high
heat flow case assuming 100 mW/m². Both models assume constant heat flow through time. A more realistic model assuming heat flow decay during the last 25 Ma, would result in maturation values between the two extreme cases.

Four sites along seismic line JM-12-85 have been modelled. Their position is shown in Fig 3.1. Site 1 is located in the downfaulted west flank of the North Ridge, site 2 in blockfaulted terrain on the central part of the ridge, site 3 on the upthrust faultblock on the eastern flank, and site 4 further down the eastern flank. The pre-opening strata observed at sites 3 and 4 are assumed to be present also at sites 1 and 2, and to represent Mesozoic sediments. Uncertainties are additionally introduced by the depth conversion being based on seismic stacking velocities.

The estimated subsidence curves for the four sites are shown in Fig 3.2. The questionmarks reflect uncertainty in the existence of and depth to the levels modelled. For points 2 and 3 an Oligocene erosion of 500 m was assumed in the calculations.

Results of the modelling are:

Site 1: Assuming relatively high heat flow the early Eocene possible source-rocks have reached the oil-window.

Site 2: The Tertiary source-rocks are immature. Assuming the postulated Mesozoic source-rocks to be at a depth of about three km below the seafloor, they have passed into the gas-window in the high heat flow case. With a moderate heat-flow history they are presently in the oil-window.

Site 3: The Tertiary source-rocks are not likely to be mature, but may have reached a very early oil-mature stage. The postulated Mesozoic source rocks are assumed to be at a depth of some 4 km below the sea-floor. In the high heat-flow case this results in over-cooking of the organic
material, in a more moderate case the source-rocks are presently producing gas. The burial of the pre-Purple reflector Brown is however decreasing north of the site, so the assumed Mesozoic source-levels may still be in the late oil-window.

Site 4: The hypothetical Tertiary source-level is presently at a burial depth of about 2-2.5 km below seafloor. With a moderate heat flow history it is early oil-mature.

Again stressing the uncertainties in these calculations, we conclude that the hypothetical early Tertiary source-rocks are likely to be early oil-mature west of the ridge, and on the eastern flank, while they are certain to be immature beneath its top. The postulated Mesozoic source-levels are likely to be in a main/late oil-window beneath the top of the ridge, while they would be in the late oil-window/early gas-window beneath the eastern flank. The post-Oligocene decrease of heat-flow in the area may hamper the effective expulsion of hydrocarbons today.
Fig 3.1 Interpretation of seismic line JM-12-85 across the Jan Mayen Ridge, showing sites where subsidence/maturation modelling has been carried out (cf. Fig.3.2). Letters show location of the principal hydrocarbon play types in the area, described in section 3.2.
Subsidence curves for 4 sites on a transect across the Jan Mayen Ridge. Location of the sites is shown in Fig 3.1.
3.2 POTENTIAL HYDROCARBON TRAPS AND ASSOCIATED PLAYS

3.2.1 TERTIARY POST-RIFT PLAYS

The sequence of interest spans the time interval from the early Eocene deposition of reflector Purple to the formation of the mid-Oligocene unconformity (Reflector Blue). Data from the boreholes give no evidence of good reservoir or source rocks. The general lithology is mudstone with variable contents of silts and sands. The sampling of the relevant sequence is however far from complete, and thus some possibilities still exist. Sand contents up to 50% were measured in hole 349. Turbiditic processes and contour currents may result in the formation of sedimentary bodies with even higher sand contents the eastern flank of the ridge (A). (Block letters in parantheses denote different hydrocarbon play types. See also Fig. 3.1.) A well developed channel sequence lies buried within the continental rise of the southern U.S.A. (Dillon and Paul 1978). Similar channel-fill deposits have also been described for the continental slopes off New Jersey (Poag 1985) and Georges Bank (Schlee et al. 1985). Such stratigraphic traps might include coarse turbidites and debris-flows forming channel filling wedges. Alternatively, coarse strata in channel ridges could be sealed by fine-grained channel infill.

The deep sea fans associated with the formation of the channel system are also possible stratigraphic traps. They are seen deep in the section on the east flank of the Jan Mayen Ridge, and seem to form well defined wedges that pinch out updip (A) (Cf. chapter 2.5.5). Their location is just above the lowermost basinal post-rift sediments, which are the most likely source rocks in post-rift times.

Oil accumulation in structural traps must also be considered possible within the Tertiary sequence. Of interest would be the subcropping against the flat main
unconformity under the top of the ridge (B). This is however dependent on the ability of the thin overlying pelagic sediments to form an effective seal, which must be considered unlikely. Block faulting, most of which was terminated by the mid-Oligocene, has caused a number of structures on the crest of the ridge that could form traps given the right combination of porous sandstone beds and tight seals (C). Local source rocks are not likely to be mature, so hydrocarbons would either have to migrate laterally a long way from possible post-rift source rocks, or originate from pre-rift sediments below the basalts. Similar fault-blocks west of the ridge (D) have experienced deeper subsidence, possibly resulting in locally mature Tertiary source-rocks.

3.2.2 PRE-RIFT HYDROCARBON PLAYS

Again no direct information exists on the reservoir quality of the pre-rift sediments of the Jan Mayen Ridge. Potential reservoirs in the Jameson Land sedimentary basin on East Greenland include thick (100 m) Upper Permian limestone units. Their porosity and permeability is however presently unknown. The basal Triassic sequence contains coarse-grained bodies of fan delta origin, but their properties have not been properly investigated. Jurassic sandstones have excellent reservoir potentials, but form the surface of Jameson Land and are therefore useless there. If a good seal was formed on top of similar sandstones on the JMR, these rocks would be of great interest for oil prospecting.

By seeking an analogy in the geology of Greenland, it is possible that a layer of continental sandstone of Paleocene age exists just below the plateau basalts associated with horizon Purple. A layer of volcanic breccia could have formed at the base of the basaltic pile by the action of water. This raises the possibility of a reservoir at the base of the Tertiary basalts, capped by the lavas or the post-rift Tertiary sediments above.
Hydrocarbon traps below the basalts should be possible in the numerous fault-blocks that have resulted from the Oligocene tectonism that affected the crest and western slopes of the North Ridge. The faultblock just east of site 2 (E) is likely to be a trap - although its geometry is not known with certainty. Hydrocarbons may have migrated from deeper buried areas in the east, or from deeper locally mature source-rocks. A number of complex rotated fault blocks further west (F) could have received migrated hydrocarbons from the Jan Mayen Basin, if the pronounced listric faults act as migration routes, or from deeper buried local sources. More seismic information is however necessary to map these structures satisfactorily. No convincing pre-Purple reflectors have been observed in these locations - so the depth to, and even existence, of Mesozoic source/reservoir rocks is hypothetical.

The observed reflectors below the basalts under the southeastern flank of the North Ridge are terminated to the west by an apparently reverse fault that has formed a high on the eastern side (G). This high is so far the most likely candidate for a hydrocarbon trap below horizon Purple. The strata of this basin have a general eastward dip and undulating topography that could create closures and traps against the western fault, or against unconformities truncating the dipping strata. Fig. 3.3.a shows an interpretation of a segment of the north-trending line JM-25 through the high just east of the fault. It shows southeast-dipping truncated strata, overlain with thin sediments of possible late Cretaceous to earliest Tertiary age, the plateau basalt and post-rift sediments. A map of reflector Brown is shown in fig 3.3.b. The unconformity associated with the reflector could be the top of a closed structure. Indications of flat-spots under the unconformity are interesting, but vague.

The Southern Ridge Complex is formed by large scale brittle
extension in the second rift phase which also block faulted the western flank of the North Ridge. The listric faulting has formed large rotated fault blocks (the "ridges") and local sedimentary basins, half grabens, in between. The fault blocks could trap hydrocarbons, and in the basins an increased temperature could accelerate oil formation. Perhaps the large scale faulting was detrimental in the sense that deep sections were exposed and the possibility of leaking increased.
a) An interpretation of a segment of line JM-25-85 (sp 200-800). The seafloor and horizons Purple, Orange, and Brown are indicated.

b) Two way reflection time to horizon Brown. Bar shows position of the line segment interpreted in Fig 3.3a). The horizon is partly truncated by the fault and partly by an unconformity. The horizon bends down towards the south-east and disappears under the wedge of seawards dipping basalts.
3.3 POCKMARK INDICATIONS

On the high flat plateau that forms the top of the North Ridge, the migrated seismic data show a multitude of crater-like depressions in the sea bottom between about 69°00'N and 70°20'N, at water depths in the range 500-1000 m. No similar depressions are detected outside this area. They are variable in size, from being just detectable up to measuring some 40 m in depth and 300 m in diameter. Some have steep sides and flat bottoms, others are V-shaped, besides other more irregular shapes. Occasionally the edges are slightly raised. About 70 holes have been noted on a roughly 150 km long and 20 km wide strip along the ridge top, and their location is shown in Fig. 3.4. Possibly we observe only some 3% of all the depressions, as this is the approximate seismic coverage of the sea bottom. This is based on the estimate that the effective swath of the seismic search is 200 m wide on the sea-bottom, and the average distance between lines in the area being about 6 km.

One cannot exclude the possibility that the holes are in reality only cross sections of channels in the sea bottom. Channels due to scouring of icebergs are known features in northern latitudes, but hardly a likely explanation in this case as no iceberg reaches a depth of 1000 m, even if the marks were thought to be a remnant of the last glaciation. We think it also unlikely that narrow erosion channels wind their way across the high plateau. These questions could be answered by detailed 3-D bathymetric mapping survey, including a side scan sonar survey.

It is tempting to compare the "craters" to the so-called pockmarks, that are for example found in the bottom of the North Sea (McQuillen & Fannin, 1979; Hovland 1981). These craters are indeed common in fine grained sediments of many continental shelves and vary from 10 to some hundred meters in diameter, on average well below hundred meters. Their
depth is proportional to the diameter, up to 15 m but usually around 5 m. Thus the observed craters on the Jan Mayen Ridge are in the upper range in size. Pockmarks are also not normally observable on conventional multichannel seismic lines because of the relatively low areal resolution of such data - so the parallel is inconclusive. Crater-like features are also observed in the Barents Sea (Solheim et al. 1985, 1987, 1988). Their origin is debated, one possibility being "eruptions" when gas hydrates (cf. below) have become unstable and "gased out". Where observed, pockmarks are thought to be formed by seepage of gas through the sea-bottom. As this gas could be methane formed in situ at shallow depth, or other gases, the features are not thought to be a clear indicator of economic hydrocarbon accumulations, although indications of clustering of these holes around major hydrocarbon fields have been observed.

The distribution of the craters is not related to any bathymetric features or waterdepth, except that they are found on the flat top of the ridge. A comparison with the geological structures, as interpreted from seismic data, indicates that they cluster in areas of structural basement highs, and are furthermore associated with either faulting of horizon Purple or erosive truncation of sub-Purple strata. If the pockmark hypothesis is correct, these observations could indicate that the gas originates in deep geological formations, i.e. the sub-Purple sediments, rather than from shallow gas formations. The latter possibility must, however, be kept in mind, as gas hydrates (see below) could seal off shallow gases and channel these to high bathymetric positions.
Fig 3.4 Distribution of observed "craters" (circles) on the Jan Mayen Ridge. Water depth in meters.
3.4 GAS HYDRATES

Gas hydrates are ice-like crystalline solids that form as a cage-like structure of water molecules surrounding a gas molecule. In nature the gas is most commonly methane (CH₄). Gas hydrates are stable below a temperature curve that increases with depth. A comparison of the phase boundary of methane hydrate and a typical temperature-depth curve for the sea and sediments of the Jan Mayen area shows that gas hydrates could occur at and below the sea bottom at water depths exceeding 300 m (see Fig. 3.6 a). The deep-sea temperature in the area is close to 0°C. The top of the gas hydrate layer will coincide with the sea bottom, and the hydrates will persist down to the depth where the phase boundary curve is intersected by the geothermal temperature curve. Below that depth, gas hydrate would be unstable and any gas would be dissolved in pore water or be present as free gas. The thickness of the gas hydrate layer increases therefore with increasing depth to the bottom, and decreases with increased geothermal gradient. As an example, we predict the thickness of the hydrate zone as about 420 m where water depth is at 2 km, 470m at 3 km and 340m at 1 km depth, assuming a gradient of 50°C/km. Because the geothermal gradient tends to vary little over sizeable areas, the base of the hydrates-region is often observed to be at approximately constant depth below the sea bottom and follow its undulations. This boundary is often recognized in seismic reflection surveys, and referred to as a bottom simulating reflector (BSR). These are widely found, e.g. on the continental margin of the eastern USA as summarized by Dillon et al. (1986), and off the northern coast of Canada. A recent review of the possible economic importance of gas hydrates (Dillon et al., 1986), seems to indicate that the possibility of producing gas bound in the hydrates is presently rather remote, although it might ultimately be possible. A more important aspect could be that sediments saturated with gas hydrate may act as seals trapping hydrocarbons.
In various locations of the Jan Mayen Ridge area clear reflectors are seen in the seismic data that could be interpreted as BSR's. These have not been previously identified in the area (Eggen 1984). It is not easy to confirm that these reflectors are really due to gas hydrates, as they tend to appear below the flat bottom of the deep ocean basin where the original stratification of the sediments is also nearly parallel to the sea-bottom. They do not show up on structural highs. This could either be due to different physical properties of the sediments on these highs, or lack of gas.

Fig. 3.5 shows the distribution of observed BSR's interpreted to be related to gas hydrates. These reflectors are most prominent in the southern part of the area and are difficult to define in the north. The BSR's are mostly detectable in the range of 1500 to 2200 m sea depth, and range from 350 to 500 m in thickness. Some discrete measurements are plotted in Fig. 3.6 b. The data points show a considerable scatter, and they do not show a definite increase of thickness with depth, contrary to expectations. The thickness tends to be slightly less on the western side of the ridge, perhaps reflecting a higher thermal gradient of the younger margin. The geothermal gradient can be estimated by referring to the phase boundary curve in Fig. 3.6 a. According to this the gradients range from 36 to 58°C/km, with about 50°C/km as the median value, but it remains to be tested if these values are realistic.
Fig 3.5 Areas of possible "bottom simulating reflectors" (BSR's) (shaded) that could indicate gas hydrates in the sediments. Waterdepth in meters.
Fig 3.6  

a) Phase boundary curve for methane and methane hydrate.

b) The observed thickness of the hydrate layer in various places in the Jan Mayen area, as a function of sea depth.
3.5 CONCLUSIONS

No direct evidence has been presented proving the existence of hydrocarbon resources in the JMR area. Geophysical data indicate however that two different types of plays are possible, one in the post-rift Tertiary sediments and the other in pre-rift sediments that are seen in places below the syn-rift plateau basalts (horizon Purple). The latter play-type is more promising as the deep sediments are probably of Mesozoic and Paleozoic age and comparable to the prospective sediments found on the continental shelf of Norway, and in East-Greenland. These sediments are best observed on the south-eastern part of the North Ridge, but their areal distribution is not well known, mainly because of limited penetration of seismic waves through the basalts.

No indication of Tertiary source rocks have been found in boreholes, but these are few and have not sampled the optimal sequences. If existent such strata are not likely to be mature for oil expulsion, except where they are thickest on the lower flanks of the ridge. Also reservoir levels in the Tertiary section remain hypothetical.

Crater-like features on the flat top of the main ridge and possible gas hydrates in deep areas are observed, indicating the possibility of some gas in the sediments, be it of deep or shallow origin.

A final test of the hydrocarbon potential can only be obtained by drilling. The seismic data indicate possible sites for exploratory wells, but a denser seismic grid would be preferable in chosen areas before drill-sites are determined.
4. RECOMMENDATIONS

The geological mapping carried out indicates that the JMR may have some hydrocarbon-potential, but it can not be considered very great. The existing database is not sufficient to give a conclusive answer to the question.

Considering today's technology and market situation, the large water depth, remoteness and exposed location of the area, exploitation of potential hydrocarbon resources is very unlikely in the near future. Technology and economics can however change rapidly, and it is advisable to have a long-term plan to advance the status of the JMR-area. For this purpose there is need for further exploration. In the following we present some research projects that are in progress, and can be regarded as the final phase of the present regional study. Then we discuss possible long-term exploration strategy for the area.

4.1 RESEARCH IN PROGRESS

Some projects are presently active and involve both processing of new seismic data, and interpretation of the existing data, mainly those of the 1985 cruise. Processing and interpretation of the geophysical data from the JMR will continue in 1989 in cooperation between the two countries.

a) A project was organized in 1988 regarding the interpretation of the sonobuoy data acquired in the 1985 cruise. This involves about 40 sonobuoys, that are expected to give new information on the velocity structure of the JMR crust, and thereby indication of the possible lithology of the upper crustal layers. The project was finished in august 1989 with a report: The Jan Mayen Ridge - Velocity structure from sonobuoy data (OS-8903C/JHD-04, Reykjavik, August 1989). The work was carried out at NEA mainly by Dr
Ingi Olafsson. NPD provided his salary for half a year, while NEA provided facilities and support. The main purpose of this study was to obtain new information on the velocity structure of the pre-Tertiary rocks, i.e. the strata below the post-rift sediments of uncertain composition. Of special interest was the possibility of detecting Mesozoic or Paleozoic sediments, and determining their distribution.

b) The seismic reflection data set is studied at the Department of Geology, University of Oslo, under the supervision of Steinar T. Gudlaugsson. The work focuses on two aspects, the stratigraphy of the Tertiary sequence in order to evaluate sedimentation and vertical movements at the ridge, and studies of velocity distribution, especially in the Tertiary sediments, as a basis for geophysical modelling of crustal structure.

c) Additional seismic data were collected in the JMR area in September 1988, when some 1000 kms were shot in a 12 day cruise by the research vessel Håkon Mosby, hired from the University of Bergen (Fig 4.1). Gravity and magnetics were also recorded, and a few sonobuoys deployed. The cruise was planned and carried out in cooperation between NPD and NEA, with participation of the University of Oslo and assistance of the Seismological Observatory, University of Bergen. The main purpose was to make a detailed survey of a small area on the JMR for a more accurate mapping of one of the most interesting locations for sedimentary studies. This area is within the Norwegian part of the shelf. The second priority task was to acquire some seismic lines in the southern part of the Jan Mayen microcontinent, in order to broaden our view of the tectonic history of the region.
Fig. 4.1 Seismic data acquired by NEA/NPD in 1988 in the Jan Mayen Ridge area.
NPD covered the cost of the survey in 1988. NEA has obtained Icelandic funds for the processing of the data in 1989. The processing is done by the seismic processing group at NEA, in consultation with the cooperative partners. This work will be finished late 1989. The data will be treated as common property of the two governments, in the same way as the 1985-data. Interpretation of these data will take place during the first half of 1990.

4.2 SUGGESTIONS FOR FUTURE EXPLORATION PROJECTS

As previously stated, our present state of knowledge is not sufficient to draw safe conclusions about whether interesting hydrocarbon accumulations exist or not on the JMR. The geological database is too small and insufficient in variety.

One of the main gaps in our knowledge of the area is lack of stratigraphic information, i.e. we do not know the type of rock and the age of the reflectors on the seismic sections. We are already attempting by indirect means to limit the range of possibilities, but final conclusions can only be reached by drilling – quite an expensive operation.

We introduce below some logical options for the continued investigation of the area in order of increasing intensity and cost.

4.2.1 INTERPRETATION AND EVALUATION OF EXISTING DATA

A considerable amount of geophysical data from the JMR exists in various stages of processing and interpretation. Work on these data would give valuable information at minimum cost. Among tasks to be done is to compile a detailed map of water depths, more detailed sedimentary
seismic stratigraphy, regional tectonic and stratigraphic studies, and modelling of crustal structure using all types of geophysical data. These studies will narrow the range of questions concerning the hydrocarbon potential of the area, but are not likely to give a final answer.

The outer continental margins of the northern Atlantic Ocean are presently being examined, and new models of their structure and formation are being presented. The Jan Mayen area is geologically speaking a part of these areas. It is important to be updated on the development in this field, in order to reevaluate our model of the JMR.

4.2.2 ADDITIONAL GEOPHYSICAL SURVEYS

Additional seismic data to increase the density of seismic lines in interesting areas is needed for more detailed mapping. It is also likely, as investigations proceed, that other types of seismic data would be needed for new purposes, for example with deeper penetration or higher resolution.

Heat-flow measurements could give information on the thermal state of the ridge, and indirectly the level of maturation of potential hydrocarbons.

In view of the discovery of fields of numerous pockmarks or craters in the seafloor on the top of the ridge, possibly related to escape of gas from below, a detailed mapping of chosen areas of the sea-bottom would be of interest. This should include side scan sonar surveying.

4.2.3 DRILLING

Drilling in the Jan Mayen area would be of great importance, as borehole calibration is limited at the time being. We expect the most suitable location to be on the main ridge just north of 69°N, in the area covered by the
more detailed survey in 1988 (Fig 4.1) with water depth of about 800-1000m. This applies to sampling the Tertiary sedimentary sequence, as well as penetrating the underlying rocks that could include older prospective sediments under cover of plateau basalts. We have defined two different drilling projects.

The larger project centers on a deep borehole that would be drilled through the Tertiary sediments and the early Tertiary lavas into probable pre-Tertiary sediments. This would require an advanced expensive rig like a semi-submersible platform or a drillship. The weather conditions and remoteness of the area can be compared to the Barents Sea, and drilling to a depth of some 4-5 km would accordingly entail costs in the order of 150 million NOK.

A much cheaper and less demanding project would be to drill a few shallow boreholes, no more than 200 m deep. This depth limitation is for safety reasons, and consistent with Norwegian rules. The drilling sites would have to be investigated with high-resolution seismics in order to avoid shallow gas and other potential geotechnical problems. The sites will be located so that each borehole samples different parts of the stratigraphic section. In this way the Tertiary sedimentary section could be sampled reasonably well, although continuous deep drilling would be preferable. It is more uncertain if deeper levels can be sampled, and this would most likely be restricted to the underlying early Tertiary lavas. Hopefully the seismic data acquired in 1988 will indicate more accurately how deep in the section it is possible to reach in this way. It can however already be stated that it is unlikely that deeper pre-Tertiary sequences can be sampled. The cost for this project would be in the order of a few tens of millions NOK.
A realistic time schedule for a shallow drilling project could be as follows:
- 1989: Processing of the seismic data from the 1988 survey
- 1990: Interpretation of the new seismic data, and evaluation of the value of the shallow borehole project based on geological interpretation, and the willingness of the Icelandic and Norwegian governments and the oil companies to invest in the area. Possible acquisition of more seismic data if drilling sites are not satisfactorily defined, and acquisition of high-resolution seismic data at the chosen sites. Seismic processing
- 1991: Reevaluation of the drilling project based on new data. Planning and drilling the holes.

It can finally be mentioned here that drilling for scientific purposes in the general JMR area is still a possibility within the program of the Ocean Drilling Project, where the Nordic countries have a membership. The drilling sites would however be chosen from general scientific points of view, rather than for the purpose of hydrocarbon evaluation. Such boreholes would therefore give incomplete information in this context, but would still be a project worth encouraging.

4.3 ORGANIZATION AND SCOPE OF FUTURE EXPLORATION

Progress should be made in preparing the area for possible future opening for exploration or licencing. In this context it must be decided if the seismic coverage is sufficient, presently about 12 x 20 km, or if a more dense grid of about 4 x 4 km is appropriate. This latter density is common procedure in the seismic acquisition program NPD carries out on the Norwegian shelf. The cost of filling in the 1985 survey to these specifications would require about three times the amount of data we already have, or some 12 000 km of seismic lines. The cost of this is estimated to
some 50 millions NOK. These numbers would naturally be reduced by a more narrow definition of the interesting areas.

An alternative to government funding is to open the area for seismic acquisition by private companies. Seismic data acquisition could also be included if production-licences with limited work-obligation are granted.

The drilling of a deep exploration hole is a major and very expensive undertaking. Such a borehole may be paid for by the governments, or be part of work-obligations connected to a granted production licence. Such a production licence could be awarded through opening of the whole area for applications, or through choosing and offering one or more key blocks. We feel that it is not realistic at present to contemplate such drilling without the involvement and backing of the oil industry, based on better hydrocarbon indications and changed technical and economical conditions.

The smaller drilling project, consisting of a few shallow holes as described above, is in comparison relatively cheap. It could be financed totally by the governments, or it could be organized as a scientific investigation funded at least partly by the oil companies. The latter arrangement has been used successfully in the Barents Sea, but depends on high level of interest by the companies.

Summing up, we like to express the opinion that it will be natural for the two responsible governmental institutions to carry on their cooperation and maintain close contact in order to further the cause of exploration and possible exploitation of the JMR-area. For this purpose some lesser cooperative research projects could be organized to answer specific questions as they arise, and academic research projects could be encouraged and supported. Here we are talking about smaller projects to a total cost of a few
millions NOK or less.

A higher level of activity would include large scale seismic mapping or shallow drilling. In view of lack of lithological information in the area, we tend to favour the drilling as a priority project.

A large scale project centered on the drilling of one or more deep exploration boreholes would be necessary to finally decide if the area offers possibilities in hydrocarbon production.
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APPENDICES

Appendix 1  Agreement between the governments of Norway and Iceland on the continental shelf in the area between Iceland and Jan Mayen

Appendix 2  The Jan Mayen Ridge 1979 and 1985 seismic surveys: Data acquisition and processing

Appendix 3  The Jan Mayen Ridge 1975 and 1985 seismic surveys: Sale of data

Appendix 4
a  Geophysical survey grid on the Jan Mayen Ridge acquired by NEA and NPD in 1985 and NPD in 1979. Scale 1 : 500 000 (Reduced versions in Fig 1.2 and 1.3)

b  Main structural and volcanic features of the Jan Mayen Ridge. Scale 1 : 500 000. (Reduced version in Fig 2.13)

c  Isochrone map of reflector Purple. Scale 1 : 500 000. (Reduced version in Fig 2.14)

d  Isochrone map of reflector Red. Scale 1 : 500 000. (Reduced version in Fig 2.20)

e  Isochrone map of reflector Blue. Scale 1 : 500 000. (Reduced version in Fig 2.22)
f  Isopach map of total sediment thickness (in TWT) above reflector Purple. Scale 1 : 500 000. (Reduced version in Fig 2.15)

g  Isopach map of the Purple-Red megasequence. Scale 1 : 500 000. (Reduced version in Fig 2.21)

h  Isopach map of Red-Blue megasequence. Scale 1 : 500 000. (Reduced version in Fig 2.23)

i  Isopach map of the sequence above reflector Blue. Scale 1 : 500 000. (Reduced version in Fig 2.24)

Appendix 5 a  Line drawings of four seismic dip lines (JM-85-4,10,12 and 17) across the Jan Mayen Ridge. (Reduced version in Fig 2.16)

b  Line drawing of a composite seismic strike line (composed of lines JM-85-1226 and 326) along the eastern flank of the Jan Mayen Ridge. (Reduced version in Fig 2.17)

c  Evolution of the Jan Mayen Ridge. (Reduced version in Fig 2.19)
Appendix 1

Samkommulag milli Norge og Island om landgrunn i "sværdinu" milli Island og Jan Mayen

Rikstorn Norge og rikstorn Island

se om næranslagda fram til 28. mai 1980 um bøktveri- og landgrunnad urðar að ef ekhahalslega Islanda skul til ná í 200 sjómilir, ennig að í þeim svæðum milli Islanda og Jan Mayen þar sem fjárlandshili milli grunnanlega er minni en 400 sjómilir, og sem í gr. 4. r. fjórðanda samkommulaga urðar að því að skylld á upphafsmálina skapa tiltaverna og rétt til þar sem ekki kópin milli Islanda og Jan Mayen, sem samsvarandi skiptu milli Islanda og Jan Mayen, og sem teltja sig gerir að að tillkinson nefndanra, hafr orði að því að skiptu milli Islanda og Jan Mayen.

1. gr.

Mork landgrunn hivi milli Islanda og Jan Mayen skulu vers hini stóru og mork ekhahalslega hivi milli Islanda og Jan Mayen.

2. gr.

Ekki skiptu 3.-9. gr. taka til svæða, sem almennt af tillifandi hini:

3. gr.

Að fyrsta stig rannsókninna sem seti er að konfunda milli Islanda og Jan Mayen.

4. gr.

Sýni þar rannsóknir, sem um er fjallað í 3. gr. um að skiptu milli Islanda og Jan Mayen.

5. gr.

Á þeim bluta þess svæða sem tilgreitt er í 2. gr. og sem ligir norðan bæðins ekkeflygla Islanda og Jan Mayen.
Dersom det ikke er mulig å oppdatere at de to parters omkostninger blir bæret av vedkommende selskap (eller selskaper), skal partene opptre for handlinger om muligheten for å drive virksomhet som et fellesforetak hvor hver av dem bærer sine omkostninger, eller hvor de deler omkostningene. Dersom Island ikke snakker på dette grundlaget, kan Norge fortsatt på egnehånd. Dersom kommer avløpet blir erklært, skal Island ha adgang til på dette stadium å tre inn med sin andel mot og godtgjøre Norge den del av de påløpne omkostningene opp til dette tidspunktet som ville være til Island andel dersom Island hadde deltatt fra begynnelsen av.

Norsk lovgivning, norsk skjønnspolitikk og norske bestemmelser om kontroll med virksomheten, om sikkerhetsåttak og om miljøvern kommer til anvendelse for virksomheten i det område som er nevnt i første ledd. Også håndhevelsen og forvaltningen i det nevnte område tilligger norske myndigheter.

Artikkelforfølgende

I den del av området som er nevnt i artikkel 2, som ligger sør for delslien, mellom de to parters økonomiske soner (ca. 12 720 km²), skal Norge ha en del av denne delen, og Island en del av denne delen. Dette er en hensikt for å oppnå en bærekraftig tilvirkning av vann som er påvirket av utfordringene ved at de to partene er i felles handlingsområde. Dersom Island ikke er i felles handlingsområde, skal Island være i felles handlingsområde for å oppnå en bærekraftig tilvirkning av vann som er påvirket av utfordringene ved at de to partene er i felles handlingsområde.

Artikkelforfølgende

I det området som er nevnt i artikkel 2, skal Island ha en del av denne delen, og Norge en del av denne delen. Dette er en hensikt for å oppnå en bærekraftig tilvirkning av vann som er påvirket av utfordringene ved at de to partene er i felles handlingsområde. Dersom Island ikke er i felles handlingsområde, skal Island være i felles handlingsområde for å oppnå en bærekraftig tilvirkning av vann som er påvirket av utfordringene ved at de to partene er i felles handlingsområde.

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Artikkelforfølgende

I det området som er nevnt i artikkel 2, skal Island ha en del av denne delen, og Norge en del av denne delen. Dette er en hensikt for å oppnå en bærekraftig tilvirkning av vann som er påvirket av utfordringene ved at de to partene er i felles handlingsområde. Dersom Island ikke er i felles handlingsområde, skal Island være i felles handlingsområde for å oppnå en bærekraftig tilvirkning av vann som er påvirket av utfordringene ved at de to partene er i felles handlingsområde.
ACQUISITION PARAMETERS
1985 SURVEY

The Survey was shot during July and August 85 by GECO A/S using the vessel M/S Malene Østervold.

The following acquisition parameters were used the 85-lines:

ENERGY SOURCE

<table>
<thead>
<tr>
<th>Type</th>
<th>Airgun Array (6 Subarrays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pop interval</td>
<td>50.0 m and 25.0 m</td>
</tr>
<tr>
<td>Shot point interval</td>
<td>50.0 m and 25.0 m</td>
</tr>
<tr>
<td>Source depth</td>
<td>7.5 m</td>
</tr>
<tr>
<td>Source power</td>
<td>3564 cu in</td>
</tr>
<tr>
<td>Pressure</td>
<td>2000 psi</td>
</tr>
</tbody>
</table>

RECEIVER PARAMETERS

<table>
<thead>
<tr>
<th>Fold of recording</th>
<th>on lines with 50m sp. interval 3000%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of groups</td>
<td>60</td>
</tr>
<tr>
<td>Hydrophones per groups</td>
<td>40</td>
</tr>
<tr>
<td>Cable length</td>
<td>3000 m</td>
</tr>
<tr>
<td>Near trace</td>
<td>1</td>
</tr>
<tr>
<td>Interval</td>
<td>50 m</td>
</tr>
<tr>
<td>Length</td>
<td>50 m</td>
</tr>
<tr>
<td>Depth</td>
<td>10 - 12m</td>
</tr>
<tr>
<td>Offset</td>
<td>188 m</td>
</tr>
</tbody>
</table>

INSTRUMENTATION

<table>
<thead>
<tr>
<th>Recording system</th>
<th>DFS V, DSS V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain constant</td>
<td>24 dB</td>
</tr>
<tr>
<td>Filters: Low cut</td>
<td>3.5 Hz</td>
</tr>
<tr>
<td>High cut</td>
<td>64.0 Hz</td>
</tr>
<tr>
<td>Tape format</td>
<td>SEG D 8015</td>
</tr>
<tr>
<td>Sample rate</td>
<td>4 ms</td>
</tr>
<tr>
<td>Slope</td>
<td>18 dB/oct</td>
</tr>
<tr>
<td>Slope</td>
<td>72 dB/oct</td>
</tr>
<tr>
<td>BPI</td>
<td>6250 BPI</td>
</tr>
</tbody>
</table>

NAVIGATION SYSTEM

| Primary                          | LORAN C                                 |
| Secondary                        | SAT NAV                                 |

![Diagram of survey setup]
# Acquisition Parameters

## 1979 Survey

The Survey was shot during July 1979 by GECO A/S using the vessel M/S GECO Alpha.

The following acquisition parameters were used on the 79-lines:

### Energy Source

<table>
<thead>
<tr>
<th>Type</th>
<th>Airgun Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pop interval</td>
<td>50.0 m</td>
</tr>
<tr>
<td>Shot point interval</td>
<td>50.0 m</td>
</tr>
<tr>
<td>Source depth</td>
<td>7.5 m</td>
</tr>
<tr>
<td>Source power</td>
<td>2970 cu in</td>
</tr>
</tbody>
</table>

### Receiver Parameters

<table>
<thead>
<tr>
<th>Field of recording</th>
<th>2400%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of groups</td>
<td>48</td>
</tr>
<tr>
<td>Cable length</td>
<td>2400 m</td>
</tr>
<tr>
<td>Near trace</td>
<td>1</td>
</tr>
<tr>
<td>Interval</td>
<td>50 m</td>
</tr>
<tr>
<td>Depth</td>
<td>13.5 m</td>
</tr>
<tr>
<td>Offset</td>
<td>194 m</td>
</tr>
</tbody>
</table>

### Instrumentation

<table>
<thead>
<tr>
<th>Recording system</th>
<th>DFS V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain constant</td>
<td>24 dB</td>
</tr>
<tr>
<td>Filters: Low cut</td>
<td>5.3 Hz</td>
</tr>
<tr>
<td>High cut</td>
<td>64.0 Hz</td>
</tr>
<tr>
<td>Slope</td>
<td>19 dB/oct</td>
</tr>
<tr>
<td>Slope</td>
<td>72 dB/oct</td>
</tr>
<tr>
<td>Tape format</td>
<td>SEG C</td>
</tr>
<tr>
<td>Sample rate</td>
<td>4 ms</td>
</tr>
<tr>
<td>1600 BPI</td>
<td></td>
</tr>
</tbody>
</table>

### Navigation System

| SAT NAV              |              |
PROCESSING SEQUENCE

PROCESSED BY: GECO, SANDVIKA  DATE: JAN 1987

REFORMAT SEGD TO SEGY/TRACE EDIT
ADJACENT TRACE SUMMATION WITH NMO CORRECTION
GEOMETRY INFORMATION/DATUM STATICS
SPHERICAL DIVERGENCE CORRECTION
COP GATHER
MUTE
DECONVOLUTION BEFORE STACK FIRST BREAK SUPPRESSION
OPERATOR LENGTH 232 MS
PREDICTIVE GAP 32 MS
DESIGN GATES AT NEAR TRC.: W.B.+ 200MS - W.B.+ 3700MS

VELOCITY ANALYSIS EVERY THIRD KILOMETER
FK MULTIPLE ATTENUATION
NORMAL MOVEOUT CORRECTION USING VELS DERIVED FROM GECO 5 CONToured VELOCITY SPECTRA
PRE-STACK MUTE OFFSET DEPENDENT
TRACE EQUALIZATION WITH WEIGHT X/X+X, X:OFFSET X:_FAR OFFSET
OFFSET weighting
COPSTACK 30 FOLD
DECONVOLUTION AFTER STACK OPERATOR LENGTH 332 MS
PREDICTIVE GAP 32 MS
DESIGN GATES: W.B.+ 200MS - W.B.+ 3700MS
FK DIP FILTER MAXIMUM DIPS -12.16 MS PER TRACE
SPACE AND TIME VARIANT FILTER BANGPASS TIMES BELOW W.B.
12 Hz - 55 Hz 0.0 - 1.2 SEC
6 Hz - 45 Hz 1.2 - 2.2 SEC
6 Hz - 25 Hz 2.2 - 4.5 SEC
4 Hz - 20 Hz 4.5 - 8.0 SEC
EXponent SCALING SCALER 0.8
AMPLITUDE BALANCE WINDOW 1000 MS

DISPLAY DATA

<table>
<thead>
<tr>
<th>Traces per CM</th>
<th>Full Scale</th>
<th>Half Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>CMS per Second</td>
<td>10.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Shotpoints Annotated</td>
<td>CDP</td>
<td>CDP</td>
</tr>
<tr>
<td>Horizontal Scale</td>
<td>1:25000</td>
<td>1:50000</td>
</tr>
<tr>
<td>One Kilometer on Section Equals</td>
<td>4 cm</td>
<td>2 cm</td>
</tr>
</tbody>
</table>
PROCESSING SEQUENCE

REPROCESSED BY: GECO. SANDVIKA
DATE: JAN 1987

DEMULTIPLEX/TRACE EDIT

TRACE MIX
5 TRACES WEIGHTS 1-2-2-2-1

PRE PROCESSING CDP GATHER
CORRECTIONS FOR SPHERICAL DIVERGENCE

DECONVOLUTION BEFORE STACK
TYPE MINIMUM PHASE INVERSE FILTER
MINIMUM PREDICTION DISTANCE: 200MS
MAXIMUM PREDICTION DISTANCE: 500MS
LENGTH OF OPERATOR 300MS
NO OF AUTOCORRELATION WINDOWS: 1
STOP OF AUTOCORRELATION: 5000MS - 7000MS
STOP OF DECONVOLUTION: 8000MS - 9000MS

NMO/STACK
NORMAL STACK, 2400%

MIX
RUNNINGMIX OF TWO ADJACENT TRACES

DECONVOLUTION AFTER STACK
OPERATOR LENGTH 332 MS
PREDICTIVE GAP 32 MS
DESIGN GATES:
W.B.+ 200MS - W.B.+ 3700MS

WAVE EQUATION MIGRATION
FINITE DIFFERENCE SOLUTION
DEPTH STEP: 24MS

FK DIP FILTER
MAXIMUM DIPS -12.12 MS PER TRACE

SPACE AND TIME VARIANT FILTER
BANDPASS TIMES BELOW W.B.
12 Hz - 55 Hz 0.0 - 1.2 SEC
8 Hz - 45 Hz 1.2 - 2.2 SEC
6 Hz - 25 Hz 2.2 - 4.5 SEC

EXPONENT SCALING
SCALER 0.8

AMPLITUDE BALANCE
WINDOW 1000 MS

DISPLAY DATA

<table>
<thead>
<tr>
<th></th>
<th>FULL SCALE</th>
<th>HALF SCALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRACES PER CM</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>CMS PER SECOND</td>
<td>10.0</td>
<td>5.0</td>
</tr>
<tr>
<td>SHOTPOINTS ANNOTATED</td>
<td>CDP</td>
<td>CDP</td>
</tr>
<tr>
<td>HORIZONTAL SCALE</td>
<td>1:25000</td>
<td>1:500000</td>
</tr>
<tr>
<td>ONE KILOMETER ON SECTION EQUALS</td>
<td>4 CM</td>
<td>2 CM</td>
</tr>
</tbody>
</table>
SEISMIC DATA IN THE JAN–MAYEN AREA

In cooperation with Orkustofnun (Iceland’s national energy authority), the Norwegian Petroleum Directorate has acquired geophysical data over the Jan Mayen ridge between Iceland and the Jan Mayen island.

The ridge is believed to be a continental fragment split off from Norway and Greenland respectively in Paleocene and Oligocene. For exploration purposes the main implications of this are:

- Mesozoic sediments have most likely been deposited in the area
- The area contains important information for regional understanding of the Norwegian and Greenland continental shelves
- The area has been exposed to some volcanic activity during rifting
- Subsidence after the rifting episodes have brought most of the area to water depth of 1000 m and more

The dataset acquired has been parted in two. Package 026 (85-data) gives a very rough regional coverage, while package 027 (79-data + rest 85-data) contains infill down to about 15 x 15 km.

Jan-Mayen-85 (026) (fig 1)
consists of 1 802 kms of seismic data shot by Geco in 1985
and processed by Geco in 1986/87.

865 kms of the lines are recorded to 15 seconds. Full record length of these lines is only shown on 5cm/sec and 3cm/sec filtered sections.
Contents: 1/1 scale filtered sections
1/2 scale filtered sections
1/1 scale migrated sections
1/2 scale migrated sections
3 cm/sec 1:200000 filtered
UKCOA-format navigation tape
Grav/Mag profiles
Maps 1:500 as listed:
Water depth contoured
-----"---- posted
Free Air contoured
----"---- posted
Bouguer contoured
----"---- posted
Magnetic contoured
----"---- posted

Cost breakdown: Seismic data 971 998.- NOK
Copying 22 100.- NOK
Nav tape 450.- NOK

Data are available from 15 nov 1987

Jan-Mayen-79/85 (027) (fig 2)
consists of 2.837 kms of seismic data shot by Geco in 1979
(611 kms) and 1985 (2 226 kms). All the data is processed
by Geco in 1986/87.

438 kms of the 1985 lines are recorded to 15 seconds. Full
record length of these lines is only shown on 5cm/sec and
3cm/sec filtered sections.

Contents: 1/1 scale filtered sections
1/2 scale filtered sections
1/1 scale migrated sections
1/2 scale migrated sections
3 cm/sec 1:200000 filtered
UKCOA-format navigation tape
Grav/Mag profiles
Maps 1:250 as listed:
Water depth contoured
-----"---- posted
Free Air contoured
----"---- posted
Bouguer contoured
----"---- posted
Magnetic contoured
----"---- posted
Cost breakdown: Seismic data 1 415 165.- NOK
Copying 35 400.- NOK
Nav tape 450.- NOK

Data are available from 15 nov 1987.

Yours faithfully

Finn R. Aamodt (e.f.)
Head of Exploration Branch

Kari Ofstad
Acting Head of
Prospect Mapping
Section

Enclosures: 2 orderforms and 2 maps
ORDER FOR GEOPHYSICAL DATAPACKAGE 027

From: 
To: Norwegian Petr. Directorate  
c/o Teknisk Kopiservice  
Jacob Askelandsvæi 13  
4300 Sandnes, Norway  
Attn: Einar Johannessen  
Tlf : 04 - 67 76 44

Our ref:  
Your ref:

THIS ORDERFORM MUST BE USED WHEN ORDERING DATAPACKAGE:  
027 JAN-MAYEN-79/85

Terms of purchase are as stated on page 5 in the NPD's publication:  
"Geophysical datapackages available from The Norwegian Petroleum  
Directorate" April-1986 edition or later.

Please note that the following prices may be subject to alteration.  

<table>
<thead>
<tr>
<th>PRICES ARE:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic data</td>
<td>1 415 165,-NOK</td>
<td></td>
</tr>
<tr>
<td>Copying</td>
<td>35 400,-NOK</td>
<td></td>
</tr>
<tr>
<td>Nav tape</td>
<td>450,-NOK</td>
<td></td>
</tr>
</tbody>
</table>

	

CONTENTS OF PACKAGE

1/2 scale filtered stack 0 3 cm/sec, 1:200000 filtered 0
1/1 scale filtered stack 0 UKOAA format nav tape 0
1/2 scale migrated stack 0 Grav/Mag profiles 0
1/1 scale migrated stack 0 1:250000 Grav/Mag/Bat maps 0

REMARKS/ADDITIONAL ORDERING INFORMATION:

BILLING ADDRESS:       DELIVERY ADDRESS:

Ordered ............../....................../Date...........  
(place)              (signature)

LETTER OF TRANSMITTAL

Please acknowledge receipt of the above data by returning this form to:  
The Norwegian Petroleum Directorate, P O Box 600, 4001 Stvg, Norway.

Received ................../....................../Date............  
(name)                (signature)

FOR USE BY THE NORWEGIAN PETROLEUM DIRECTORATE

Date/Sign: Mottatt Nav bestilt Postlagt Fakturert

............. ............. ............. .............

01.09.1987-4802020027-027
ORDER FOR GEOPHYSICAL DATAPACKAGE 026

From:  
To: Norwegian Petr. Directorate  
c/o Teknisk Kopiservice  
Jacob Askelandsvei 13  
4300 Sandnes, Norway  
Attn: Einar Johannessen  
Tlf: 04 - 67 76 44

Our ref:  
Your ref:

THIS ORDERFORM MUST BE USED WHEN ORDERING DATAPACKAGE:  
026 JAN-MAYEN-85

Terms of purchase are as stated on page 5 in the NPD’s publication:  
"Geophysical datapackages available from The Norwegian Petroleum  
Directorate" April-1986 edition or later.

Please note that the following prices may be subject to alteration.  
PRICES ARE:  
Seismic data 971 998,-NOK  
Copying 22 100,-NOK  
Nav tape 450,-NOK

CONTENTS OF PACKAGE

1/2 scale filtered stack 0 3 cm/sec, 1:200000 filtered 0
1/2 scale filtered stack 0 UKOOA format nav tape 0
1/2 scale migrated stack 0 Grav/Mag profiles 0
1/2 scale migrated stack 0 1:500000 Grav/Mag/Bat maps 0

REMARKS/ADDITIONAL ORDERING INFORMATION:

BILLING ADDRESS:  
DELIVERY ADDRESS:

Ordered ...................../................../Date...........  
(place) (signature)

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Date/Sign: Mottatt  Nav bestilt  Postlagt  Fakturert

............... ............. ............. .............

01.09.1987-4802020026-026