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The continental margins of the Norwegian–Greenland Sea: recent results and outstanding problems

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Within a framework of plate tectonics the passive continental margins of the Norwegian–Greenland Sea may be classified as composed of rifted and sheared segments. An exception is the margin north of the Greenland–Senja Fracture Zone which appears to be of a combined sheared–rifted type. The margins south of the Greenland–Senja Fracture Zone are in part underlain by basement highs on the lower continental slope. Associated features are: marginal escarpments, depth anomalies, smooth opaque acoustic basement and changes in the geophysical parameters across the landward termination of the marginal basement highs. Drilling results have revealed basalts at the level of the acoustic basement. These observations have been related to Early Cainozoic rifting and the transition between continental and oceanic crust. Recent studies have mainly focused on the eastern margin. Off Spitsbergen there is a typical north-trending structural fabric, including a prominent fault of the central shelf. Structurally, the margin between Jan Mayen and Greenland–Senja fracture zones appears to be composed of two parts. The southern part is characterized by a northward plunging basement high (Vøring Plateau) underlain by an inner zone of sub-basement reflectors, whereas prominent block faulting is typical for the northern part. North of the Vøring Plateau the acoustic basement appears to extend almost to the shelf edge and is probably a flow basalt. We believe that these observations are related to the rifting and the earliest phase of seafloor spreading in the Norwegian–Greenland Sea.

INTRODUCTION

The investigations of the passive continental margins may be characterized by two stages of scientific development. The first stage has been dominated by regional surveys using different geophysical techniques. Although an integrated analysis of the various geophysical and geological data has proved valuable, the reliability of the interpretations has often been limited by the moderate depth of seismic penetration. The second stage started with the advent of multichannel seismic profiling and deep sea drilling applied together with detailed conventional surveying. Considerable new information is now being obtained, which may eventually enable us to define a history of development in both time and space. This includes the rifting of the continental crust and the subsequent formation of a deep ocean and passive continental margins.

Recent studies have shown that the Norwegian–Greenland Sea passive margins exhibit features that may be important, not only in an understanding of this particular region, but also in the general context of passive margin development. Here, we shall briefly review the present state of research and introduce new results including data from deep sea drilling and multichannel seismic profiles. A large portion of the new results refers to the Norwegian margin between 66 and 70° N, and we have concentrated our main discussion on this area.

Main features of the Norwegian–Greenland Sea margins

The development of the continental margins is closely related to the Cainozoic plate tectonic evolution of the Norwegian–Greenland Sea. Sea floor spreading started between anomaly 24 and 25 time (late Palaeocene) and evolved in two main phases (Talwani & Eldholm 1977). During the first phase, which terminated at anomaly 13 time (early Oligocene), the relative plate motion was NNW, resulting in the opening of the Norwegian Sea. The second phase is characterized by a WNW plate motion, the change being associated with the cessation of

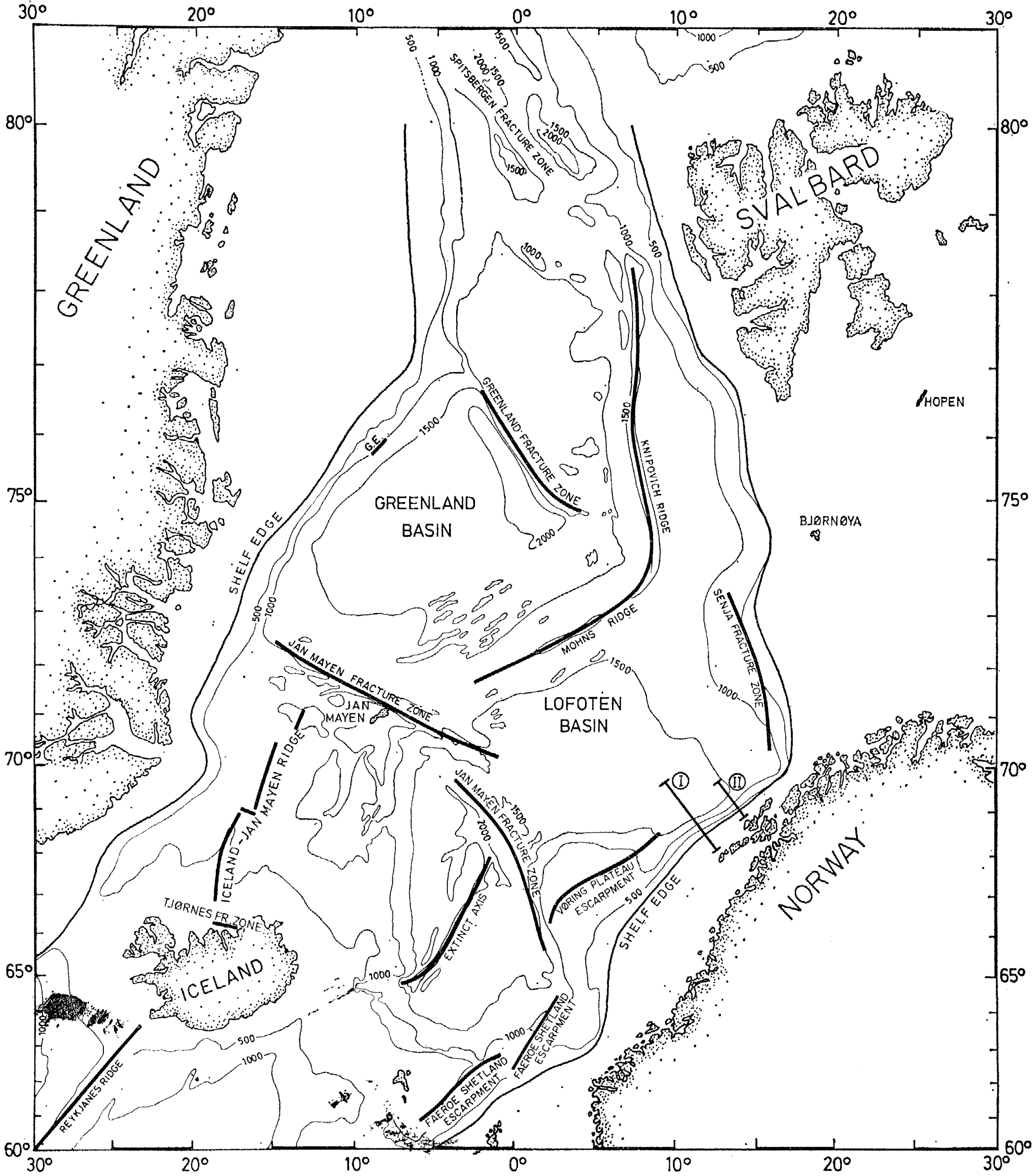

Figure 1. Regional bathymetry (in uncorrected fathoms) and major structural features of the Norwegian–Greenland Sea. Based on data from Talwani & Eldholm (1977). G. E. refers to the Greenland Escarpment and I and II indicate the location of the multichannel profiles in figure 4.

spreading in the Labrador Sea. Thus, there has been no crustal extension in the Greenland Sea before anomaly 13 time, and the Greenland Sea is therefore considerably younger than the sea south of the Greenland–Senja Fracture Zone. Except for the Lofoten and Greenland basins, the plate tectonic history is quite complex and is characterized by migration of the spreading axis, including the formation of the Jan Mayen Ridge microcontinent. Two major fracture zone systems, the Jan Mayen and Greenland–Senja, intersect the ocean and have significantly influenced the margins (figure 1). Noting that original offsets in the spreading axis are reflected in the later history of the margins, Talwani & Eldholm (1972, 1973) proposed that the passive margins are composed of rifted and sheared segments representing different structural styles. Hence, there are two types of transitional areas between the continental and oceanic crust. These marginal types appear to be associated with typical changes in the geophysical parameters. This mode of marginal development is illustrated schematically in figure 2. Within this

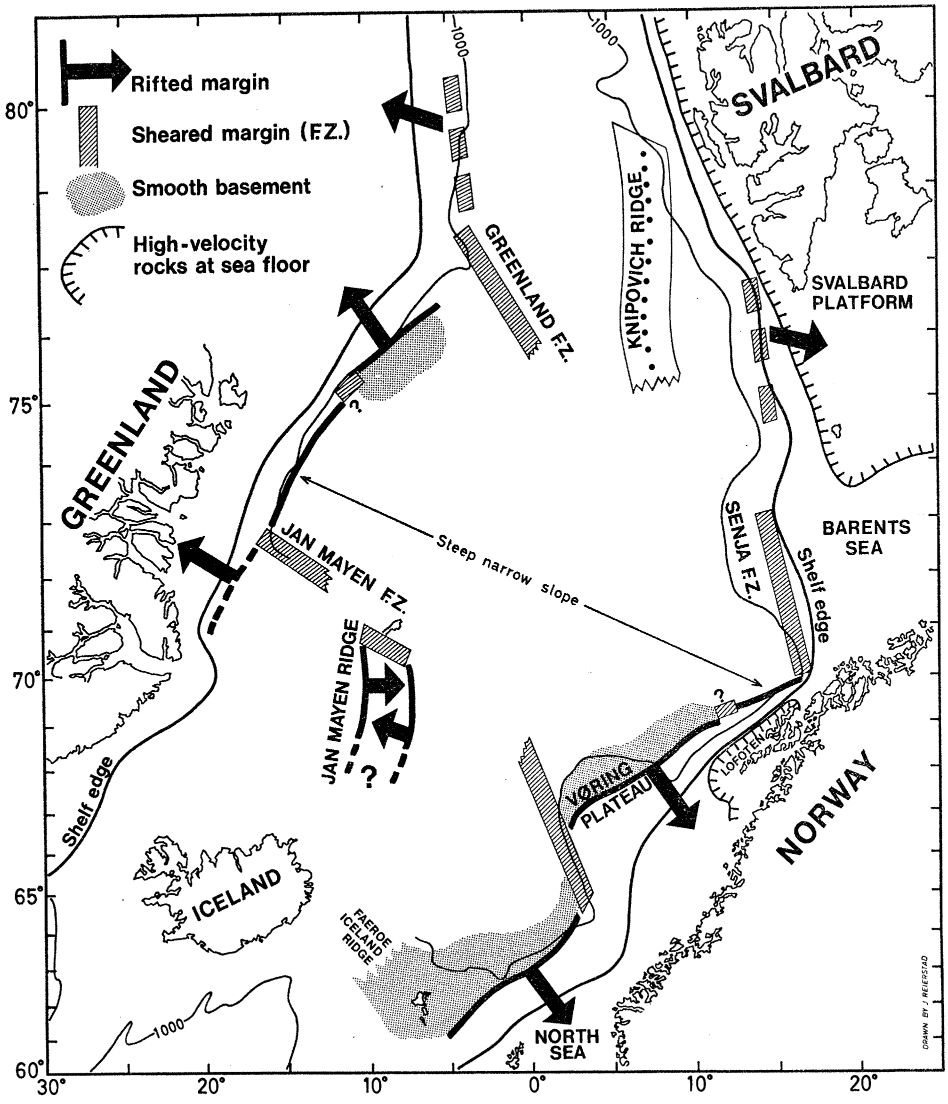

FIGURE 2. Simplified sketch map showing the main marginal features discussed in the text. The rectangular area along the Knipovich Ridge indicates the elevated young oceanic crust.

framework the margins north of the Greenland–Senja Fracture Zone may be defined as a combined type which, in the early Tertiary, acted as regional shear zone and later became a rifted margin.

The eastern margin south of 70° N is by far the most extensively studied, partly because the marginal Vøring Plateau (figure 1) has posed challenging problems. The North Sea sedimentary basin has been traced northwards beneath the shelf and upper slope, revealing a system of basins and ridges which appear to have been established before the Cainozoic (Rønnevik & Navrestad 1977). The most typical features seaward of the shelf edge are buried regional structural highs underneath the lower slope. The highs are bounded landward by steeply dipping interfaces, the Faeroe–Shetland and Vøring Plateau escarpments (figure 1.) The escarpments have been associated with prominent changes in the geophysical parameters. There are significant contrasts in the sediment thickness and the velocity–depth function across the escarpment. The thickness of sediments increases from a few hundred meters on top of the highs to 6–8 km in the landward basins. Furthermore, a gradient in the isostatic gravity anomaly and a magnetic edge anomaly which bounds a landward quiet zone are related to the seismic expression of the escarpment. The surface of the acoustic basement defining the highs appears to be continuous with the oceanic basement in the adjacent basins, but its opaque surface is much smoother than what is typical for the oceanic layer 2. Talwani & Eldholm (1972) interpreted the escarpments as representing the location of Cainozoic rifting in the Norwegian–Greenland Sea, separating areas of subsided continental crust from young oceanic crust created by the process of sea floor spreading. North of the Vøring Plateau Escarpment, the Lofoten–Vesterålen region forms a unique part of the margin. The continental slope becomes progressively narrower northwards and the shelf is underlain by high-velocity sediments at the sea floor. It appears that the Tertiary and part of the Mesozoic sedimentary sequence is missing, possibly reflecting an area that has been relatively elevated for long periods before the Quaternary.

The major part of the Barents Sea is underlain by sediments exhibiting seismic velocities above 2.7 km/s, indicating that the area was emergent during the Tertiary (Eldholm & Talwani 1977). The Barents Sea margin south of Bear Island is of the sheared type defined by the Senja Fracture Zone (figures 1 and 2). This fracture zone is deeply buried, but is prominently outlined as an elongate gravity anomaly (Talwani & Eldholm 1974) and by changes in the magnetic field (Åm 1975). A prograded Cainozoic sedimentary wedge overlies older sediments on the slope and westernmost shelf suggesting that the Barents Sea has been a major source area during the Cainozoic.

A north-trending structural pattern dominates the margin north of 75° N, the most prominent feature being a major fault or sharp flexure at the central shelf (Sundvor & Eldholm 1976; Sundvor *et al.* 1977). This structure separates a region of sea floor velocities above 3.5 km/s and few sub-bottom reflectors from a low-velocity prograded wedge underlying the outer shelf and the slope. The former region extends into the Svalbard Platform (figure 2). It is also important to note that the active rift axis in the Greenland Sea, the Knipovich Ridge, progressively approaches the slope towards the north. The rift mountains have acted as a sediment barrier forming a basin between the eastern ridge flank and the continental slope. In some areas recent sediments have overflowed into the axial valley (figure 3). The mid-oceanic ridge migrated to its present position about 5–6 Ma ago, and the oceanic crust formed at the Knipovich Ridge appears as an elevated central block bounded by basement escarpments on either side. A continent–ocean boundary has not yet been inferred, but must lie between the elevated oceanic crust and the fault on the central shelf (figure 2). It has been noted that the trend of the shelf fault closely follows that of the relative plate motion before anomaly 13 (Sundvor & Eldholm 1976).

Comparatively little is known about the East Greenland margin (Talwani & Eldholm 1974; Johnson *et al.* 1975). Perhaps the most interesting feature is the existence of a marginal basement high (figure 2) underlying the slope just to the south of the Greenland Fracture Zone (Eldholm & Windisch 1974). Geophysically, it is similar to the Vøring Plateau basement high and appears to be bounded landward by an escarpment. The Vøring Plateau and Greenland basement highs appear to be continuous in a pre-anomaly 23 reconstruction (Talwani & Eldholm 1977). Furthermore, we note that in general the continental slope and the main part of the shelf are magnetically quiet.

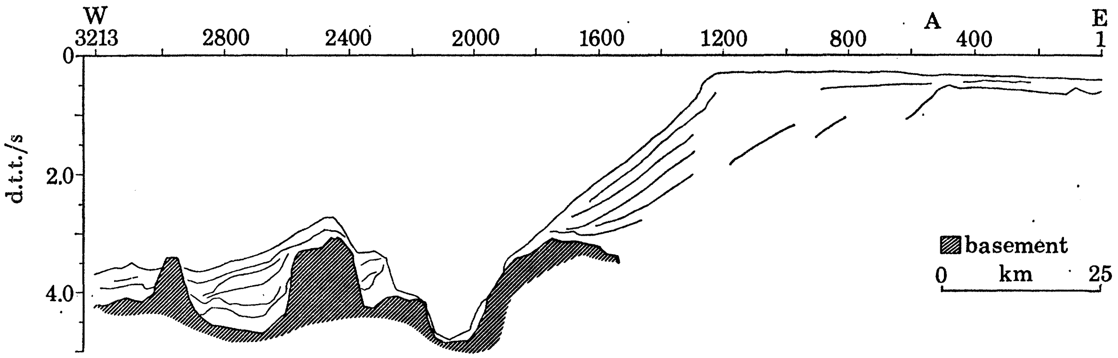

Figure 3. Line drawing of a seismic reflexion profile running east–west at 78° N (Sundvor *et al.* 1977). A refers to the change in seismic character on the shelf. Note the location of the rift valley at the lower continental slope, the elevated crestal region and the infill of sediments into the axial valley. The basement peak at the western end is the southeasternmost part of the Hovgaard Fracture Zone.

Results from multi-channel seismic profiling and deep sea drilling

We now turn the attention to the margin off Norway between the Jan Mayen and Senja fracture zones which have been extensively studied recently. Hinz & Weber (1976) observed reflectors below the smooth acoustic basement at the outer Vøring Plateau and in a profile in the Lofoten Basin just north of the plateau. Similar observations have been made by the C.N.E.X.O. surveys (L. Montadert & V. Renard, personal communication). In a study of the margin north of the Vøring Plateau proper, Eldholm *et al.* (1977) also reported a zone of sub-basement reflectors seaward of the base of the slope (figure 4, line 1). Possibly, reflectors of this kind may occur from within oceanic layer 2, but the fact that these reflectors have only been obtained in a zone lying seaward of the Vøring Plateau Escarpment is intriguing. It was also noted (Eldholm *et al.* 1977) that the sub-basement reflectors always appear to occur below the smooth opaque basement in such a way that the acoustic basement is in part underlain by deeper interfaces and in part represents the deepest reflecting horizon. Moreover, the smooth basement reflector always lies landward of anomaly 23. Noting that similar areas of acoustic basement exist elsewhere on the margins in the Norwegian–Greenland Sea (figure 2), one may expect a similar geological development. The Vøring Plateau Escarpment has been mapped to about 69.1° N (figure 5), its seismic expression becoming progressively less distinct north of the plateau proper. The margin north of the escarpment is very narrow and is characterized by major block faults trending along the bathymetric contours (figure 4, line II). In this area the acoustic basement appears to continue all the way from the Lofoten Basin to the shelf edge. South of Lofoten, the edge of the basement turns seaward and loses distinction as the northern flank of the Vøring Plateau is approached (figure 5).

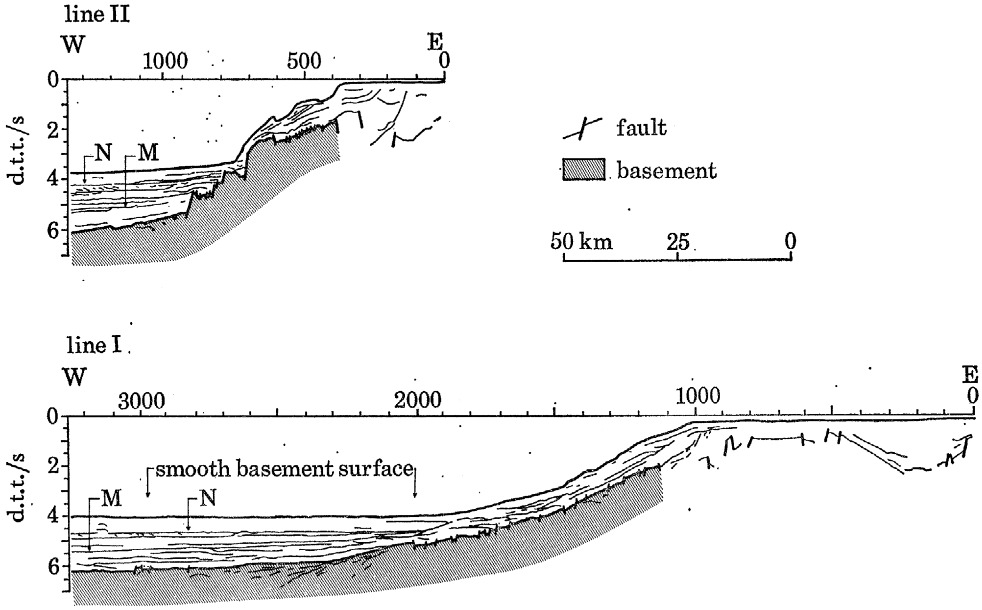

Figure 4. Line drawings of two multi-channel profiles across the margin off Lofoten–Vesterålen. Location in figure 1. A detailed discussion of these profiles is presented by Eldholm *et al.* (1977).

Leg 38 of the Deep Sea Drilling Project covered areas of the Norwegian–Greenland Sea (Talwani *et al.* 1976). Both basement ages and inferences from the palaeontological studies are generally in accord with the evolutionary model proposed by Talwani & Eldhom (1977). Of special interest are the Sites 338 and 342 at the outer Vøring Plateau and Site 343 near the base of the plateau. At these sites oceanic basaltic rocks were drilled and the oldest sediments recovered were of early Eocene age (49–53 Ma). The smooth basement reflector has been correlated with the top of the basalts. In this context, we point out that D.S.D.P. Site 336 which lies on the upper northern flank of the Faeroe Island Ridge also terminated in a typical mid-oceanic basalt at the level of a smooth opaque basement reflector. At this site there is evidence of subaerial basalt extrusion (Talwani & Udintsev 1976).

A programme of drilling into the sub-basement reflectors was proposed for D.S.D.P. Leg 49, but could not be carried out owing to nonscientific problems.

Main problems and tentative history of evolution

These observations appear to have a close relationship to the rift formation and the initial accretion of oceanic crust by sea floor spreading, thus figuring prominently in an understanding of the margin development. In other words, we have to explain the nature of the marginal basement highs including the areas of smooth basement in places underlain by reflecting horizons. How has the Vøring Plateau obtained its shallow elevation, and what is the significance of the shallow acoustic basement underlying the slope in the north? Finally, we have to make inferences about the structural and compositional changes across the margin.

Both oceanic crust landward (Bott 1975; Russell 1976) and continental crust seaward (Hinz 1972) of the Vøring Plateau Escarpment have been suggested. The overall geophysical data have been analysed by Talwani & Eldholm (1972) and Eldholm *et al.* (1977), and show that

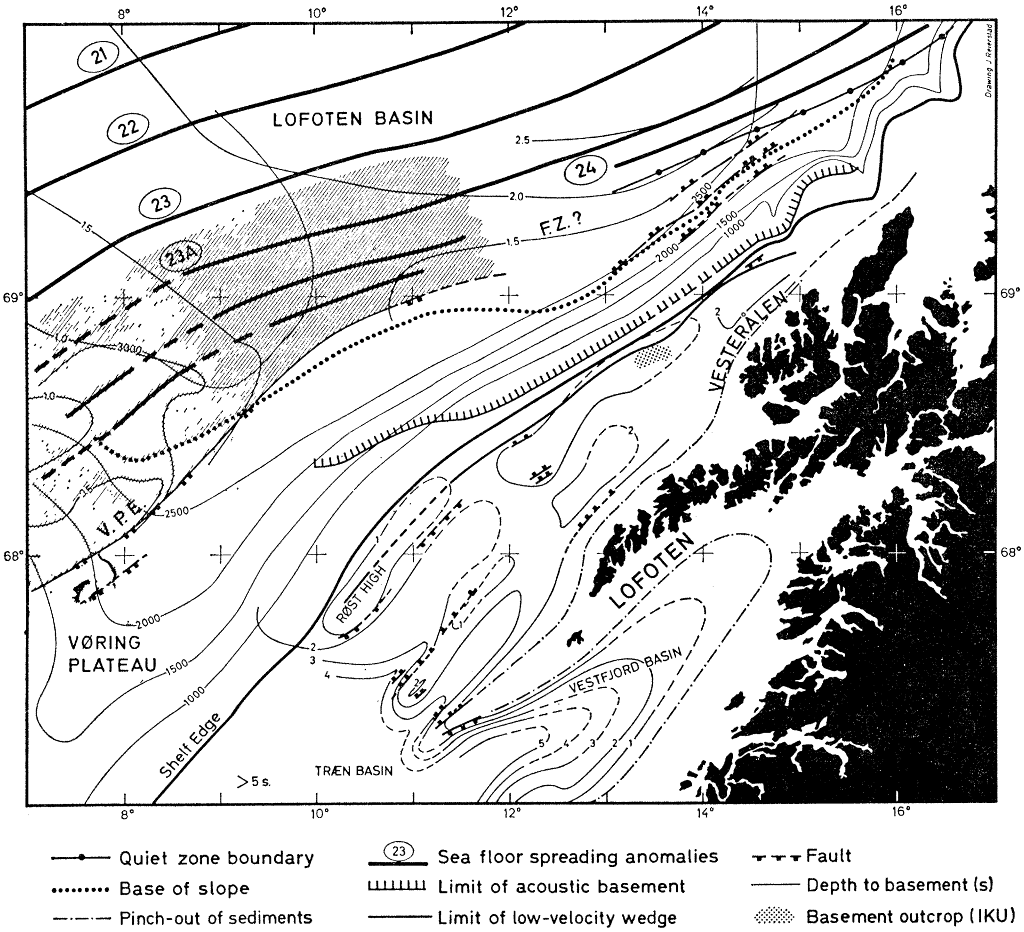

FIGURE 5. Regional map of the main geophysical and geological features on the margin off Norway between latitudes 67 and 70° N. V. P. E. refers to the Vøring Plateau Escarpment and the hachured area shows the extent of smooth acoustic basement seaward of the escarpment (Eldholm *et al.* 1977). This zone is partly underlain by sub-basement horizons.

the observations are most easily reconciled if one introduces a relatively narrow transition zone associated with the escarpment and the quiet zone boundary (figure 5). This solution is supported by the fact that well-developed seafloor spreading type magnetic anomalies overlie and transect the region of smooth acoustic basement and sub-basement horizons. Moreover, commercial exploration results (Rønnevik & Narvestad 1977; Ziegler 1977) do not favour the formation of a deep ocean between Norway and Greenland in the Mesozoic or late Palaeozoic. We do not claim that a solution of this kind is applicable to all margins or that the continental crust is undeformed in the marginal area. It appears, however, that there is a significant contrast in the geophysical signature of the basement across the escarpment. From seismic crustal refraction results, Hinz (1972) characterized the crust beneath the Vøring Plateau as neither continental nor oceanic. We suggest that the subsided continental basement extends to the escarpment or quiet zone boundary. This does not rule out a complex underlying crust which may have been altered owing to thinning, stretching, contamination and subsidence, thus being of a mixed or modified type as shown in figure 6.

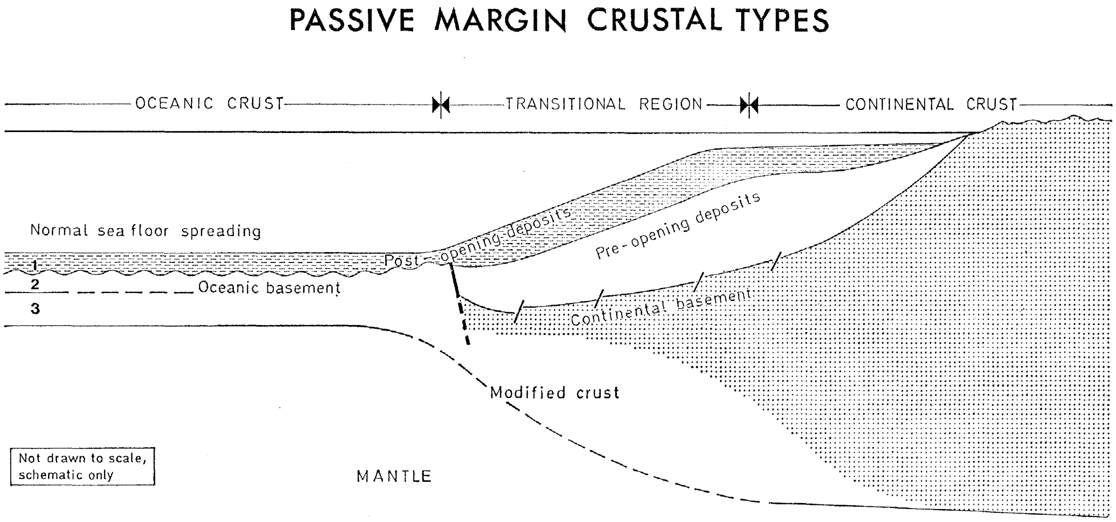

Figure 6. Sketch of the main structural units across the Vøring Plateau type passive margin. The transition between subsided continental crust and the younger oceanic basement is relatively sharp, but little is known about the central and lower crust which we have designated as 'modified' owing to processes related to the break up and separation of the continental crust.

We therefore tentatively suggest a sequence of events in which the area between Norway and Greenland has been subjected to tension before the Cainozoic. It is natural to propose a northward extension of the North Sea Mesozoic tensional system. Accretion of oceanic crust by sea floor spreading did not start until the late Palaeocene. Approximately 2 Ma after the onset of spreading a minor adjustment of the spreading axis took place (figures 2, 5). It appears that the initial phase of spreading was accompanied by an exceptionally high rate of basaltic extrusion forming the smooth acoustic basement. This may have been a continuous or intermittent process, possibly associated with the shift in spreading axis. In the latter case, the acoustic basement surface may reflect flows and pyroclastic material intermingled with terrigeneous sediments overlying slightly older oceanic crust. Regardless of the mode of basement formation, the analogy with the Faeroe–Iceland Ridge suggests extrusion at a subaerial level. According to figure 5, the period of smooth basement formation ended before anomaly 23 time. This observation is interesting in view of D.S.D.P. core analysis which indicates that a basalt was being eroded until uppermost early Eocene time (Caston 1976).

North of the Vøring Plateau, the volcanic material overflowed onto the adjacent continental crust in the young rift zone. The landward extent of the smooth reflector off Lofoten–Vesterålen appears to be bounded by the flanks of the rift depression. No similar reflector has yet been identified landward of the Vøring Plateau Escarpment, but may exist below the thick section of Cainozoic sediments.

The rifting took place within a sedimentary basin of epicontinental nature, the rift zone crossing the basin diagonally in such a way that the central basin lies on the Norwegian side in the south and on the Greenland side in the north. Hence, the initial rift was located on the basin margin off Vesterålen. This, possibly together with the early shift in the spreading axis, may explain the different structural styles of the margin. In the north, marginal subsidence has occurred in a narrow region between the rift axis and the emerged continent, causing the displacement to take place along major fault zones. Flexuring and minor fault diplacement dominate in the south, where the distance to the basin margin becomes considerably larger (figure 4). An early Tertiary age for maximum subsidence is indicated by the absence of fault structures in the overlying sediments.

The early Tertiary marginal subsidence has been accompanied by a relative uplift of the Fennoscandian continent. Multichannel seismic data from the northern North Sea margin indicate a broad monoclinal flexuring of the continent during the early Eocene (Egeberg 1977).

It has been proposed (Eldholm 1978) that the marginal highs could be ascribed to the following: initial high rate of basaltic intrusion at the onset of normal sea floor spreading; a drag effect adjacent to the continental crust, caused by a complete coupling between the two crustal types; extinct spreading ridge high; spreading axis within a hot spot region (Talwani & Eldholm 1977); and faulting within the newly formed oceanic crust. Obviously, a combination of mechanisms may have occurred. We suggest that faulting has taken place in the virginal oceanic crust and may be partly responsible for the elevation of the Vøring Plateau.

As noted above this discussion applies to a particular segment of the margin off Norway and is based on limited high resolution data. However, areas of smooth basement, adjacent to the transitional zone between continental and oceanic types of basement, exist from the Greenland–Senja Fracture Zone to the Faeroe–Iceland Ridge (figure 2), possibly extending southwards along the western flank of Hatton Bank. A similar type of basement exists along the entire Faeroe–Iceland Ridge. The observations may be interpreted in terms of two accretional modes of the oceanic crust. One is the normal type of irregular oceanic basement created at the mid-oceanic ridge, the other 'Islandic type' is characterized by high rates of volcanic extrusion at subaerial levels.

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Discussion

G. Wissmann (*German Geological Survey, Hanover, Germany*). In their introductory remarks the authors stated the Jan Mayen Ridge to be a microcontinent. Could they present supporting evidence, as their paper did not focus on this particular problem.

O. Eldholm. The continental nature of the northern part of the Jan Mayen Ridge appears to be well documented; however, there is considerable uncertainty as to the extent of the continental fragment, particularly its southern continuation. For a detailed analysis we refer to Talwani & Eldholm (1977) and Talwani & Udintsev (1976).