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Seismic volcanostratigraphy of the Norwegian Margin: constraints on tectonomagmatic break-up processes

C. BERNDT[1,2], S. PLANKE[1,3], E. ALVESTAD[1,4], F. TSIKALAS[1] & T. RASMUSSEN[1]
[1]*Department of Geology, University of Oslo, PO Box 1047 Blindern, N-0316 Oslo, Norway*
[2]*Present address: Department of Geology, University of Tromso, Dramsveien 201, N-9037 Tromso, Norway*
(e-mail: cberndt@ibg.uit.no)
[3]*Present address: Volcanic Basin Petroleum Research AS, Forskningsparken, Gaustadalleen 21, N0349 Oslo, Norway*
[4]*Present address: Petroleum Geoservices AS, Lysaker, Norway*

Abstract: Voluminous volcanism characterized Early Tertiary continental break-up on the mid-Norwegian continental margin. The distribution of the associated extrusive rocks derived from seismic volcanostratigraphy and potential field data interpretation allows us to divide the More, Vøring and Lofoten–Vesterålen margins into five segments. The central Møre Margin and the northern Vøring Margin show combinations of volcanic seismic facies units that are characteristic for typical rifted volcanic margins. The Lofoten–Vesterålen Margin, the southern Vøring Margin and the area near the Jan Mayen Fracture Zone show volcanic seismic facies units that are related to small-volume, submarine volcanism. The distribution of subaerial and submarine deposits indicates variations of subsidence along the margin. Vertical movements on the mid-Norwegian margin were primarily controlled by the amount of magmatic crustal thickening, because both the amount of dynamic uplift by the Icelandic mantle plume and the amount of subsidence due to crustal stretching were fairly constant along the margin. Thus, subaerial deposits indicate a large amount of magmatic crustal thickening and an associated reduction in isostatic subsidence, whereas submarine deposits indicate little magmatic thickening and earlier subsidence. From the distribution of volcanic seismic facies units we infer two main reasons for the different amounts of crustal thickening: (1) a general northward decrease of magmatism due to increasing distance from the hot spot and (2) subdued volcanism near the Jan Mayen Fracture Zone as a result of lateral lithospheric heat transport and cooling of the magmatic source region. Furthermore, we interpret small lateral variations in the distribution of volcanic seismic facies units, such as two sets of Inner Seaward Dipping Reflectors on the central Vøring Margin, as indications of crustal fragmentation.

Keywords: Norway, seismic stratigraphy, tectonostratigraphy, volcanism, tectonics.

In this work we present a map of the distribution of volcanic seismic facies units on the mid-Norwegian volcanic rifted margin (Fig. 1), and evaluate its implications for the tectonic and magmatic breakup processes. Such an investigation is timely for several reasons. Previous compilations of the distribution of breakup volcanic rocks (e.g. Eldholm & Grue 1994) were based primarily on the work carried out in the 1970s and 80s (Hinz 1981; Mutter *et al.* 1982; Hinz *et al.* 1987; Eldholm *et al.* 1989; Skogseid & Eldholm 1989). In the meantime the understanding of the temporal evolution of breakup volcanism has improved significantly by scientific drilling (ODP Legs 152 (Larsen & Saunders 1998) and 163 (H.C. Larsen *et al.* 1999)) and land-based work (L.M. Larsen *et al.* 1999). Furthermore, improved multichannel seismic (MCS) data have allowed the development and usage of seismic volcanostratigraphy (Planke *et al.* 2000) to study volcanic deposits and processes. Here, we apply this new method to new MCS data acquired on the Vøring and Møre margins, and to previously recorded data.

Further understanding of the evolution of volcanic rifted margins is both scientifically and economically important. The principal questions include the identification of the mode of crustal extension and the influence of the emplacement of a large igneous province on climate change, ecology and oceanology (Coffin & Eldholm 1994). Volcanic rifted margins are further prime locations to investigate mantle plume processes and the rheological properties of the upper mantle. Finally, volcanic passive margins are targets of future hydrocarbon exploration and it is therefore important to understand the geodynamic processes that lead to their present configuration.

The objective of this study is to constrain the processes that control the lateral variation of breakup magmatism along a volcanic rifted margin. These processes include extensional thinning of the crust, crustal thickening due to emplacement of magmatic material, variation in regional magma supply, and the influence of the tectonic setting on the amount of volcanism. To achieve this goal we map the spatial distribution of volcanic seismic facies units. Because these units commonly relate to individual tectonic or magmatic processes (Planke *et al.* 2000), knowledge about their distribution allows us to identify areas where the different processes played a major role in the development of the margin.

Geological evolution of the Norwegian Margin

The mid-Norwegian margin consists from south to north of the Møre, Vøring and Lofoten–Vesterålen margins (Fig. 1). The Møre and Vøring margins are separated by the Jan Mayen Fracture Zone and Jan Mayen Lineament, whereas the transition from the Vøring to the Lofoten–Vesterålen Margin is called the Bivrost Fracture Zone and Bivrost Lineament

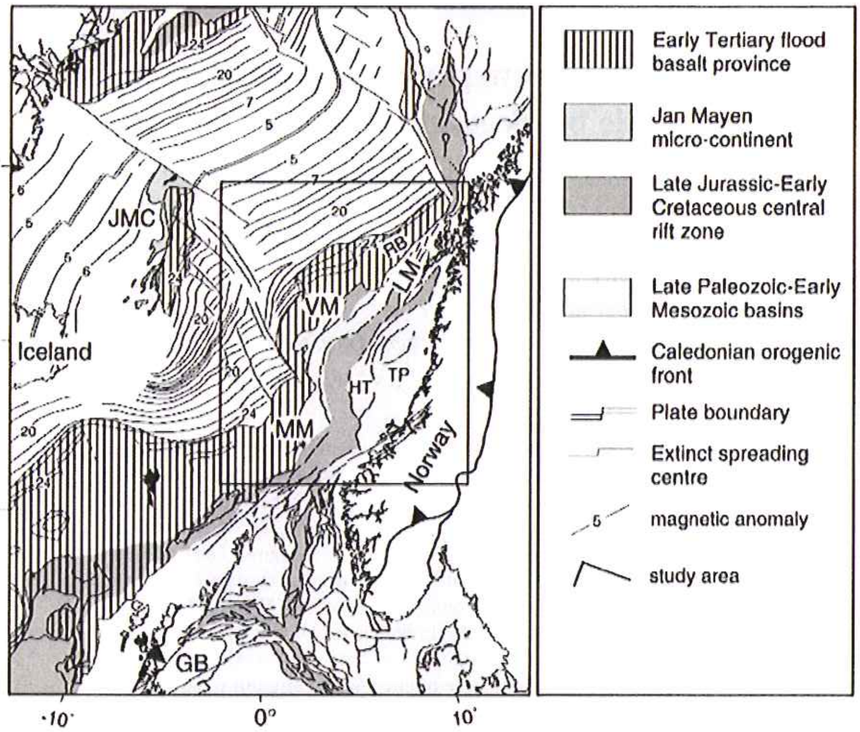


Fig. 1. Tectonic setting of the northeast Atlantic (modified from Skogseid *et al.* 2000). Note the wide distribution of break-up related volcanic rocks and the major transform zone between the Møre (MM) and the Vøring (VM) margins. LM, Lofoten–Vesterålen Margin; JMFZ, Jan Mayen Fracture Zone; BFZ, Bivrost Fracture Zone; JMC, Jan Mayen micro-continent; RB, Rst Basin; HT, Halten Terrace; TP, Trndelag Platform; GB, Great Britain.

(Blystad *et al.* 1995). Whereas the Jan Mayen Fracture Zone is a major transfer system throughout both the rift and drift phase of the North Atlantic (Skogseid & Eldholm 1987), activity along the Bivrost Fracture Zone was mainly confined to the early drift phase (Hagevang *et al.* 1982). However, the boundary between the Vøring and Lofoten–Vesterålen margins is important as it coincides with a high-velocity lower-crustal body interpreted as the result of magmatic underplating (Mjelde pers. comm. 2000).

The entire mid-Norwegian margin underwent considerable extension during the Late Jurassic/Early Cretaceous and Late Cretaceous/Early Tertiary (Brekke & Riis 1987; Skogseid & Eldholm 1989; Doré *et al.* 1997; Skogseid *et al.* 2000). With each rift episode the rift centre stepped progressively towards the incipient breakup axis (Doré *et al.* 1999). The last rifting episode culminated in continental break-up at the Palaeocene–Eocene boundary.

Pedersen & Skogseid (1989) calculated, based on uniform stretching models and the observed amounts of volcanism and uplift, that the mantle temperature at the base of the lithosphere was increased by about 50–80 K during continental breakup. This temperature anomaly is ascribed to the presence of the Icelandic mantle plume and caused extensive melting of the upper mantle when the pressure on the upper mantle was decreased during continental breakup (White & McKenzie 1989). The associated magmatism resulted in intrusion of volcanic rocks into the sedimentary basins, magmatic underplating at the base of the crust, and large amounts of extrusive material (Hinz 1981; Mutter *et al.* 1982; Hinz *et al.* 1987; White & McKenzie 1989; Eldholm *et al.* 1989; Skogseid *et al.* 1992*a*; Eldholm & Grue 1994).

The breakup extrusive rocks have been the subject of several deep-sea drilling surveys: DSDP Leg 38 and ODP Leg 104 on the Vøring Margin and ODP Legs 152 and 163 on the southeast Greenland Margin. In particular, Sites 642 and 917 have shown that the breakup volcanic rocks have been deposited during two phases of volcanism. The first consists of scattered basaltic, andesitic and dacitic volcanism in a continental environment from 63 to 55.5 Ma. The second phase during continental breakup lasted from 55.5 to 53 Ma. It was more voluminous and ranged petrologically from basalts to picrites, showing very little evidence of continental contamination (see Saunders *et al.* 1997 for a review).

The amount and distribution of the volcanic deposits on the Vøring Margin was the subject of work by Hinz (1981), Mutter *et al.* (1982), Skogseid & Eldholm (1989), Skogseid (1994), and Eldholm & Grue (1994). Eldholm & Grue (1994) calculated that the flood basalts within the North Atlantic Volcanic Province cover an area of 1.8×10^6 km^2. The sediment distribution on top of the volcanic deposits has been described in detail by Skogseid & Eldholm (1989). The bulk of the sediments on the outer margin are of Eocene to Oligocene age with thin units of younger sediments on top. The post-break-up sediments experienced only moderate tectonic deformation and are rarely more than 1 km thick. Thus, they do not impede the study of the underlying volcanic deposits.

Data

A new multi-channel seismic (MCS) survey recorded by the Norwegian Petroleum Directorate consisting of 12 dip profiles and one strike profile comprises the core of this work. The data are of high quality and cover the entire outer Vøring Margin (Fig. 2). Examples, including acquisition and processing parameters, are shown in Figure 3. Furthermore, we have interpreted other MCS data in the area affected by break-up volcanism on the Norwegian Margin, comprising ten surveys recorded by the government and petroleum industry from 1974 to 1994 and five academic surveys recorded from 1976 to 1987 (Fig. 2). The data include recently recorded high quality profiles on the Møre Margin and previously uninterpreted data from the Lofoten–Vesterålen Margin. Generally, the data density is high enough to correlate facies units laterally along the margin and observe the

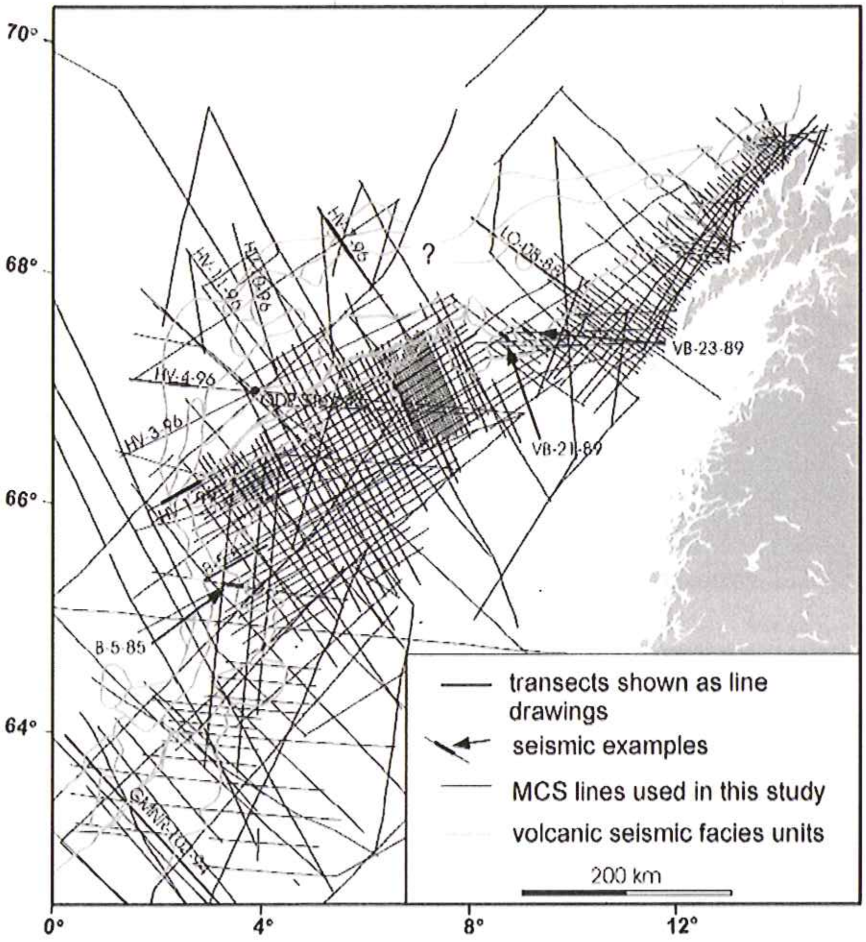


Fig. 2. Multi-channel seismic data coverage. Note that most volcanic seismic facies units are well covered by the data. The only gap exists at the Vøring/Lofoten–Vesterålen Margin transition.

transitions between individual units. However, there is a data gap at the seaward end of the transition between the Vøring and Lofoten–Vesterålen margins (Fig. 2).

The free-air gravity anomaly data presented in this study is calculated from Geosat and ERS satellite altimetry data (Sandwell & Smith 1997). The data have an accuracy of 3–6 mGal when compared to ship track data. The magnetic anomaly grid is based on aeromagnetic data compiled by Verhoef *et al.* (1996).

Interpretation strategy

The intra-basalt impedance contrasts are large in comparison to those found in sedimentary basins and exhibit strong variability on small horizontal and vertical scales (Planke 1994). These heterogeneities in elastic properties cause scattering and interference of seismic waves. Consequently, it is difficult to image intra- and sub-basaltic geological features, and seismic data recorded in volcanic terrain require an adequate interpretation strategy. In this study we use the concept of seismic volcanostratigraphy (Planke *et al.* 2000) for the interpretation of large volcanic constructions. The method consists of three steps. In the first step (the seismic sequence analysis) the extrusive volcanic construction is interpreted as one seismic sequence, i.e. a depositional unit of genetically related strata bounded by unconformities or correlative conformities. The second step is the mapping of seismic facies units within the volcanic sequence. A volcanic seismic facies unit is a part of the volcanic seismic sequence which has a uniform internal seismic character. It must be mappable, i.e. it must differ from the adjacent units, extend laterally to the neighbouring seismic profiles, and it must have a uniform overall shape. Mapped volcanic seismic facies units are interpolated between the seismic profiles. In areas with less dense seismic data coverage we utilized potential field data in our interpretation. In the final step we interpret the volcanic nature of the mapped volcanic seismic facies units taking into account well ties, field analogues, wave propagation phenomena such as internal multiples, and seismic processing. It is frequently possible to associate objectively identified seismic facies units with typical volcanic deposits, which in turn may be indicative of distinct emplacement environments (Planke *et al.* 2000).

Seismic sequence analysis

The top of the basaltic sequence is the top unconformity/conformity between the post-break-up sediments and the basaltic basement. It is the landward continuation of the 'top oceanic basement' reflection. This reflection is easily identified because of the high impedance contrast between post-rift sediments and volcanic basement, resulting in a major reflector. However, for both the area along the transform margin and the area at the boundary between the Vøring and Lofoten–Vesterålen margin the identification of the upper sequence boundary is less straight forward. For the transform margin area it extends from the oceanic crust of normal depth in a steep slope to a smooth, planar surface farther landward where it abruptly terminates in one of several continuous,

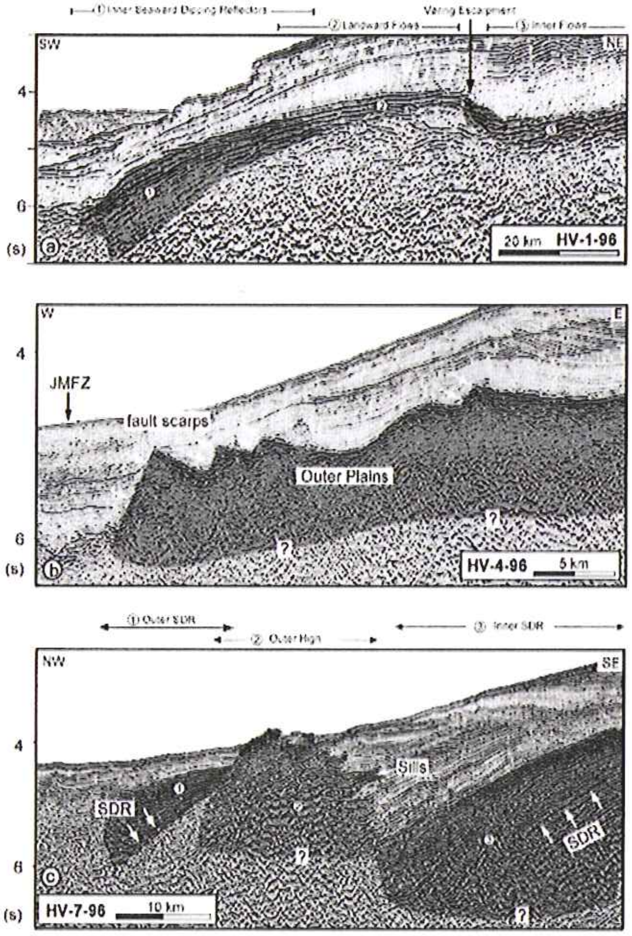


Fig. 3. Three examples of seismic data from the Vøring Margin (Fig. 2 for locations). The circled numbers within the seismic sections denote volcanic seismic facies units and correspond to the labels above the section where applicable. The data are recorded with a 192-channel streamer and 50 m shot interval using an air gun array with a volume of 2080 in^3. Processing sequence: designature, amplitude scaling, diversity scaling, F-K frequency filtering for multiple suppression, dip moveout correction, F-K constant velocity migration, normal moveout correction, stack, static correction, demigration, minimum phase deconvolution, frequency filtering, amplitude balancing, wave-equation migration, frequency filtering and amplitude balancing.

low-amplitude sedimentary reflections. The reflection strength of the top of the volcanic sequence is in some areas not much higher than that of sedimentary reflections. Therefore, the interpretation that the underlying sequence is indeed of volcanic origin is based on the small number of continuous internal reflections for a wide variety of differently processed data, and on the similarities with unambiguously identified volcanic rocks on the same stratigraphic level. Similarly, the volcanic nature of the interpreted volcanic sequence at the boundary between the Vøring and Lofoten–Vesterålen margins is primarily inferred from the high-amplitude top reflection, the absence of reflections underneath, and the stratigraphic position. Only in very few places it is possible to identify the base of the basaltic sequence, for example at the base of the Landward Flows on the Møre Margin (Planke *et al.* 1999). Therefore, the lower boundaries of the volcanic seismic facies units in Figs 3 and 5 must be considered tentative.

Volcanic seismic facies units

In this study we identify and map ten volcanic seismic facies units based on their shape, reflection pattern and boundary reflections (Table 1 and Fig. 4). It is possible to define more units locally. However, the data quality varies along the margin. Therefore, a too-detailed definition might result in lateral variations along the margin that are data-driven. In order to avoid such artefacts, we chose a limited number of distinctive units. Several volcanic seismic facies units that have previously been identified and interpreted are used in this study (Table 1). We define and discuss in more detail five additional units: the Outer Plains, the Transform Margin Flows, the Lofoten Margin Flows, the Tuff Sheet and the Shallow Intrusions.

Ewing & Houtz (1979) and Hinz (1981) referred to the area where the Outer Plains and Transform Margin Flows are found, as thickened oceanic crust. New data show distinct differences between the Outer Plains and Transform Margin Flows. The Outer Plains is located seaward of the Inner SDR (Seaward Dipping Reflectors) in the southwestern part of the Vøring Margin immediately adjacent to the Jan Mayen Fracture Zone (Fig. 4). The upper boundary of this unit is commonly marked by a strong basement reflection with several offsets resembling fault scarps (Fig. 3b). On a regional scale the top of this unit dips gently towards oceanic crust of normal thickness, where it frequently stops at the most seaward fault scarp. A lower boundary reflection is absent. The internal reflection pattern of this unit is chaotic, showing high-amplitude, low-frequency events. We define the boundary toward the Inner SDR as the transition between the absence and presence of laterally continuous internal reflections.

The Transform Margin Flows has a high-amplitude top reflection, lacks a base reflection, and shows very few internal reflections (Fig. 5a). The extent of the Transform Margin Flows is confined to the southern part of the Vøring Margin (Fig. 4). The Transform Margin Flows differs from the Landward Flows to the north and south by the absence of internal reflections, whereas it has a more continuous top reflection than the Inner Flows and lacks the fault scarps of the Outer Plains.

The Lofoten Margin Flows is characterized by a high-amplitude top reflection with occasional offsets resembling normal oceanic crust (Figs 4 & 5b, c). Its internal reflection pattern is frequently subhorizontal. The Lofoten Margin Flows terminate landward against large fault scarps (Fig. 6e) and seaward against Outer SDR.

The Tuff Sheet is located in the landward part of the transition between the Vøring and Lofoten–Vesterålen margins (Fig. 4). The unit is characterized by a high-amplitude, very smooth top reflection, a weak, continuous bottom reflection and lacks internal reflections (Fig. 5b).

Additionally, we have mapped shallow sills as a Shallow Intrusions facies unit (Figs 4 and 5a). The unit is by definition not part of the extrusive volcanic sequence. However, its origin is closely related to the extrusive volcanism so we include it for completeness. Generally, the reflections from shallow sills differ from the seismic character of the Inner Flows by up and down stepping through the sedimentary column, abrupt terminations and strong reflections. The Shallow Intrusions has a

Table 1. *Volcanic seismic facies units*

Seismic facies unit	Reflection characteristics			Volcanic facies	Emplacement environment	Reference	Figure
	Shape	Boundaries	Internal				
Inner Flows	Sheet	Top: high amplitude; bottom: negative polarity	Chaotic, disrupted	Volcaniclastics, hyaloclastics and flows	Shallow marine	1	3a
Landward Flows	Sheet	Top: planated; bottom: disrupted, low amplitude	Subparallel	Flood basalts	Subaerial	1, 2	3a
Inner SDR	Wedge	Top: high amplitude; bottom: not visible	Diverging	Flood basalts	Subaerial	1, 2, 3, 4	3a, c
Outer High	Mound	Top: rough, high amplitude Bottom: not visible	Chaotic	Volcaniclastics	Shallow marine	1, 2	3c
Outer SDR	Wedge	Top: high amplitude; bottom: not visible	Diverging, low amplitude	Flows	Submarine	1	3c
Outer Plains	Sheet	Top: faulted, high amplitude; bottom: not visible	Chaotic, high amplitudes, opaque	Flows	Submarine	5	3b
Transform Margin Flows	Dipping Sheet	Top: high amplitude; bottom: not visible	Opaque	Flows?	Submarine	5	5a
Lofoten Margin Flows	Sheet	Top: high amplitude, faulted; bottom: low amplitude	Subparallel mainly opaque	Flows	Submarine	5	5b, c
Tuff Sheet	Thin sheet	Top: very smooth, high amplitude; bottom: smooth	Layered	Tephra deposits	Shallow marine	5	5b
Shallow Intrusions	Complex	High amplitude	n.a.	Intrusions	Shallow sediments	5	5a

References: (1) Planke *et al.* (2000); (2) Planke *et al.* (1999); (3) Hinz (1981); (4) Mutter *et al.* (1982); (5) this study. n.a., not applicable.

clear boundary in the southwestern and northern part of the Vøring Basin, but it gradually merges with deeper intrusions in the border area between Møre and Vøring basins, where the intrusions have been described by Skogly (1998).

Escarpments

The breakup volcanic sequence includes two prominent escarpments: the Vøring Escarpment on the Vøring Margin and the Faeroe–Shetland Escarpment on the Møre Margin. The Vøring Escarpment begins in the south close to the Jan Mayen Fracture Zone (Fig. 4) and continues to the northern end of the Vøring Plateau where its height gradually decreases and it finally stops between the two northernmost evaluated MCS profiles. A sharp offset in the general direction of the escarpment approximately 20 km from its southern end indicates that it consists of a short southern and a long northern segment. The escarpment is a major scarp in the top of the volcanic sequence and reaches heights of several hundred metres in its central part. Generally, it is confined to a single scarp, but between 30°30'E and 40°15'E it widens and is replaced by a hummocky, gently downsloping, terrain. With the exception of the hummocky terrain the Vøring Escarpment is characterized by a continuous magnetic low.

The Faeroe–Shetland Escarpment begins in the NE at approximately 2°E and continues southwestward into the British sector. Similar to the Vøring Escarpment it consists of a single, laterally undulating scarp (Fig. 4). It does not have a distinctive potential field signature.

Both escarpments are situated at the boundary between Inner Flows and Landward Flows and are absent elsewhere. They strike parallel to the breakup axis and are shorter than previously mapped (e.g. Blystad *et al.* 1995).

The continuity and undulation of both the Faeroe-Shetland Escarpment and the Vøring Escarpment (Fig. 4) make it very unlikely that the escarpments are dominantly fault-controlled as suggested by Skogseid & Eldholm (1989) and Brekke *et al.* (1999). The fact that the escarpments exist exclusively between the Landward Flows and Inner Flows suggests that they are rather the result of a generic margin forming process as suggested by Smythe *et al.* (1983) for the Faeroe–Shetland Escarpment. Alvestad (1997) and Planke & Alvestad (1999) interpreted the prograding reflections underneath the Landward Flows to result from the foresets of a Gilbert-type lava delta terminating with the escarpment. Such a setting is similar to those of lava deltas and bench collapse at Kilauea volcano, Hawaii (Moore *et al.* 1973). An origin of this kind implies that the escarpments develop after or during the emplacement of the Landward Flows and submergence of the marginal high under sealevel. Detailed mapping of the southern part of the Faeroe–Shetland Escarpment has led to the same conclusion for this escarpment (Kiørboe 1999).

Distribution of volcanic seismic facies units

The map in Figure 4 shows the distribution of volcanic seismic facies units. It is far more detailed than older maps of the extrusive volcanic deposits (Talwani *et al.* 1981; Skogseid & Eldholm 1989; Blystad *et al.* 1995) due to denser data coverage and subdivision into volcanic seismic facies units (Fig. 4). The volcanic seismic facies unit distribution allows us to divide the margin into five provinces. Each of these provinces contains a distinct combination of volcanic seismic facies units.

Central Møre Margin

The central Møre Margin (Figs 1 and 3a) includes five main volcanic seismic facies units: Inner Flows, Landward Flows,

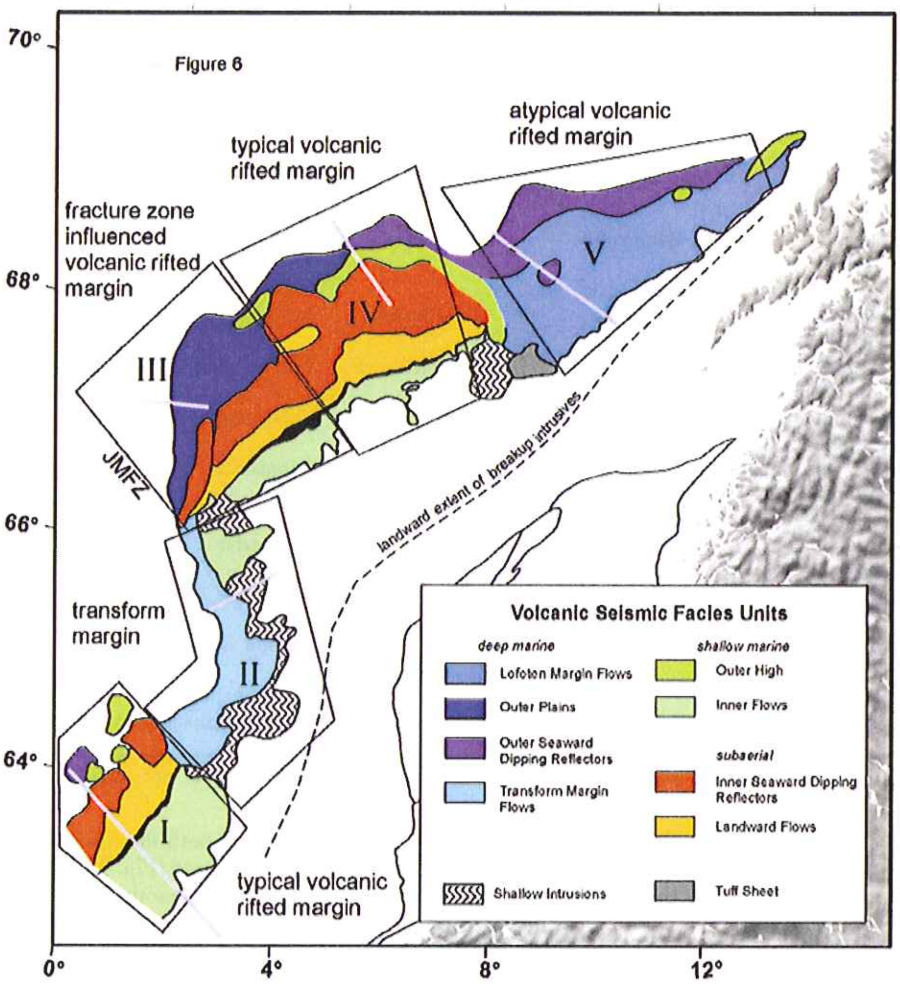


Fig. 4. Distribution of volcanic seismic facies units at top basalt level. The thick black lines between the Landward Flows and Inner Flows show the Vøring and Faeroe–Shetland escarpments. The roman numbers correspond to the provinces discussed in the text and shown in Figure 6. JMFZ, Jan Mayen Fracture Zone.

Inner SDR, Outer High and Outer SDR. At top basalt level the Inner Flows and the Landward Flows are separated by the Faeroe–Shetland Escarpment. The post rift sediments lie conformably on the Landward Flows and Inner Flows and lap on the escarpment. Generally, the top volcanic basement shows less topography than on the Northern Vøring Margin. Alvestad (1997) has shown that the Inner Flows continue under the Landward Flows, and identified two additional volcanic seismic facies units on the Møre Margin: the Lava Delta and Volcanic Basins. However we omit them in this study as the data quality in most of the study area does not allow us to map these units.

Transform margin

The transform margin is located in the southern part of the Vøring Plateau and in the corner between the Møre and Vøring margins (Figs 4 and 5a). It comprises Transform Margin Flows, Shallow Intrusions and a small area of Inner Flows in the northwestern part of the transform margin. The Transform Margin Flows is most extensive near the landward extension of the Jan Mayen Fracture Zone on the Møre Margin. Generally, it terminates abruptly landward and is followed by Shallow Intrusions. The area close to the Vøring Escarpment with Inner Flows is an exception.

Southern Vøring Margin

The landward part of the southern Vøring Margin is characterized by Inner Flows. This facies unit is separated by the Vøring Escarpment from Landward Flows, but unlike the Inner Flows of the Møre Margin the Inner Flows in this area cannot be mapped under the Landward Flows. The Inner SDR is located seaward of the Landward Flows. Two MCS profiles show that this unit is subdivided into a smaller part with reflections dipping toward the Jan Mayen Fracture Zone and a bigger northern part with reflections that dip approximately normal to the rift axis. The most seaward unit on the southern Vøring Margin is the Outer Plains. It is located between the Inner SDR and oceanic crust of normal thickness. The outer boundary of this unit turns in a wide curve from being parallel to the fracture zone in the south to being parallel to the rift axis in the north (Fig. 4). Profiles HV-3-96 and HV-11-96 (Fig. 2) show evidence for planation at the top of the Outer Plains close to the Inner SDR.

Northern Vøring Margin

The landward part of the northern Vøring Margin shows the same distribution of volcanic seismic facies units as the southern Vøring Margin: the Vøring Escarpment separates Inner Flows from Landward Flows. The Inner SDR is located westward of the Landward Flows. Its extent normal to the

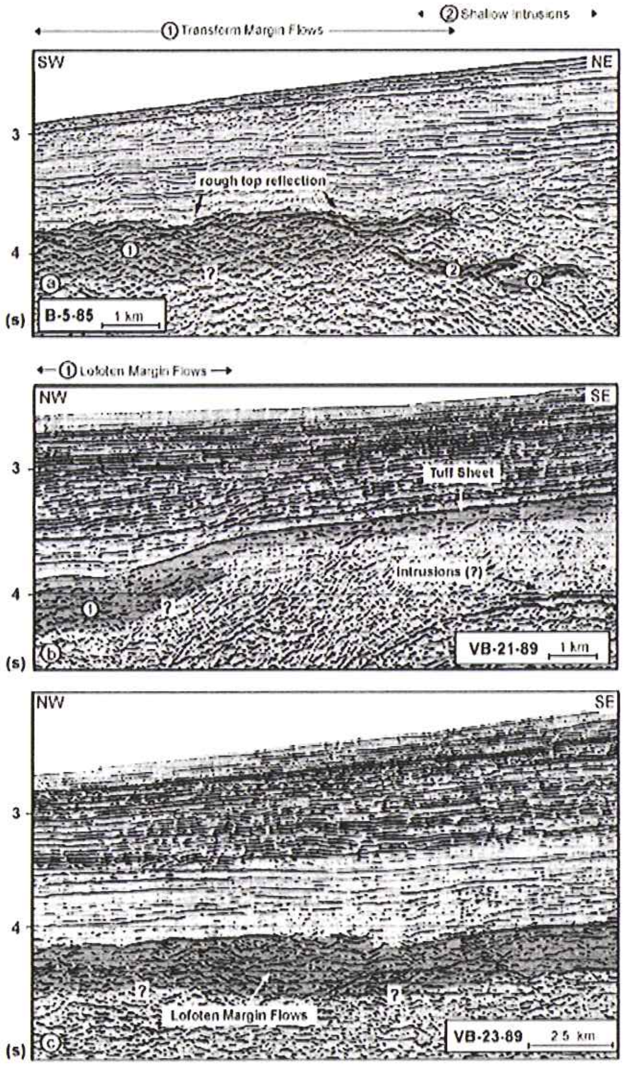


Fig. 5. Examples of seismic data from the transform margin near the Jan Mayen Fracture Zone (a), and from the Lofoten–Vesterålen Margin (b & c). Processing sequence for (a): amplitude scaling, deconvolution, F-K filtering for multiple suppression, normal moveout correction, trace equalization, stack, deconvolution, wave equation migration, F-K filtering, frequency filtering, trace mixing. Processing sequence for (b & c): designature, spherical divergence correction, F-K filtering for multiple suppression, dip moveout correction, weighted stacking, F-K filtering, seabed deconvolution, predicted deconvolution, frequency filtering, F-D migration, frequency filtering, scaling.

breakup axis is wider than on the southern Vøring Margin (Fig. 4). The outer part of the margin is distinctly different. Commonly, an Outer High exists seaward of the Inner SDR and in the northern part an Outer SDR is located seaward of the Outer High. The transition between the southern Vøring Margin and the northern Vøring Margin is gradual. We did not assign profiles HV-10-96 and HV-11-96 to any of these margin provinces as Outer Highs and Outer Plains can be interpreted on both profiles.

Lofoten–Vesterålen Margin

The Lofoten–Vesterålen Margin includes four different facies units: the Lofoten Margin Flows, Outer Highs, Outer SDR and a Tuff Sheet (Fig. 6e). The innermost unit is the Lofoten Margin Flows. In the east it commonly terminates against a prominent fault scarp. It extends seaward for about 50–100 km (Fig. 4) across the inferred Røst Basin (Sellevoll *et al.* 1988; Mjelde *et al.* 1992; Mokhtari & Pegrum 1992). To the west it terminates against the Outer SDR, which is similar to the Outer SDR on the northern Vøring Margin both in terms of reflection strength and extent. The data coverage is too sparse to delineate the northern and southern extent of the Lofoten Margin Flows and the Outer SDR on this margin segment. In the very southeastern part of the Lofoten–Vesterålen Margin the Lofoten Margin Flows disappear underneath the Tuff Sheet and a well defined Outer High exists in the northwesternmost part of the Lofoten–Vesterålen Margin. A second, small Outer High is located in the middle of the Røst Basin (Fig. 4).

Constraints from potential field data

Due to their high density and strong magnetization, volcanic rocks have prominent expressions in the potential field data. A comparison of the distribution of the volcanic seismic facies units with these independent data sets shows that the units commonly have a characteristic signature in either the gravity data, the magnetic data or in both.

Free-air gravity anomaly data

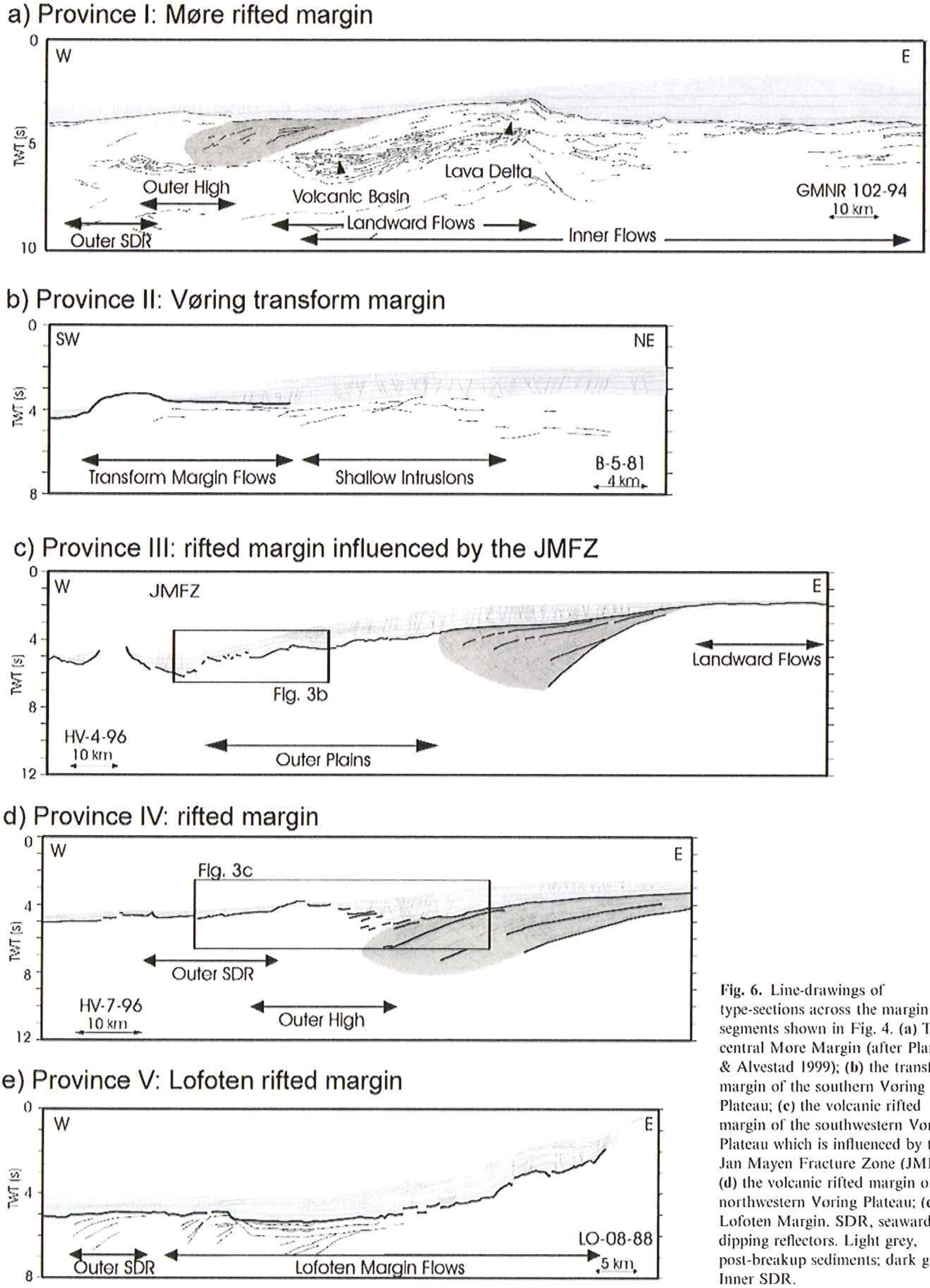
Figure 7 shows the free-air gravity anomaly and the distribution of volcanic seismic facies units as mapped by MCS data. The Landward Flows, the Inner SDR, and the Outer Plains are associated with high positive gravity anomalies on the order of 100 mGal. Only a small area of the Landward Flows on the Vøring Margin between 3° and 4°E shows decreased gravity values. Generally, the anomalies are slightly lower on the Møre Margin. Similarly, the extent of the Lofoten Margin Flows matches the gravity data well. This unit is associated with a negative free-air gravity anomaly which is lower than the values observed for the adjacent Outer SDR in spite of a constant water depth in the area.

The Inner Flows extend frequently farther landward in areas with low gravity values and are closer to the escarpments in areas with positive gravity anomalies. The Transform Margin Flows and the seaward limit of the Outer SDR do not correlate with the gravity data. The absence of both a bathymetric and a gravity anomaly difference between the Outer SDR and the oceanic crust indicates that the volcanic rocks that result in Outer SDR have densities similar to the oceanic basalts.

Magnetic anomaly data

The magnetic anomaly data (Fig. 8) correlates well with the seismically mapped Lofoten Margin Flows, Landward Flows, and Transform Margin Flows. All these units closely match negative magnetic anomalies. In particular the landward termination of the Landward Flows, i.e. the top of the Vøring Escarpment on the Vøring Margin, coincides with a sharp increase of the magnetic anomaly from values of −250 nT to small, 0–50 nT, positive values.

The Inner SDR matches a high positive magnetic anomaly on the northern Vøring Margin. This anomaly has been successfully modeled by Schreckenberger (1997), who showed that the magnetic signal can be explained as the superposition of an upper normally polarized series of flood basalts and a


a) Province I: Møre rifted margin

b) Province II: Vøring transform margin

c) Province III: rifted margin influenced by the JMFZ

d) Province IV: rifted margin

e) Province V: Lofoten rifted margin

Fig. 6. Line-drawings of type-sections across the margin segments shown in Fig. 4. **(a)** The central Møre Margin (after Planke & Alvestad 1999); **(b)** the transform margin of the southern Vøring Plateau; **(c)** the volcanic rifted margin of the southwestern Vøring Plateau which is influenced by the Jan Mayen Fracture Zone (JMFZ); **(d)** the volcanic rifted margin of the northwestern Vøring Plateau; **(e)** the Lofoten Margin. SDR, seaward dipping reflectors. Light grey, post-breakup sediments; dark grey, Inner SDR.

lower reversely polarized series. On the southern part of the Vøring Margin and on the Møre Margin the positive magnetic anomaly matches only the landward boundary of the seismically determined extent of the Inner SDR. In these areas the magnetic anomaly high extends 5–15 km farther seaward than the outer boundary of the Inner SDR.

A small area within the seismically mapped Inner Flows on the Møre Margin shows a positive anomaly both in the gravity and magnetic data, but no anomalies in the seismic data. This indicates that a highly magnetized and dense body is located underneath thin Inner Flows.

Volcanological interpretation

The next step in the interpretation strategy is the volcanological analysis of the mapped volcanic seismic facies units. Drilling results and recent seismic studies (Planke *et al.* 1999, 2000) have led to the following model for the development of the rifted volcanic passive margin segments. They suggest that the volcanic constructions on rifted margin segments develop through five main phases. (1) Initial small-volume volcanism in a wet basin or shallow marine environment. The deposits of this phase are located underneath the Landward Flows (Fig. 6a). (2) Emplacement of large-volume effusive volcanism at seaward propagating volcanic centers creating the Landward Flows. Coeval coastal erosion of the landward termination of the Landward Flows generates a Gilbert-type, volcaniclastic, lava delta between the escarpment and thin basalt flows and volcaniclastic material (Inner Flows) within the former rift valley. (3) Effusive volcanism fills the wedge-formed accommodation space caused by continued subsidence at a seaward propagating central rift zone and creates the Inner SDR. (4) As subsidence continues the eruption vents will eventually submerge beneath sea level and phreatomagmatic eruptions will result in the build-up of hyaloclastic Outer Highs that erode rapidly and create basins filled with volcaniclastic deposits around them. (5) Increasing water pressure finally prohibits explosive volcanism and the last volcanic seismic facies unit emplaced is an Outer SDR consisting of pillow basalts and sheet flows, before volcanism continues as normal oceanic seafloor spreading.

Whereas this interpretation is consistent with the observations on the northern Vøring and central Møre margins, the volcanic seismic facies unit distribution on the Lofoten–Vesterålen Margin indicates a different volcanic development. The Lofoten Margin Flows does not show any planation surfaces on top and its seismic character is very similar to normal oceanic crust. The presence of Outer Highs in the northern and central part of the Lofoten–Vesterålen Margin (Fig. 4) indicates that these areas were in a shallow marine environment during break-up volcanism (Planke *et al.* 2000). We conclude that the major, western part of the Lofoten Margin Flows in the Røst Basin was at greater water depth at the time of breakup volcanism, because the Outer Highs are located at the landward termination of the Røst Basin. A smaller amount of magmatic underplating of the Lofoten–Vesterålen Margin than of the adjacent Vøring Margin with its subaerial deposits is a possible explanation for faster subsidence of this area. Skogseid *et al.* (1992*b*) calculated that crustal thickening by 5 km of underplating results in 1 km less subsidence for otherwise equal crustal configuration.

The southern Vøring Margin differs significantly from the northern Vøring Margin, as it has no Outer SDR and no Outer High. Instead Outer Plains are located between the Inner SDR and normal oceanic crust. Based on the laterally continuous top reflection and the positive gravity anomaly we interpret the Outer Plains as an accumulation of volcanic material which differs from oceanic crust mainly in its thickness. Indications of planation near the Inner SDR might either indicate that this unit formed partly under subaerial conditions (subaerial seafloor spreading) or that an uplift episode occurred after its emplacement. Passing of the Aegir Ridge south of the Jan Mayen Fracture Zone at anomaly 19 time (Skogseid *et al.* 2000) might have provided the necessary heat for a moderate uplift episode. The absence of internal reflections suggests that the Outer Plains does not consist of a pile of flows similar to the Inner SDR or the Landward Flows and the clear signal of continuous north–south-striking magnetic anomalies suggests that this unit might be underlain by oceanic crust. Skogseid & Eldholm (1987) suggested that it was generated at a north–south-striking ridge segment shortly before and after anomaly 23 time. However, parts of the Outer Plains might have formed as the result of renewed volcanism during the passing of the Aegir Ridge. Such a rejuvenation of breakup volcanism is reported for a similar outer corner setting in the Vestbakken Volcanic Province on the western Barents Sea margin (Faleide *et al.* 1998).

The Inner SDR on the southern part of the rifted Vøring Margin consists of two parts (Fig. 4). The northern boundary of the first part coincides with the position of the northeastern segment of the Jan Mayen Fracture Zone which is marked by a pronounced free-air gravity anomaly low (Fig. 7 and Skogseid & Eldholm (1987)). Following the models of Pálmason (1981); Hinz (1981) and Mutter *et al.* (1982), and by assuming that subsidence is the most important process for the development of seaward dipping reflectors, this match suggests that the southern group is emplaced into a local depression. Berndt (2000) infers a pull-apart basin as the reason for this local depression, because of the location between two major strike-slip faults. The southern set of Inner SDR extends not as far seaward as the related magnetic anomalies (Fig. 8). This might indicate that the Inner SDR is covered by the deposits of a subsequent volcanic phase which obscures underlying it. The mismatch is significant, because the Inner SDR elsewhere match the positive magnetic anomaly to a high degree (Schreckenberger 1997).

The Transform Margin Flows is associated with a magnetic anomaly low, which reveals the volcanic origin of this unit. The strong, relatively continuous but generally not planated, top reflection suggests that this seismic facies unit is possibly caused by submarine extrusive rocks. The Transform Margin Flows must be relatively thin as this unit is not associated with a high-amplitude positive free-air gravity anomaly as for example the Landward Flows or the Inner SDR. However, the mismatch between gravity signal and mapped extent of this unit might be partly due to rough seafloor topography that obscures the gravity signal of the Transform Margin Flows. This unit is most prominent at the transition between the Vøring and Møre margins (Figs 5b and 6b).

Syn-break-up tectonomagmatic processes

Volcanic seismic facies units reveal primarily the emplacement environment for the volcanic deposits that result in these units (Planke *et al.* 2000). The difference between subaerial and submarine emplacement environment seems to be the single most important reason for differences in volcanic seismic facies

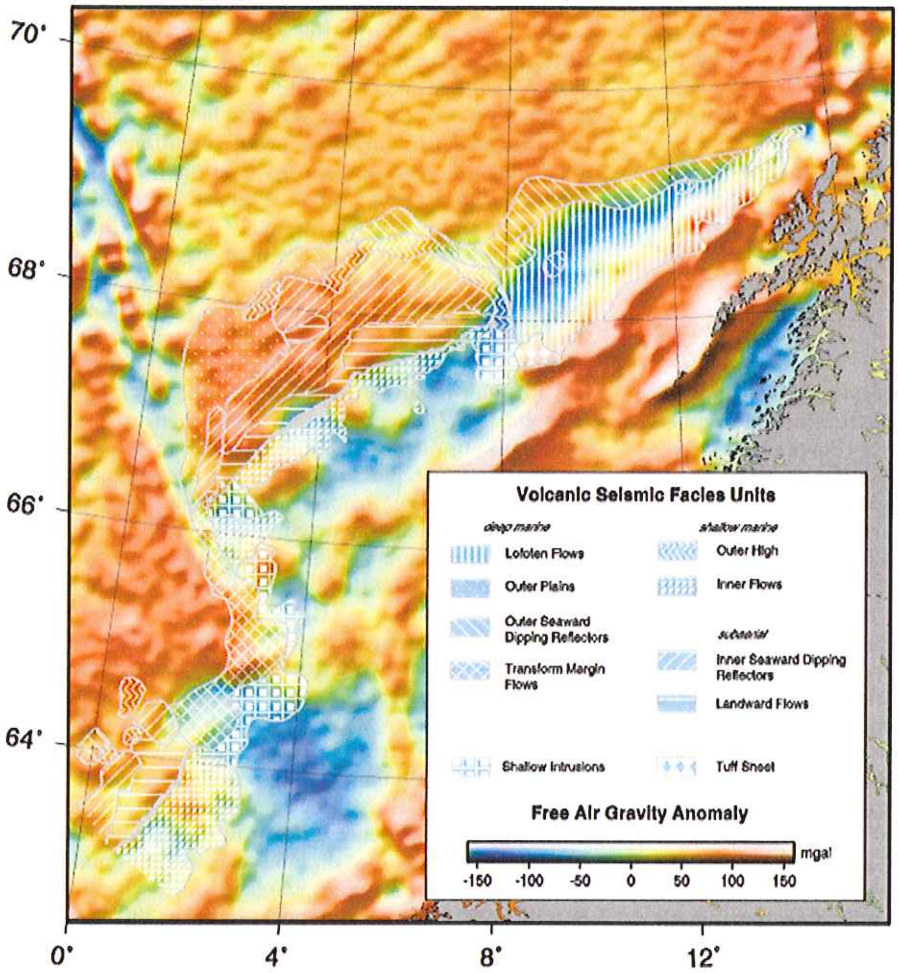


Fig. 7. Free-air gravity anomaly (after Sandwell & Smith 1997) and the distribution of volcanic seismic facies units. Note the strong correlation between high positive gravity anomalies and the Inner SDR and Landward Flows, and high negative gravity anomalies and the Lofoten Margin Flows.

unit distribution. Figure 9 shows the interpreted distribution of subaerial and submarine palaeo-environments along the margin during continental break-up. We identify three principal factors that controlled the palaeoenvironment, and which suffice to explain the main features of the observed lateral variation along the mid-Norwegian margin: the regional variation in the amount of break-up volcanism, the amount of crustal thinning due to extension, and interaction between tectonic and magmatic processes. In addition to these factors Clift & Turner (1995) and Clift (1997) proposed that dynamic uplift related to the Icelandic mantle plume influenced the subsidence history of the northeast Atlantic margins of the area. However, we do not include dynamic uplift in the following considerations because it is a long-wave length phenomenon, and its amount on the Vøring Plateau is ill-defined because of a limited number of age determinations of pre-break-up sediments near the rift axis (Clift *et al.* 1995).

Northward decrease of breakup-related volcanism

The width of the volcanically influenced margin decreases northwards (Fig. 9). Furthermore, Inner SDR and Landward Flows that are related to large amounts of volcanism are confined to the Møre and Vøring margins and lack on the Lofoten–Vesterålen Margin. Seismic wide-angle data Sellevoll *et al.* (1988) further indicates that the Lofoten Margin Flows are thin and that underplating is mainly confined to the Vøring and Møre margin (Eldholm & Mutter 1986; Mjelde *et al.* 1992; Olafsson *et al.* 1992). On a regional scale, the amount of volcanic deposits decreases from the axis of the Faeroe–Iceland Ridge northwards (Eldholm & Grue 1994). Whereas the extrusive successions on the Faeroe–Shetland Margin cover a width of more than 500 km (Eldholm & Grue 1994; Larsen & Saunders 1998; Skogseid *et al.* 2000), their width and volume decrease until they terminate in the north of the Lofoten–Vesterålen Margin. The Vestbakken Volcanic Province on the western Barents Sea margin is detached from the continuous cover of break-up volcanic extrusive rocks south of the western Barents Sea margin (Faleide *et al.* 1993). It is feasible to explain the northward decrease of magmatism by the increasing distance from the Icelandic hotspot (Barton & White 1997), which was located south of the study area during breakup (White & McKenzie 1989; Lawver & Müller 1994). The plume models of White & McKenzie (1989) and Campbell & Griffiths (1990) both predict a decreasing heat anomaly with increasing distance from the plume centre due to radial asthenospheric flow and cooling of the plume head. This, in turn, decreases the potential temperature and the amount of partial melting.

The most voluminous volcanic deposits are associated with Inner SDR and Landward Flows (Planke *et al.* 2000). These volcanic seismic facies units are most abundant on the rifted margin segments of the Møre and Vøring margins (Fig. 4). Whereas the Inner SDR terminates abruptly on the Møre

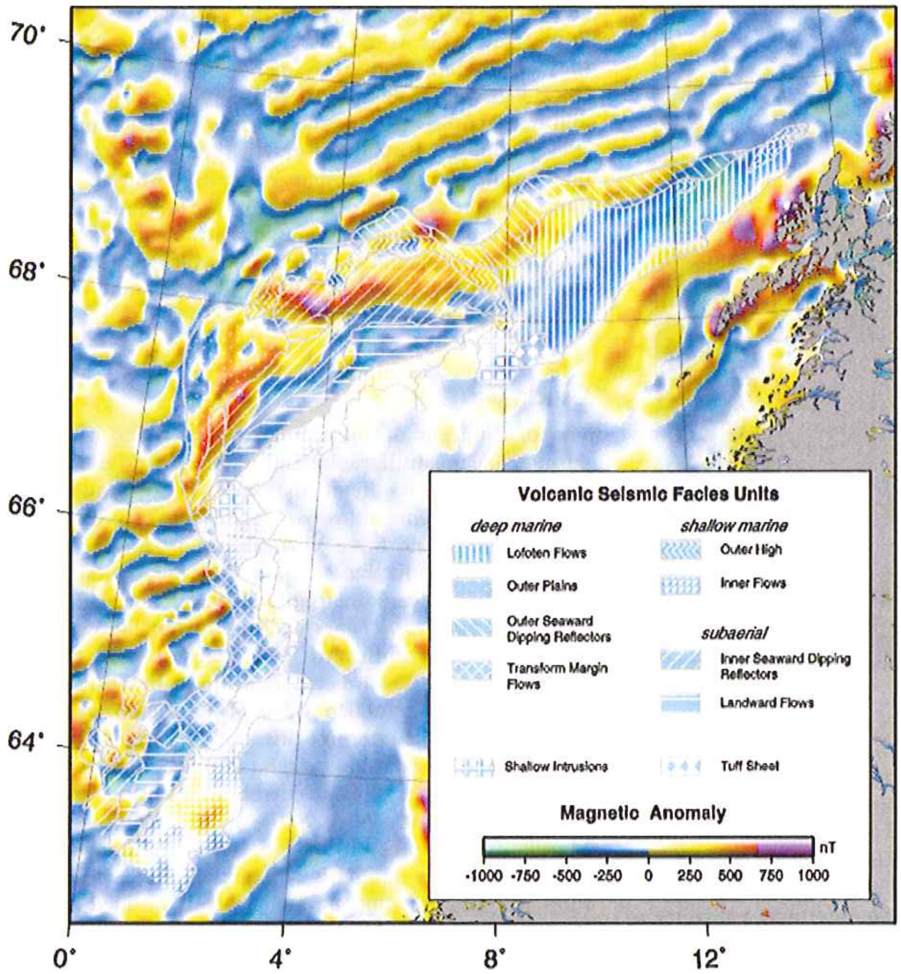


Fig. 8. Magnetic anomalies (after Verhoef *et al.* 1996) and the distribution of volcanic seismic facies units. Note the strong correlation between the landward boundaries of a high positive magnetic anomaly and the landward termination of the Inner SDR. Also note the sharp termination of magnetic seafloor spreading anomalies at the transform margin between the Møre and Vøring Margins.

Margin, they pinch out on the northern and southern Vøring Margin. This might indicate that most magma was supplied at the centres of the rifted Møre and Vøring margins. Although the amount of crustal thickening due to magmatic intrusions (Skogseid *et al.* 1992*a*; Skogly 1998) and magmatic underplating (Eldholm & Mutter 1986; Skogseid *et al.* 1992*a*; Olafsson *et al.* 1992) is less well constrained, it appears that these processes were mainly confined to the Vøring and Møre margins. Skogseid (1994) and White *et al.* (1995) have shown that the emplacement of magmatic material within the crust reduces subsidence significantly. Thus, we ascribe the subaerial emplacement environment of the Inner SDR and Landward Flows in a tectonic setting that is otherwise characterized by extension and subsidence, mainly to this mechanism. We note, however, that little is known about amount of break-up-related volcanic rocks on the conjugate Greenland Margin and a quantitative analysis of the ambient mantle temperature at break-up needs to incorporate this information.

Crustal extension and fragmentation

The amount of extensional crustal thinning is an important control on the subsidence history. Within the study area, the β factor, denoting average crustal thinning, changes from 1.57 to 1.80, from 1.48 to 1.70 and from 2.12 to 2.35 for the Møre, Vøring and Lofoten–Vesterålen margins, respectively (Skogseid 1994). The stretching factors are based on the analysis of subsidence and crustal thickness and take underplating into account. The actual amount of crustal thinning on any given point along the margin depends significantly on the distance to the break-up axis. Taking underplating into account, the area within 50 km of the break-up axis experienced fairly uniform stretching throughout the entire study area (Skogseid 1994). Thus, extensional crustal thinning seems to have contributed little to the observed variations in the initial subsidence of the margin on a margin-wide scale. However, the distribution of Inner SDR and Inner Flows (Fig. 4) suggests that crustal extension and subsidence show pronounced local variations. If the emplacement model of Skogseid & Eldholm (1989) is correct and the wedge shape of Inner SDR results from differential subsidence, their distribution indicates a relatively uniform increase of subsidence towards the central rift zone on the northern Vøring and central Møre Margin. Noteworthy is the split of the Inner SDR on the central Vøring Margin with a non-subsiding area in between (Fig. 4). A possible explanation for this lack of subsidence is the existence of a fragment of continental crust at this location (Fig. 9). The continent–ocean transition is commonly located at the seaward termination of the lowermost seaward dipping reflector, i.e. landward of the gap between the two sets of Inner SDR (Eldholm *et al.* 1989). It is, however, possible that the continental crust and mantle split up into several boudinage-like blocks. Such a splinter of continental material would subside less than the surrounding, cooling

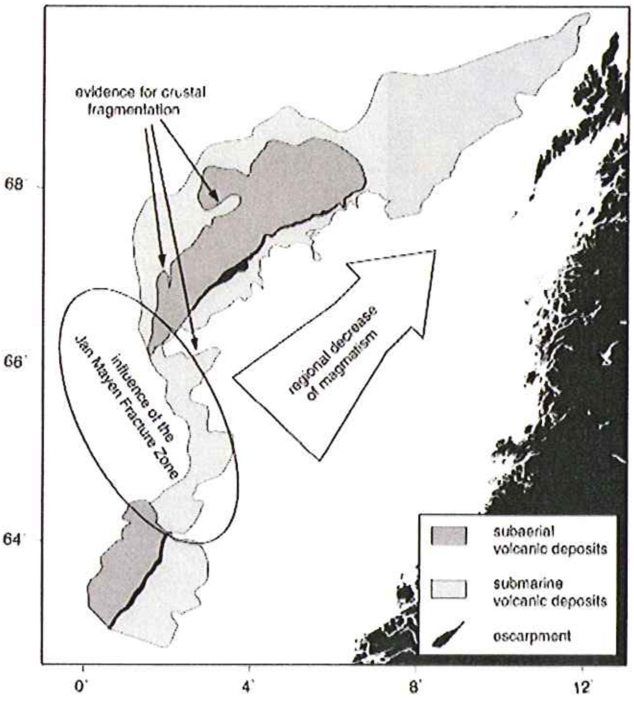


Fig. 9. Simplified emplacement environment and tectono-magmatic processes.

basalts, thereby generating less accommodation space for subsequent flood basalt flows. Crustal fragmentation on the rifted margin segments implies a continent–ocean transition zone with a landward boundary at the last unambiguously identified pre-break-up sediments, and an outermost boundary at the first clear seafloor spreading anomalies. Within this zone, both continental and oceanic crust are likely to exist. Such a wide transition zone is very different from the sharp termination of seafloor spreading anomalies that constitutes the continent–ocean boundary on the transform margin (Fig. 8).

Another indication of crustal fragmentation is the match between the distribution of Inner Flows and gravity anomaly lows. The pre-break-up rifting was concentrated at several margin-parallel extension centers, such as Vigrid Syncline in the central Vøring Basin, Fenris Graben west of the Gjallar Ridge, and the final breakup axis (Skogseid & Eldholm 1989; Doré *et al.* 1999). The structural highs between the extension centres, e.g. Gjallar Ridge, must have acted as barriers for the initial emplacement of the Inner Flows. This mechanism might explain the match between gravity lows and wide Inner Flows.

Influence of the tectonic setting on volcanism

The vicinity of the Jan Mayen Fracture Zone is a pronounced exception to the general trend of northward decreasing and more submarine volcanism which can be explained by increasing distance from the plume and an associated decrease of magmatic crustal thickening (Fig. 9). This area is a good example of the interplay of tectonic and magmatic processes. Berndt (2000) infers that much smaller volumes of volcanic rocks occupy this area than the adjacent rifted margin segments, based on the narrow width of the volcanically influenced area and its low gravity anomaly signal. A possible explanation for this decrease of volcanism is heat conduction across the fracture zone into the adjacent cool continental lithosphere. This would decrease the potential temperature in the melting zone and thus the melt volume (White & McKenzie 1989; Pedersen & Skogseid 1989). Similar processes act along mid-ocean ridges and are collectively named transform fault effects (Phipps Morgan & Forsyth 1988). The transition from the Vøring to the Lofoten–Vesterålen Margin is another important break in the continuity of the volcanic seismic facies unit distribution along the margin. However, we attribute this break from subaerial to submarine volcanism rather to the regional northward decrease of volcanism than to the influence of a fracture zone.

Conclusions

The distribution of breakup extrusive rocks derived from seismic volcanostratigraphy and potential field data interpretation allows us to divide the Møre, Vøring and Lofoten–Vesterålen margins into five segments. The central Møre Margin and the northern Vøring margins show combinations of volcanic seismic facies units that are characteristic for typical rifted volcanic margins. However, the width of *Inner SDR* and *Landward Flows* decreases from the center of the Vøring Margin southward. We conclude that the magma supply decreased towards the Jan Mayen Fracture Zone.

The Lofoten–Vesterålen Margin is characterized by *Lofoten Margin Flows*. We interpret this unit as a result of submarine emplacement based on its rough top reflection and the lack of planation surfaces. This is corroborated by its stratigraphic level close to the *Outer SDR* on the Lofoten–Vesterålen Margin and the presence of two *Outer Highs* at its landward termination. The submarine nature of the Lofoten Margin Flows implies that this margin segment subsided earlier than the margin segments farther south. We interpret this and the absence of Inner SDR and Landward Flows as evidence for a general northward decrease of volcanism.

The presence of two sets of Inner SDR on the central Vøring Margin possibly indicates the presence of a fragment of continental crust subsiding less than the surrounding newly-formed crust and might indicate crustal fragmentation. Other evidence of crustal fragmentation stems from the correlation of the Inner Flows with gravity lows. This correlation possibly indicates that blocks of pre-breakup material existed at the time of the emplacement of the Inner Flows. Such ridges would have imposed barriers against continuous distribution of the Inner Flows.

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