The formation of the Jan Mayen microcontinent: the missing piece in the continental puzzle between the Møre-Vøring Basins and East Greenland

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Introduction

This paper presents a study of the crustal structure and sedimentary sequences of the Jan Mayen Ridge and the Jan Mayen Basin (Fig. 1). These structures, constituting the Jan Mayen microcontinent, were split off from East Greenland in the late Oligocene–early Miocene. By the use of OBS data we define the continent-ocean transition along the western margin of the Jan Mayen Basin, being conjugate to the East Greenland continental margin. The eastern margin of the microcontinent represents the conjugate margin of the Vøring and Møre continental margins, adjacent to the Møre and Vøring Basins which are currently the focus of petroleum exploration efforts. The study of the Jan Mayen microcontinent provides information valuable to the study of the evolutionary history of these areas. Using both OBS and seismic reflection data, we suggest a model which may explain the geometrical problems introduced by the fan-shaped spreading pattern along the Aegir Ridge in the Norway Basin.

The seafloor spreading history of the Norwegian-Greenland Sea is rather well known except for the area between the Faeroe Islands and the Jan Mayen Fracture zones (Fig. 1). In this area, a stepwise opening involving several westward shifts of the spreading axis has been suggested, and the time intervals for different axes are a matter for debate. With reference to the time scale of Berggren et al. (1994), initial seafloor spreading occurred in the Norway Basin at anomaly 24B time (53 Ma) (Talwani & Eldholm 1977; Nunns 1983; Eldholm et al. 1990). The Aegir Ridge (Fig. 1), well-known because of its fan shaped pattern of magnetic anomalies (between anomaly 20 and 7 time) (Nunns 1983), probably became extinct just prior to anomaly 7 time (Talwani & Eldholm 1977). A westward shift of the spreading axis split off a part of Greenland, forming the Jan Mayen microcontinent. An extinct axis at the Iceland Plateau was suggested by Talwani & Eldholm (1977) but later Vogt et al. (1980) argued against this axis, suggesting continuous spreading along the Kolbeinsey Ridge after anomaly 7. The seafloor spreading along the Aegir axis, which generated a wider area of oceanic crust in the north than in the south, introduced a major geometric problem to the area. In order to solve this problem, different hypotheses of complementary spreading along adjacent spreading axes have been suggested (Talwani & Eldholm 1977; Nunns 1983; Larsen 1988).

The Jan Mayen Ridge extends ≈ 300 km southward from the island of Jan Mayen, a Norwegian protectorate (Fig. 2). Jan Mayen is a volcanically active island lying about 500 km to the north of Iceland. The Jan Mayen Ridge has water depths increasing from 300 m in the north to over 1000 m in the south. In the north, the ridge is a single bathymetric structure. In the south, two ridge complexes are present, separated by the Jan Mayen Trough.

Earlier studies of the microcontinent east of the Iceland Plateau have mostly considered the actual Jan Mayen Ridge, and gravity-, magnetic-, seismic reflection and velocity measurements (Grönlie et al. 1979; Navrestad & Jørgensen 1979; Sundvor et al. 1979; Myhre et al. 1984; Johansen et al. 1988) support a continental origin. The eastern boundary of the microcontinent consists of a volcanic passive margin conjugate to the Møre and Vøring margins and the ocean-continent transition lies below a wedge of seaward dipping reflectors. The western and southern boundaries are much more uncertain.

Interpretation

Seismic reflection data

Several authors have interpreted and discussed the geological framework of the Jan Mayen Ridge (Gairaud et al. 1978; Eggen 1984; Myhre et al. 1984; Gudlaugsson et al. 1988;
Kuvaas 1994). In this study, seismic data obtained by the Norwegian Petroleum Directorate and the National Energy Authority of Iceland have been interpreted. We present line drawings of five E-W profiles (Figs 2 and Fig. 3) where three semi-regional reflectors have been mapped. Reflector JO extends from the oceanic crust in the Norway Basin towards the middle parts of the Jan Mayen Ridge, corresponding to the top of the wedge of seaward dipping reflectors. This wedge corresponds to the seaward dipping flood basalts along the More and Voring margins. Skogseid & Eldholm (1987) correlated reflector JO to reflector EE on the Voring margin, hence giving it an age of early Eocene.

Reflector JA represents a major unconformity truncating the eastward prograding sedimentary sequence of the Jan Mayen Ridge. The reflector is particularly evident on the northern profiles and may be traced downslope along the eastern margin, but the interpretation along the western margin is more problematic. Reflector JA has been dated by DSDP Leg 38, separating deposits of late Eocene and late Oligocene age (Talwani et al. 1976).

The western margin is strongly faulted into several eastward rotated fault blocks which have partly slid into the Jan Mayen Basin, and are probably present across this basin, as suggested by profile JM-8-85, Fig. 3.

Reflectors F is mainly observed within the Jan Mayen Basin and the Jan Mayen Trough. The reflector is horizontal, has a strong amplitude and is continuous over varying distances. It lies more or less at the same stratigraphic level, varying with only 50–100 ms. The reflector probably represents basaltic layers within the sedimentary section (sills).

Although the age of reflector F is difficult to estimate, it must be younger than the rotation of the fault blocks within the Jan Mayen Basin, as the reflector is horizontal and undisturbed towards these blocks (Fig. 3).

In several areas, faulted reflector bands are observed below reflector JO. These are interpreted as pre early Eocene fault blocks which can be observed within the actual Jan Mayen Ridge and along the western margin.

When studying the seismic profiles from the north towards the south, several changes are observed (Fig. 3):
- to the north, the Jan Mayen Ridge is a separate structure where its western margin is characterized by eastward rotated fault blocks. These blocks may also be observed within the Jan Mayen Basin;
- the Jan Mayen Ridge becomes more fragmented to the south, progressively developing into rotated fault blocks;
- the general relief decreases to the south;
- erosion at the level of reflector JA is especially evident in the north;
The total width between the seaward dipping wedge of the eastern margin and the westernmost observable rotated block increases to the south.

The ridge complex probably continues farther southward as buried rotated fault blocks, as suggested by Talwani & Eldholm (1977). Nunns et al. (1983) found a pattern of weak, sinuous lineations in this area.

**OBS-data**

The crustal models obtained from the analysis of our OBS-data (Fig. 2) are a result of a forward modelling (Zelt & Ellis 1988) and travel-time inversion procedure (Zelt & Smith 1992). The initial model is a digitized and depth-converted version of the reflection data. Calculated travel-time curves produced by ray-tracing are compared with the observed data. By performing adjustments to our model until we obtain a sufficient match between the calculated and observed travel-time curves, a reliable crustal model results. Further details of the modelling procedure are described by Kodaira et al. (in prep.).

The crustal model of profile L4 (Fig. 4) crosses the Jan Mayen Ridge, extending into the Jan Mayen Basin. Profile L3S (Fig. 5) lies somewhat to the south of L4, and partly overlaps before extending into the Iceland Plateau.

The OBS data have provided velocities for the different layers observed on the seismic reflection data. Velocities of 2.2–2.4 km s\(^{-1}\) and 4.6–4.8 km s\(^{-1}\) are inferred in the Cenozoic sediments and the seaward dipping wedge along the eastern margin of the Jan Mayen Ridge, respectively. Beneath the flood basalts, the model indicates the presence of a thin layer of Mesozoic or older sediments (Vp 4.0–4.7 km s\(^{-1}\)), probably corresponding to the reflector band observed below reflector JO in the seismic reflection data.

On the western flank of the Jan Mayen Ridge, the previously described eastward rotated fault blocks correspond to the 2.2–3.2 km s\(^{-1}\) layer. From the model, this layer seems to extend across the Jan Mayen Basin, and is also supported by the seismic reflection data. A layer with velocities of 4.0–4.7 km s\(^{-1}\) is observed across the Jan Mayen Basin, suggesting the presence of older sediments. A 5.0–5.5 km s\(^{-1}\)
Fig. 3 Interpreted line drawings of seismic reflection profiles across the Jan Mayen Ridge and the Jan Mayen Basin. SDW = Seaward dipping wedge. Location of profiles is shown in Fig. 2. Note the southern increase in fragmentation. I, II and III refers to tectonic phases as described in text.
layer between the Jan Mayen Ridge and parts of the Jan Mayen Basin may be a local deep sedimentary basin. A similar deep sedimentary basin with a velocity of more than 5.5 km s\(^{-1}\) has been found at the conjugate eastern Greenland margin (Weigel et al. 1995), and the deepest part of that basin is interpreted as Devonian–Lower Permian (Suryk 1991). We thus suggest that the 4.0–4.7 km s\(^{-1}\) layer and the 5.0–5.5 km s\(^{-1}\) layer correspond to sediments with a Mesozoic and a Palaeozoic age, respectively.

The crystalline continental upper crust (velocities 6.0–6.4 km s\(^{-1}\)) is generally of uniform thickness throughout the studied area (c.3 km). However, the thickness of the crystalline
continental lower crust (velocities 6.7–6.8 km s$^{-1}$), varies significantly from 12 km beneath the Jan Mayen Ridge to almost zero thickness beneath the western part of the Jan Mayen Basin. These velocities correspond to the velocity distribution obtained at the Mare and Voring margin (Mutter et al. 1988; Olafsson et al. 1992) and the Lofoten margin (Mjelde et al. 1992; Mjelde et al. 1993).

The modelling of profile L3S (Fig. 5) illustrates the crustal model from the Jan Mayen Basin to the Iceland Plateau, characterized by a transition from the extremely thinned continental crust to a moderately thicker oceanic crust. Further to the NW, velocities in the upper (3.8–5.1 km s$^{-1}$) and middle crust (5.9–6.5 km s$^{-1}$) are within the mean velocity of oceanic layer 2 (2.5–6.6 km s$^{-1}$, White 1992) and the velocities of the lower crust are within the mean velocities of oceanic layer 3 (6.6–7.6 km s$^{-1}$). Hence, these layers are interpreted as oceanic crust. Vogt et al. (1980) also identified clear magnetic anomalies in this part. In terms of the mean thickness of normal oceanic crust (7.0 ± 0.8 km, White et al. 1992), our obtained thickness is c. 2 km thicker.

In view of the observations described, we suggest that the ocean/continent transition lies within a 10 km-wide zone along the western edge of the Jan Mayen Basin, corresponding to the western margin of the magnetic quiet zone, described by Gronlie et al. (1979).

The typical high velocity underplated material (Vp larger than 7.1 km s$^{-1}$) beneath the continental lower crust off mid-Norway (Skogsied et al. 1992) has not been found beneath the western margin of the Jan Mayen Ridge or beneath the Jan Mayen Basin.

**Geological history**

In Mesozoic time, the Jan Mayen Ridge and the Jan Mayen Basin were parts of Greenland, probably situated off Liverpool Land (Fig. 1). The oldest fault blocks observed in the study area, below reflector JO, are interpreted as a result of Mesozoic or possibly early Cenozoic extension episodes, denoted as tectonic phase I in Fig. 3 and Fig. 6.

Seafloor spreading within the Norway Basin started in the late Palaeocene–early Eocene, creating a basaltic seaward dipping wedge along the eastern Jan Mayen Ridge (tectonic phase II, Fig. 3 and 6). The conjugate wedge is present along the Møre and Voring marginal highs, and reflector JO has an early Eocene age (Skogsied & Eldholm 1987).

In order to explain the geometrical problem created by the formation of the fan-shaped pattern of magnetic anomalies along the Aegir Ridge, we suggest simultaneous stretching within East Greenland. The southward increase in fragmentation and width of the Jan Mayen microcontinent further suggest a higher degree of extension or possibly a longer period of rifting in the south. A prolonged period of extension resulted in block faulting along the western margin of the Jan Mayen Ridge and within the Jan Mayen Basin (tectonic phase III, Fig. 3) and an extreme thinning of the continental lower crust (Fig. 5). Following the extension, the area was uplifted and eroded, as observed by reflector JA. The fault blocks slid westward both prior to and after the JA erosion.

Rellying on Nunns’ (1983) interpretation of magnetic anomalies, we suggest that the extensional period within East Greenland lasted until the period just prior to the time of anomaly 7 (24.5 Ma), a period of ≈30 Myr. In the final stages, the onset of seafloor spreading produced small amounts of volcanic material and thus formed a non-volcanic passive margin. Considering the conjugate margin at the Liverpool Land coast, only erratic and shallow developments of seaward dipping reflectors are observed here (Larsen 1990). The basaltic material represented by reflector F intruded the sediments after the sliding of the major fault blocks and are presumably related to a younger phase of magmatic activity.

**Discussion**

The Jan Mayen microcontinent has a typical volcanic margin in the east and a non-volcanic margin in the west. The presence of flood basalts within the seaward-dipping wedge along the eastern margin is suggested from both the OBS data and the reflection data. Because of poor ray coverage at the southeastern end of profile L4 (Fig. 4), we cannot identify possible high-velocity underplated material, as found along the conjugate Norwegian margin (Mutter et al. 1988; Mjelde et al. in prep.). The eastern margin of the microcontinent was formed as a result of continental break-up with significant magmatic activity about 18 Myr after initiation of lithospheric extension, referring to the tectono-magmatic model of Skogsied et al. (1992).

The western margin, on the other hand, was formed as a result of continental breakup after an extension period of ≈30 Myr with only modest amounts of volcanic material. Interpretation of one seismic reflection profile may indicate a possible less well developed seaward dipping wedge at the suggested continent-ocean boundary (profile JM-11-85, Fig. 3), but its areal extent is unclear. The stretching factor at the ocean/continent transition is estimated to be ≈5 close to 69°N, considering the crustal thickness beneath the Jan Mayen ridge as original thickness of the continental crust before rifting.

In our model, the oceanic crust at the Iceland Plateau is c. 2 km thicker than the mean thickness of oceanic crust. Similar thicknesses are found several places in the north Atlantic (White et al. 1987; Fowler et al. 1989; Skogsied et al. 1992; Mjelde et al. 1992; Goldschmidt-Rokita et al. 1994; Kodaira et al. 1995) and have been explained as formation from ascending material 100–200 °C higher than normal asthenospheric temperatures, related to the Icelandic hot spot (White & McKenzie 1989). Referring to the studies of White & McKenzie (1989), our higher crustal thickness of the oceanic crust at the Iceland Plateau should therefore imply an ascending asthenosphere with a temperature of about 1320°C, assuming that the potential temperatures did not change during the rifting and oceanic spreading stage. The amount of melt generated by continental rifting is strongly dependent on the duration of extension, as first demonstrated by Pedersen & Ro (1992). According to Bown & White (1995), insignificant thicknesses of melt are expected to be generated for a 20–30 Myr rifting period, a stretching factor of 5 and an asthenosphere temperature of about 1320°C. Because of the long duration of rifting, conductive heat loss from the upwelling material occurred and consequently only small amounts of extrusive and intrusive material were generated.
The modelled results are thus in agreement with our obtained crustal structure along the western part of the Jan Mayen Basin, which is characterized by small amounts of extrusive material and no observable high velocity underplated material.

**Conclusions**

In this study, we focus on the Jan Mayen microcontinent, which has conjugate margins to the Voring, More, and East Greenland continental margins. It is thus comparable to the deep water Atlantic margins which are currently a focus of petroleum exploration.

We suggest that the Jan Mayen microcontinent constitutes both the Jan Mayen Ridge and the Jan Mayen Basin. The microcontinent has a typical volcanic passive margin in the east and a non-volcanic margin in the west, where the continent-ocean boundary lies along the western margin of the Jan Mayen Basin. Velocities typical for oceanic layer 2 and three
have been found at the Iceland Plateau where the oceanic crust is thicker than normal. The N-S variations in the geometry and relief of the structural elements and the southern increase in width suggest a higher degree of extension in the south. In our model, we find no complementary seafloor spreading axis to account for the fan-shaped pattern of magnetic anomalies along the Aegir Ridge. Instead, we suggest that initial stretching within East Greenland commenced simultaneously with the initial seafloor spreading along the Aegir Ridge in the Norway Basin, culminating with continental break-up after c.30 Myr. A N-S variation in the timing of rifting and/or in the degree of stretching thus resulted in a microcontinent being wider to the south, explaining the asymmetry in the Norway Basin.

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