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1. SEISMIC VOLCANOSTRATIGRAPHY OF THE EXTRUSIVE BREAKUP COMPLEXES IN THE NORTHEAST ATLANTIC: IMPLICATIONS FROM ODP/DSDP DRILLING[1]

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ABSTRACT

Seismic reflection data calibrated by scientific boreholes have proven the presence of voluminous early Tertiary extrusive volcanic complexes along the northeast Atlantic continental margins. Seismic facies interpretation of representative seismic profiles reveals the presence of one or more characteristic units of seaward-dipping reflectors (SDR) along most margin segments. Other volcanic seismic facies units, including Inner Flows, Lava Delta, Landward Flows, and Outer High are also identified regionally. More than 15 boreholes have sampled the extrusive volcanic complex, recovering subaerial flood basalts, shallow marine hydroclastites, and pillow lavas. Most of the deep holes are drilled into the Landward Flows unit. However, no well-defined reflectors have ever been penetrated within the extrusive complexes. Several of the volcanic facies units have not been drilled at all, including the Inner Flows and the Lava Delta, and only a few shallow holes have been drilled into the SDR. The nature of the intrabasement reflectivity is therefore presently poorly constrained. Representative seismic transects across the conjugate Southeast Greenland-Hatton Bank margins and the Jan Mayen Ridge-Møre Margin reveal a gross symmetry, as shown by the presence of SDR on all margin segments. In general, however, a lack of symmetry and significant variation in the nature, extent, and volume of the extrusive complexes are apparent. We suggest that the lack of symmetry is largely related to a tectonic control on the emplacement of the lava flows.

INTRODUCTION

Scientific drilling in the northeast Atlantic during the past three decades has been crucial for establishing the presence of voluminous basaltic constructions along more than 2000 km of the ocean's conjugate margins (Fig. 1). These volcanic rocks were erupted in a short period during the early Tertiary continental breakup between Greenland and Eurasia, forming so-called rifted volcanic margins (Eldholm and Grue, 1994). The results from the northeast Atlantic drilling legs have been utilized for interpretation of voluminous volcanic breakup complexes along many of the world's rifted margins (Coffin and Eldholm, 1994). Voluminous volcanism is now regarded as a common response to continental breakup, having potentially important implications for the paleoenvironment and for crustal deformation and growth (Eldholm et al., in press).

Several drilling legs have been devoted to studies of the northeast Atlantic volcanic margins. Initially, the acoustic basement on the Vøring Plateau was found to represent basaltic volcanics in Deep Sea Drilling Project (DSDP) Sites 338, 342, and 343 (Talwani, Udintsev, et al., 1976). Similarly, basalts were recovered in the shallow-basement penetrating DSDP Sites 552–555 on the Rockall Margin, suggesting that the intrabasement seaward-dipping reflectors (SDR) and the Outer High represented subaerial and shallow-marine volcanic constructions, respectively (Roberts, Schnitker, et al., 1984). Later, more than 900 m of subaerial lavas were drilled at Ocean Drilling Program (ODP) Site 642 near the apex of the SDR on the Vøring Margin (Eldholm, Thiede, Taylor, et al., 1987; 1989). Recently, seven ODP sites were drilled to as much as 779 m into basaltic basement on the Southeast Greenland Margin, recovering dominantly subaerially emplaced lava flows (Larsen, Saunders, Clift, et al., 1994; Duncan, Larsen, Allan, et al., 1996).

Seismic reflection data are essential for extrapolating the detailed geological information provided by the boreholes in two and three dimensions. Unfortunately, seismic reflection data are often of poor quality in volcanic terrains. This is related to large acoustic impedance contrasts and rough structures, both between the sediments and underlying lavas and within the basaltic lava piles because of large changes of physical properties within individual lava flows (Planke and Eldholm, 1994). Recently, fairly high-quality reflection images have been obtained within and below the volcanic pile in different volcanic provinces (Symonds et al., 1998; Alvestad, 1997). These improved intrabasement reflectivity images have led to the development of the concept of seismic volcanostratigraphy (Fig. 2).

The aim of this study was to reassess and reinterpret seismic reflection data in the vicinity of boreholes penetrating breakup volcanic rocks in the northeast Atlantic. Special emphasis was on the constraints that the well data provide for interpretation of characteristic seismic facies units identified in volcanic terrains. An understanding of the cause and significance of the variations in reflection patterns is important for understanding the nature and severity of tectonic and volcanic processes that occurred during continental breakup and the early phase of seafloor spreading. The study focus was on using the recent drilling and seismic data from the Southeast Greenland Margin, both locally and along a conjugate margin transect. Furthermore, these results were compared with a conjugate margin transect to the north crossing the southern Jan Mayen Ridge and the central Møre Margin (Fig. 1). The northern and southern transects are located at a similar distance from the Iceland plume trail but show distinctly different seismic volcanic reflection characteristics.

DATA AND METHODS

Only a few wells in the northeast Atlantic have penetrated extrusive breakup volcanics imaged by seismic reflection data. Of the 15 relevant ODP/DSDP basement sites, only Sites 642 and 917 have drilled more than 250 m into the volcanic basement (Fig. 1). Voluminous extrusive complexes are exposed in the British Tertiary Volcanic Province, on central east Greenland, and on the Faeroe Islands (Saunders et al., 1997) and provide an important reference for the interpretation of the offshore volcanics. Breakup-related intrusive complexes and sills have been penetrated by more than 15 industry wells

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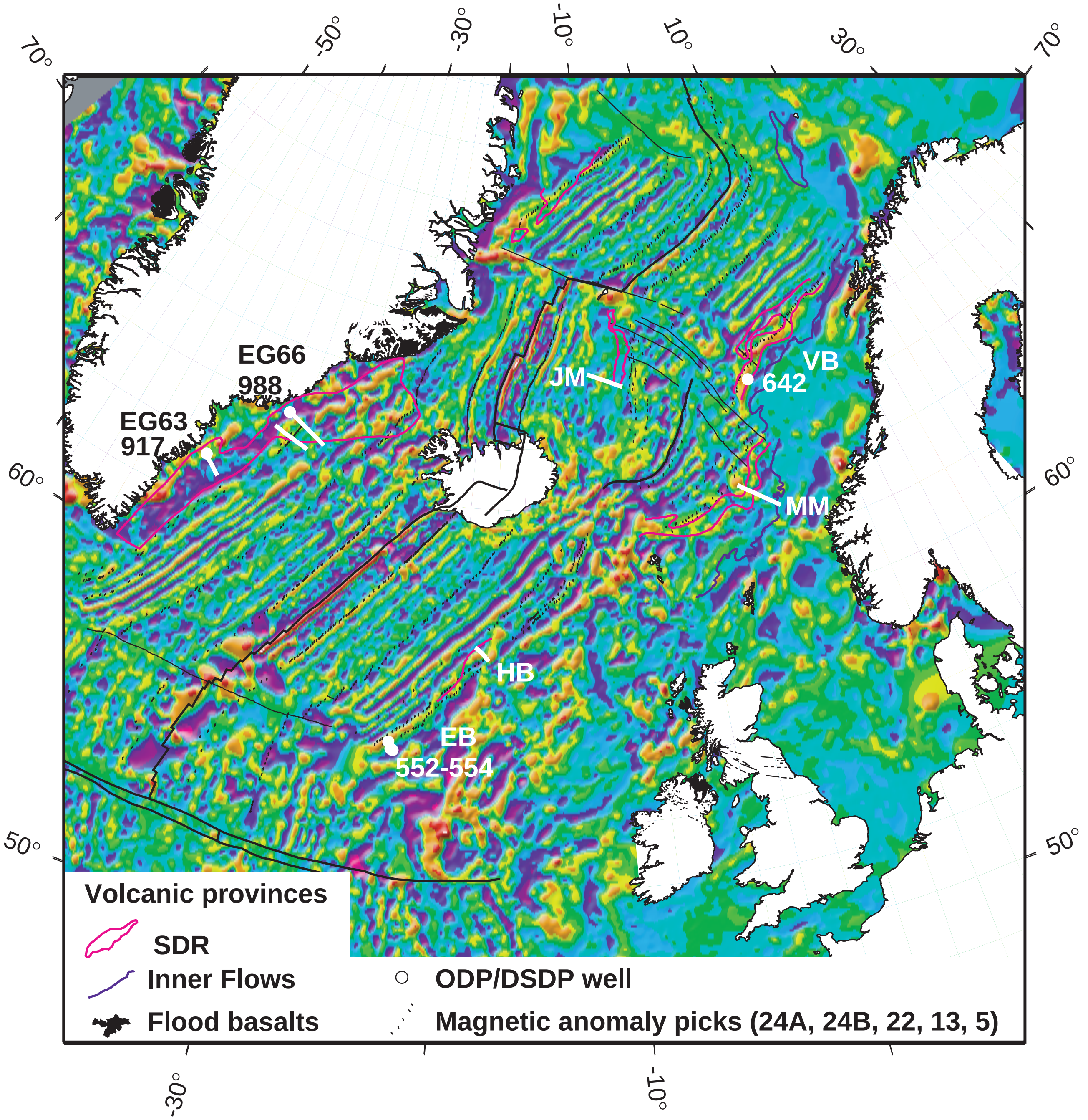
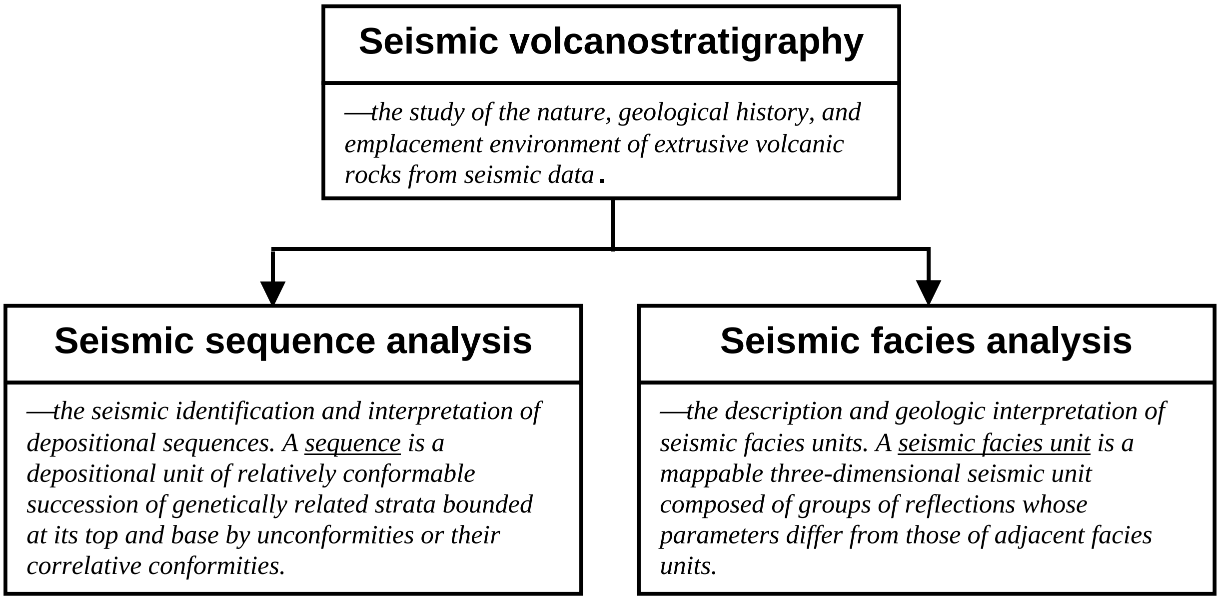


Figure 1. Magnetic anomaly map of the northeast Atlantic, showing main structural and magmatic features, selected drill sites penetrating breakup volcanics, and location of seismic profiles. Shown are DSDP Sites 552–554 (Roberts, Schnitker, et al., 1984), ODP Site 642 (Eldholm, Thiede, Taylor, et al., 1987), and Transects EG63 and EG66 (Larsen, Saunders, Clift, et al., 1994; Duncan, Larsen, Allan, et al., 1996). EB = Edoras Bank, HB = Hatton Bank Margin, JM = Jan Mayen Ridge, MM = Møre Margin, VB = Vøring Basin. Magnetic data from Verhoef et al. (1996).

west of Shetland and one in the Vøring Basin (Skogly, 1998; K. Hitchen, pers. comm., 1997) but have not been considered in this study.

Only key well-tie and conjugate margin transects are presented and discussed in this study. On the Southeast Greenland Margin, five regional multichannel seismic (MCS) profiles from the GGU-81 and -82 surveys, in addition to a regional grid of high-resolution seismic data along the EG63 and EG66 transects, were reinterpreted (Fig. 1) (Duncan, Larsen, Allan, et al., 1996). On the Møre Margin 12 regional, high-quality MCS reflection profiles were interpreted within a 150-km-wide margin corridor (Alvestad, 1997). Published reflection data and line drawings were assessed for the Jan Mayen Ridge (Åkermoen, 1989), the Vøring Margin (Eldholm, Thiede, Taylor, et al., 1987, 1989; Planke and Eldholm, 1994), and the Rockall Margin (Roberts, Schnitker, et al., 1984; White et al., 1987; Neish, 1993; Barton and White, 1997a, 1997b).

Various methods have previously been used for interpreting the top- and intrabasement seismic reflection patterns on volcanic margins. Initially, characteristic basement reflection configurations were used to map four basement provinces on the Vøring Margin, repre-



Seismic volcanostratigraphy

—the study of the nature, geological history, and emplacement environment of extrusive volcanic rocks from seismic data.

Seismic sequence analysis

—the seismic identification and interpretation of depositional sequences. A sequence is a depositional unit of relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities.

Seismic facies analysis

—the description and geologic interpretation of seismic facies units. A seismic facies unit is a mappable three-dimensional seismic unit composed of groups of reflections whose parameters differ from those of adjacent facies units.

Figure 2. Definition of key terminology in seismic volcanostratigraphy. This study is primarily concerned with seismic facies analysis. From Planke et al. (in press) based on the concept of seismic stratigraphy (Mitchum et al., 1977).

senting I = Inner Flows; II = irregular basement between the SDR and the Vøring Escarpment; III = SDR; and IV = normal oceanic basement (e.g., Hinz et al., 1982; Skogseid and Eldholm, 1987, 1989). Elsewhere, aspects of seismic stratigraphic have been used, for example, on the Southeast Greenland Margin and around the Faeroe Islands (Larsen and Jakobsdóttir, 1988; Andersen, 1988). Here, we have used the seismic volcanostratigraphic approach (Fig. 2; Table 1) (Planke et al., in press). The entire breakup-related volcanic complex landward of normal oceanic crust has been defined as one seismic sequence. However, the interpretation focus has been on the characterization and mapping of volcanic seismic facies units, which are calibrated by borehole data. This approach provides for a more detailed interpretation of the structure and morphology of the volcanic constructions, being particularly useful because improved seismic data quality of the volcanics has revealed a more complex internal seismic pattern than previously imaged.

VØRING AND ROCKALL MARGIN WELL-TIES

Site 642 on the Vøring Margin penetrated a more than 750-m-thick upper series of tholeiitic basalts and terminated in a more than 100-m-thick lower series of andesites and dacites (Eldholm, Thiede, Taylor, et al., 1987). Identified in the hole were 137 lava flows and 63 thin interbedded sedimentary units. Downhole data reveal characteristic changes in seismic properties within the flow units, with low *P*-wave velocities in the flow top (2.5–3 km/s) and high *P*-wave velocities in the lava interior (5–6 km/s) (Planke, 1994).

Seismic reflection data over Site 642 show a well-defined high-amplitude, rough top-basement reflector at about 2.15 s (Fig. 3A). No coherent reflectivity is found in the following 0.35-s interval, but a positive reflector at 2.5 s can be correlated with reflector K, which is the base of the SDR unit. Synthetic seismogram modeling suggests that K is an interference reflector originating from two thick flow units near the base of the upper series, not the upper/lower series transition (Planke and Eldholm, 1994). Seismic facies interpretation of profile BGR74-1 shows that Site 642 is located within the Landward Flows facies unit, a few kilometers east of the termination of the SDR (Fig. 3A). It is not possible to correlate reflectors from the SDR to the Landward Flows, with the exception of the top and base reflector.

DSDP Leg 81 was designed to drill a representative transect across a volcanic rifted margin, and volcanic basement was reached at Sites 552–555 (Fig. 1) (Roberts, Schnitker, et al., 1984). The sites were located on the flank of the Outer High (Site 554) and within the SDR (Site 553) and the Landward Flows (Site 552) (Fig. 3B). Site 552 terminated 31 m into the basement, penetrating only one thick, massive basaltic unit, which was possibly deposited in a marine environment. Farther seaward, a 181.5-m-thick basaltic pile was drilled at Site 553. Thirty-four basalt units were identified, with an average thickness of ~6 m. The basaltic lava flows frequently had red flow tops suggesting subaerial weathering. In addition, a 1-m-thick submarine tuffaceous hyaloclastite unit was recovered from the basement section. Site 554 drilled 82 m into basement on the flanks of the Outer High, with a recovery of only 16%. Pillow-lava fragments, submarine hyaloclastites, and coastal eroded and deposited volcaniclastic conglomeratic and sandy sedimentary rocks were recovered.

None of the Rockall Margin holes penetrate any reflectors below the top-basement event, and thus they cannot provide direct information about the nature of the intrabasement reflectivity. However, Sites 552–553 show that the upper part of the Landward Flows and SDR may consist of subaerial or shallow-marine–deposited basaltic lavas, and that hydroclastic material also may be present. Site 554 reveals that the Outer High has a strikingly different volcanic morphology, consisting of hyaloclastites, fragmented basalts, and coastal eroded volcaniclastic rocks deposited in a near-shore environment.

SOUTHEAST GREENLAND–HATTON BANK TRANSECT

Southeast Greenland Transect EG63

Six basement-penetrating drill sites are located along the EG63 transect on the Southeast Greenland Margin (Fig. 1). Five sites are located near the landward termination of the volcanic complex, whereas Site 918 is located within the main SDR unit. Both conventional MCS and high-resolution seismic data are available on the margin (Figs. 4, 5) (Larsen and Jakobsdóttir, 1988; Larsen and Saunders, 1998).

Two well-defined SDR units are imaged on profile GGU-81-08, separated by a 20-km-wide zone with more disrupted intrabasement

Table 1. Dominant characteristics of the main volcanic extrusive seismic facies units on rifted volcanic margins.

Seismic facies unit	Reflector characteristics			Volcanic facies	Emplacement environment
	Shape	Boundaries	Internal		
Outer SDR	Wedge	Top: high-amplitude, smooth being onlapped. Pseudo-escarpments. Base: seldom defined.	Divergent-arcuate or -planar. Disrupted, non-systematic truncations.	Flood basalts mixed with pillow basalts, sediments and sills.	Deep marine
Outer high	Mound	Top: high-amplitude being onlapped. Often planated. No base.	Chaotic.	Hyaloclastic flows and volcaniclastics.	Shallow marine
Inner SDR	Wedge	Top: high-amplitude, smooth being onlapped. Pseudo-escarpments. Base: seldom defined.	Divergent-arcuate. Disrupted, non-systematic truncations.	Flood basalts.	Subaerial
Landward flows	Sheet	Top: high-amplitude, smooth being onlapped or concordant. Base: low-amplitude, disrupted.	Parallel to subparallel. High-amplitude, very disrupted.	Flood basalts.	Subaerial
Lava delta	Bank	Top: high-amplitude, or reflector truncation. Base: reflector truncation.	Prograding clinoform. Disrupted.	Massive and fragmented basalts. Volcaniclastics.	Coastal
Inner flows	Sheet	Top: high-amplitude, disrupted, being onlapped or concordant. Base: negative polarity but often obscured.	Chaotic or disrupted, subparallel.	Massive and fragmented basalts. Volcaniclastics.	Subaqueous

Note: Data from Planke et al. (in press).

reflectivity (Fig. 4). Distinct reflectors are typically 5 to 10 km long, with a vertical extent of up to 1.5 s. The reflectors terminate upward at, or merge with, the top-basement reflector. Site 918 was drilled 121 m into the volcanic basement, recovering 21 basaltic lava flows (Larsen, Saunders, Clift, et al., 1994). Deep, subaerial weathering affected the top three units, while several recovered red flow tops within the entire basement interval indicate persistent subaerial conditions during construction of the lava pile.

The top-basement reflector can be traced landward from the SDR until it intersects the seafloor near the western end of profile GGU-81-08 (Fig. 4). Segmented, low-frequency reflectors characterize the interval below the top-basement reflector landward of the SDR. Both the seafloor and the top-basement represent high acoustic impedance contrast boundaries, causing numerous short- and long-path multiples and converted waves in the shallow-water part of the profile. Much of the intrabasement reflectivity is therefore interpreted as non-primary energy. The relatively smooth, high-amplitude nature of the top-basement reflector and its position landward of the SDR lead us to define this seismic facies unit as the Landward Flows.

High-resolution seismic data along the inner part of the EG63 transect show characteristics similar to the conventional MCS data (Fig. 5). A smooth, high-amplitude top-basement reflector is easily identified, showing characteristic irregular down-to-northwest stepping at the seafloor and between Sites 989 and 917. Deeper intrabasement reflectivity is segmented and irregular, with an overall seaward dip. A weak basal reflector can be identified in some places but is largely obscured by strong seafloor multiples. The reflector was drilled at Site 917 where it was found to be the base of the volcanic complex (Larsen, Saunders, Clift, et al., 1994). The basement is divided into two slightly different units southeast of Site 990, with the upper unit having a somewhat better-defined internal reflector pattern. Landward, the reflector pattern clearly changes below and northwest of Site 989, where well-defined, steeply landward-dipping reflectors are imaged down to about 0.9 s.

Site 917 penetrated 779 m of subaerially emplaced basalts and dacites of a late Paleocene age and terminated in a steeply inclined metamorphosed sedimentary section of possibly Paleocene age (Larsen, Saunders, Clift, et al., 1994; Larsen and Saunders, 1998). Wireline log data reveal a similar characteristic impedance structure as on Site 642, with low-velocity and low-density lava tops (Vp ~2.5–3 km/s, ρ ~2.2–2.4 g/cm^3) and high-velocity lava interiors (Vp ~5–6 km/s, ρ ~2.8–3.0 g/cm^3) (Planke and Cambray, 1998). At Site 917, the top-basement reflector clearly represents the top of the lava pile, while the southeastward-dipping reflector at 1.13 s is interpreted as the base of the volcanics (Fig. 5). Few coherent reflectors are identified within the volcanic sequence, and no primary reflectors can be interpreted with confidence.

The four shallow basement sites along the inner part of the EG63 transect (Sites 915, 916, 989, and 990) all terminated within the volcanic pile, and numerous subaerially emplaced basaltic lava flows were recovered from them. No intrabasalt reflectors were penetrated at any of these sites. Site 989 almost reached a reflector at 0.68 s depth (Fig. 6) but was terminated at 84 mbsf. Two flow units were drilled, the upper was a 69-m-thick, compound, massive basalt, while the lower was >11-m-thick massive lava. The negative-polarity reflector just below the termination of the hole is interpreted to represent the base of this flow unit (Fig. 6). The nature of the underlying rocks is undetermined but may correspond to low-velocity, thin lava flows, or pre-breakup sediments as drilled at Site 917 and interpreted to be present farther west. The great thickness of the composite flow unit may be related to lava ponding. No weathered top was recovered from this unit. It was probably removed by glacial erosion, leaving the more resistant interior. The southwest end of the flow unit is clearly identified at shotpoint (SP) 450 (Fig. 6) as a 30-m-high erosional escarpment. The northwestward stepping of the top-basement reflector on Fig. 5 is interpreted to represent similar erosional features, forming on of the characteristic “trapps” (stairs) frequently found in flood-basalt provinces. These staircase-like erosional features are typically developed in interlayered hard and soft rocks, such as flood-basalt constructions with soft lava tops and hard lava interiors.

Southeast Greenland Transect EG66

One well-defined SDR unit is imaged on the composite EG66 transect (Fig. 7). The unit is ~50 km wide, with a high-amplitude, undulatory top-basement reflector. The top-basement reflector is locally onlapping or interfering with intrabasement reflectors (e.g., near SP 2000; Fig. 7). Seaward, the top-basement reflector becomes more segmented and chaotic, forming a buildup near the southeastern termination of the profile. A basal reflector is identified below the inner part of the SDR (GGU-82-02, SP 1000–1400; Fig. 7). Internal reflectors are characterized by an overall divergent/arcuate pattern with short, segmented reflectors continuing down to about 1.5 s below the top-basement. The SDR unit is clearly not continuous along the strike of the margin, as no well-defined SDR can be identified on the seaward continuation of profile GGU-82-01 ~50 km to the north (Figs. 1, 7).

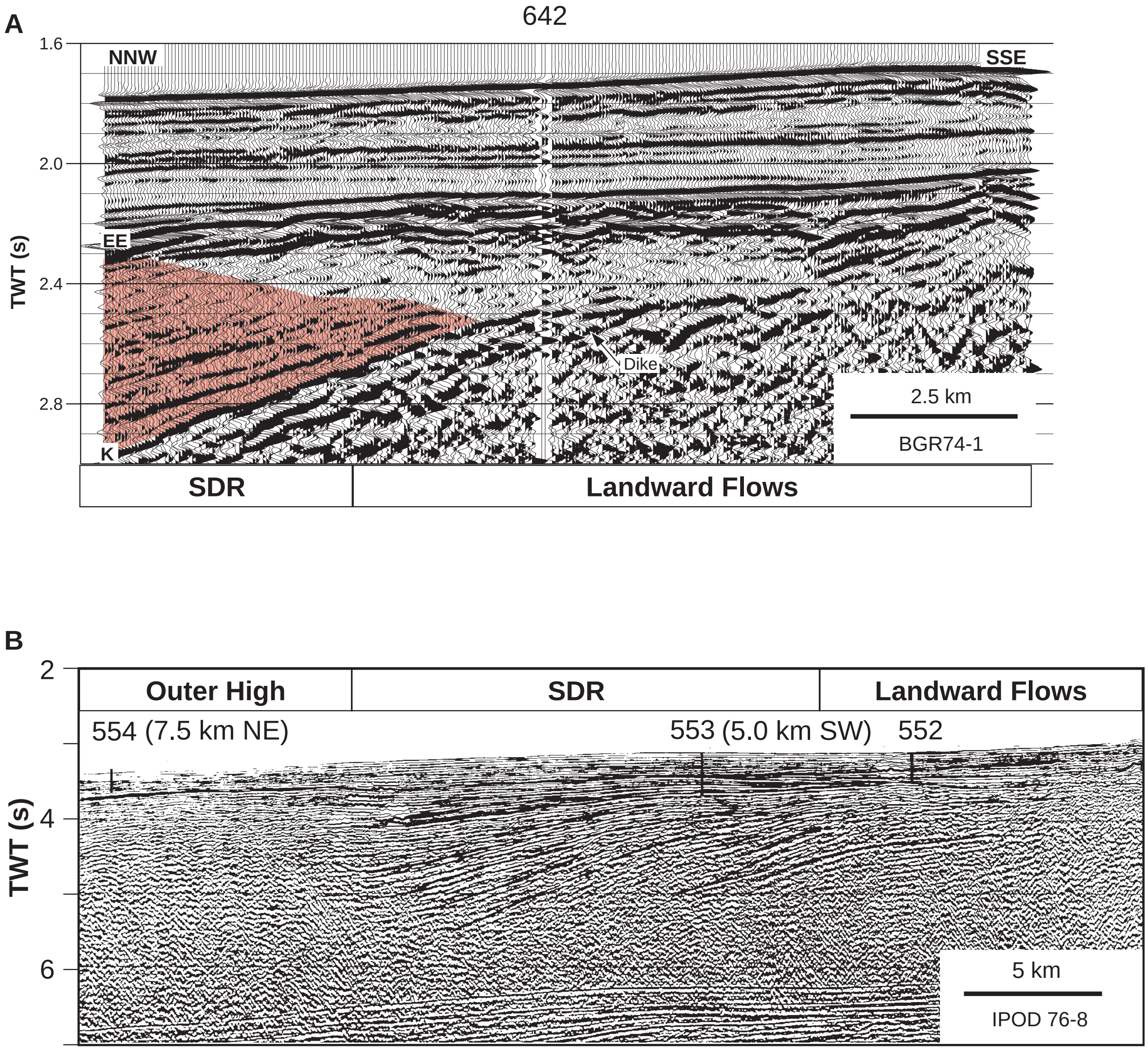


Figure 3. Seismic profiles across boreholes penetrating extrusive volcanics. **A.** ODP Site 642 on the Vøring Margin, modified from Planke and Eldholm (1994). **B.** DSDP Sites 552–554 on the Edoras Bank Margin, modified from Roberts, Schnitker, et al. (1984). EE = top-basement, K = base-SDR.

A wide Landward Flows unit is primarily identified based on the nature of the top-basement reflector (Fig. 7). This reflector is a high-amplitude, smooth event identified landward of the SDR. The reflector becomes rougher and more segmented just before intersecting the seafloor near the northwest termination of profile GGU-82-01. The top-basement reflector identified on high-resolution data (Fig. 8) shows a down-to-northwest stepping pattern interpreted as erosional escarpments (trapps) along the EG63 transect. The intrabasement reflectivity is dominated by nonprimary energy related to short- and long-path multiples and converted waves, and hardly any coherent events can confidently be interpreted as primary reflectors. The base of the facies unit is only identified near the SDR/Landward Flow transition (GGU-82-02, SP 1500–1800) and below the region where the unit is subcropping at the seafloor (Fig. 7).

Conjugate Hatton Bank Transect

The Rockall Margin is conjugate to the Southeast Greenland Margin, as shown by the well-defined symmetric magnetic lineation pattern to at least Anomaly 22 time on both sides of the spreading axis (Fig. 1) (Skogseid et al., in press). The seismic data from the Edoras Bank and Hatton Bank margins reveal characteristic SDR on most profiles (White et al., 1987; Barton and White, 1997a, 1997b). Additionally, a several-hundred-kilometer-wide zone landward of the SDR is covered by breakup-related volcanic extrusive and shallow intrusive rocks (Joppen and White, 1990; Neish, 1993).

The Hatton Bank Margin profiles are approximately conjugate to the Southeast Greenland Margin EG63 transect (Fig. 1). Interpretative line drawings show several major similarities and differences on the conjugate margins (Fig. 9A). The Hatton Bank Margin profile shows two SDR units separated by an Outer High (Fig. 9A). Two SDR units are also identified on EG63. The characteristic Outer High is not identified (Fig. 4) but likely corresponds to the hummocky-type basement mapped seaward of magnetic Anomaly 24B by Larsen and Jakobsdóttir (1988). The external shape and internal reflector characteristics of the SDR are quite different. The Hatton Bank Margin profile is dominated by a wedge-shaped unit with divergent reflector segments. In contrast, the EG63 transect reveals a more rhombic-shaped unit, where the arcuate intrabasement reflector segments are dominantly subparallel.

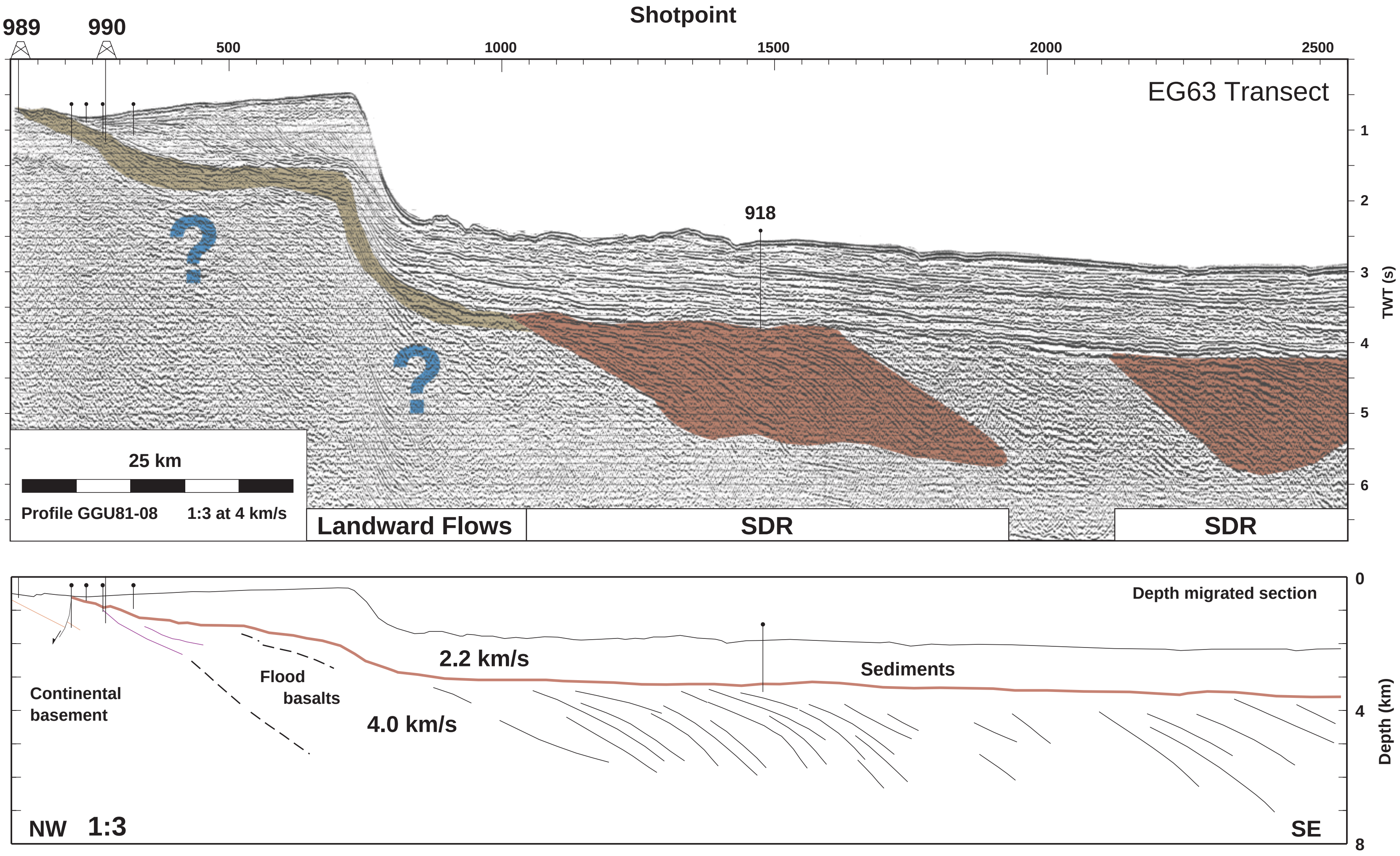


Figure 4. Interpreted and depth-converted MCS reflection profile along the EG63 transect. Ball-and-line symbols = Legs 152 and 163 sites. Based on Duncan, Larsen, Allan, et al. (1996).

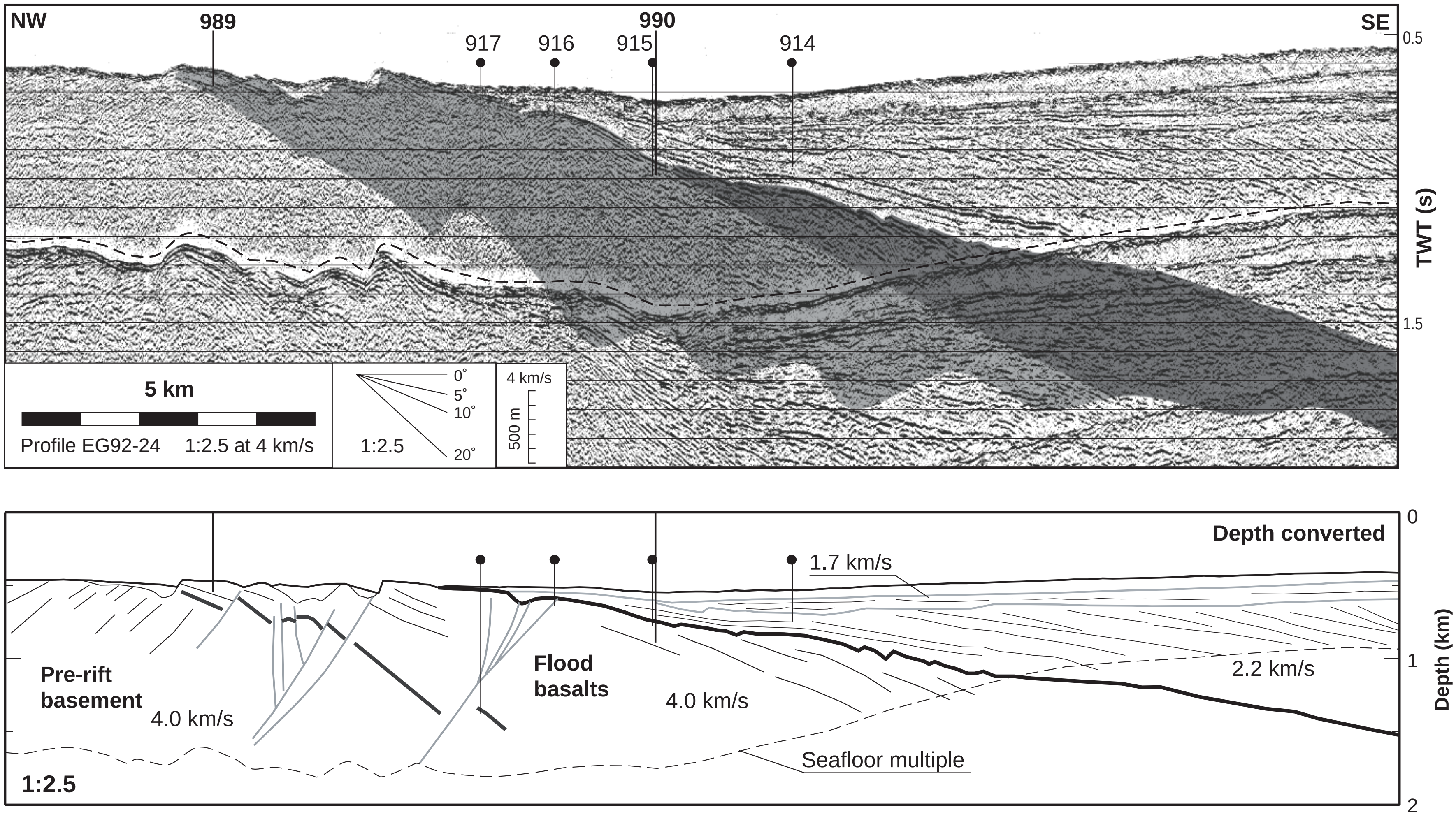


Figure 5. Interpreted and depth-converted high-resolution seismic reflection profile along the inner part of the EG63 transect. Based on Duncan, Larsen, Allan, et al. (1996).

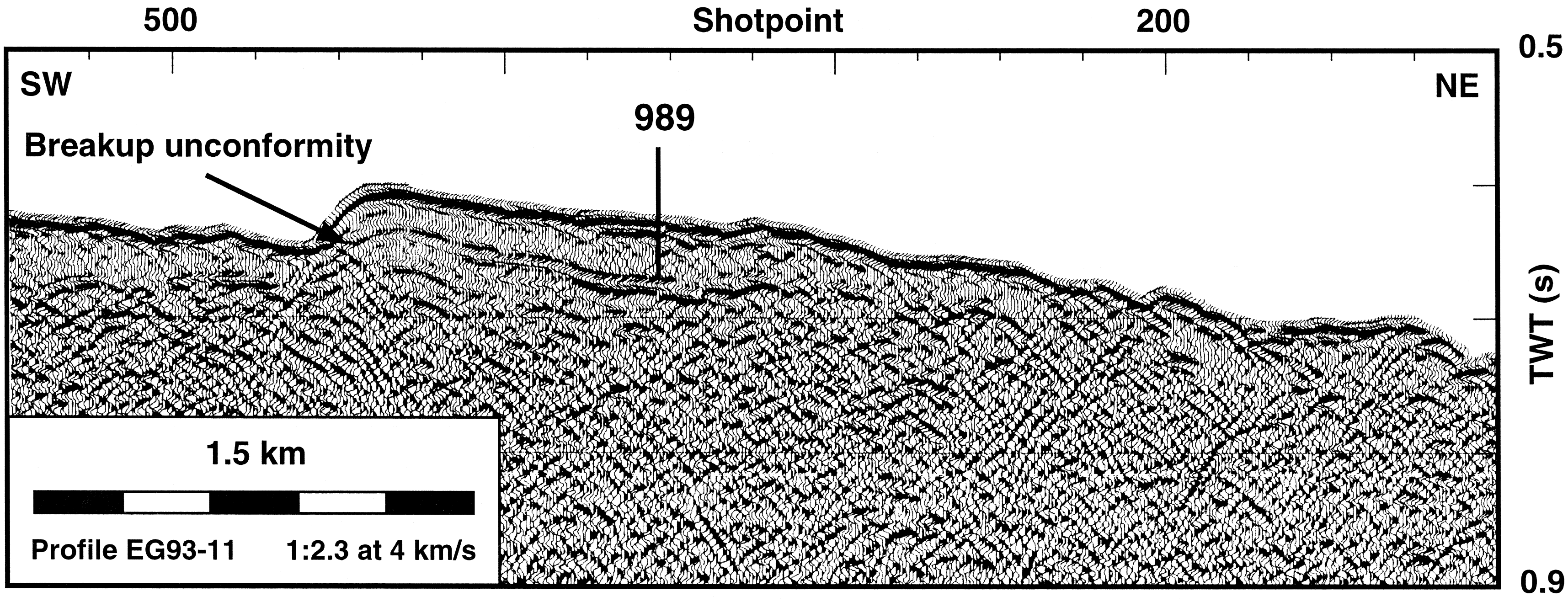


Figure 6. High-resolution seismic strike profile across the inner part of EG63 transect. Based on Duncan, Larsen, Allan, et al. (1996).

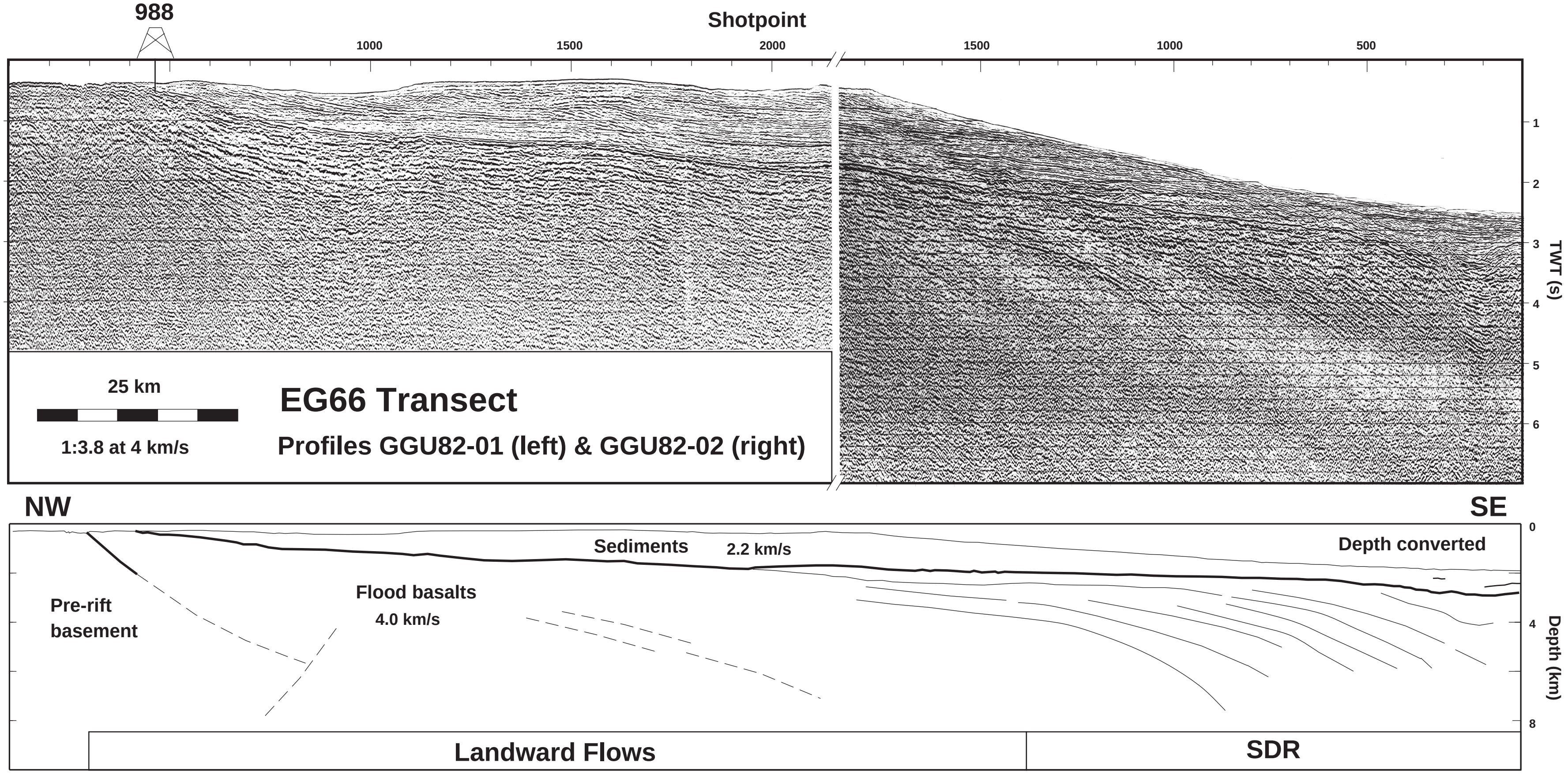


Figure 7. Interpreted and depth-converted composite MCS reflection profile along the EG66 transect. Based on Duncan, Larsen, Allan, et al. (1996).

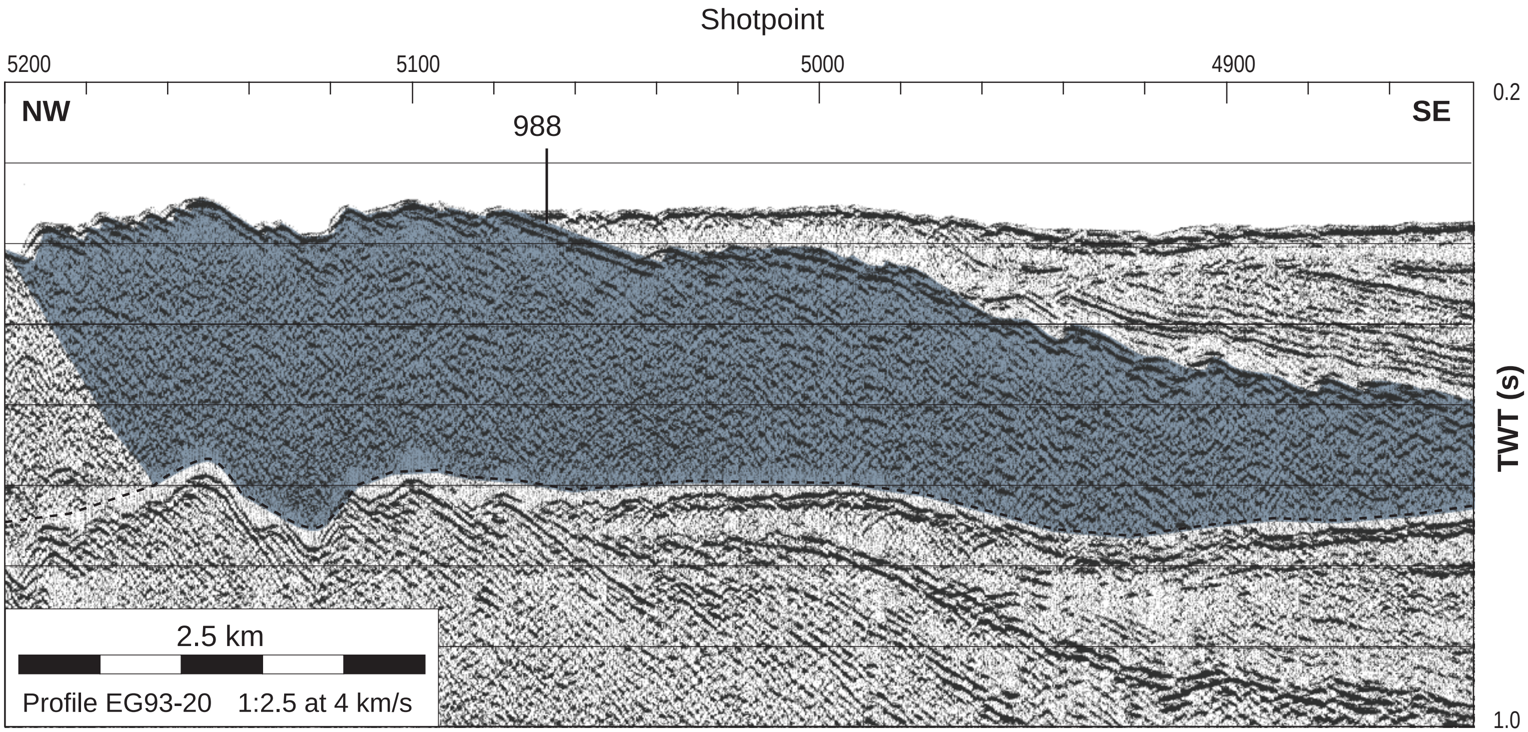


Figure 8. Interpreted high-resolution seismic reflection profile along the inner part of the EG66 transect. Based on Duncan, Larsen, Allan, et al. (1996).

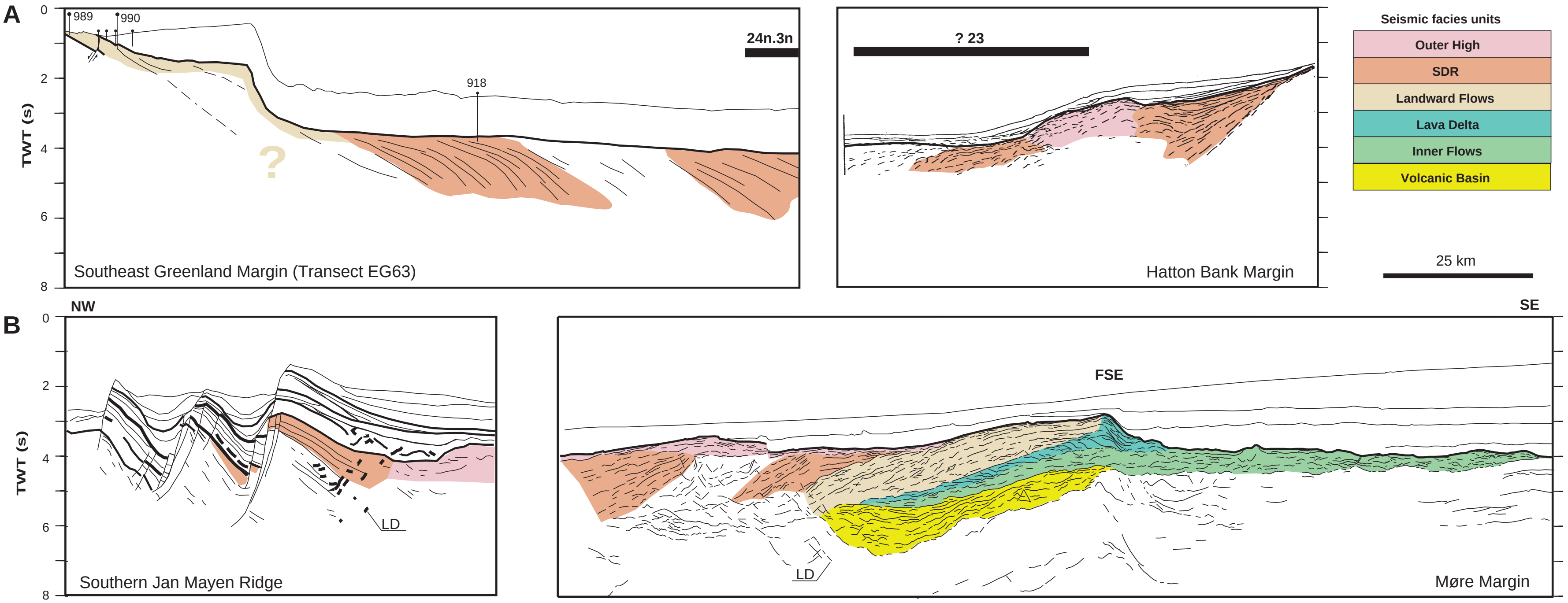


Figure 9. Interpretive line-drawings showing main seismic facies units on representative conjugate margin profiles. See text for references and discussion. LD = landward-dipping reflectors; FSE = Faeroe-Shetland Escarpment.

Landward, reflection data on both margins have high noise levels related to multiple and converted energy in relatively shallow-water environments. The subsequent post-breakup margin development has further influenced the ability to image intrabasement structures. In particular, the deposition of prograding glacial sediments on the Southeast Greenland Margin has locally degraded the intrabasement images (e.g., near SP 750 on profile GGU-81-08; Fig. 4). Further, erosion has reduced the initial landward extent of the volcanics off East Greenland.

JAN MAYEN RIDGE-MØRE TRANSECT

A regional grid of high-quality MCS data on the Møre Margin has provided more detailed structural information of the extrusive breakup complex here than presently available offshore elsewhere in the northeast Atlantic (Alvestad, 1997). However, volcanics have never been drilled on the margin. The drilling results from elsewhere in the northeast Atlantic are important for constraining the seismic volcanostratigraphic interpretation of the Møre Margin profiles, whereas the high-quality data from the Møre Margin can provide constraints for understanding the volcanic history of less well-imaged margin segments. In addition, the Møre Margin and EG63 transects are situated at a similar distance from the Iceland plume trail (Fig. 1). Previous studies have suggested that there is an overall relationship between melt production and the distance to the main plume source (Barton and White, 1997b), providing an additional reason for comparing the two margin transects.

Several distinct seismic facies units are identified on the Jan Mayen Ridge and Møre Margin profiles (Fig. 9B)—the SDR, Outer High, and Landward Flows are interpreted as being on the Southeast Greenland-Hatton Bank transect. However, Lava Delta, Inner Flows, and Volcanic Basin units are also identified below and landward of the SDR. Finally, a set of segmented, steeply landward-dipping reflectors are interpreted below the Outer High and within the main part of the SDR.

The seismic facies units on the Møre Margin have been interpreted in terms of volcanic eruption and emplacement environment (Table 1) (Alvestad, 1997). Landward Flows are penetrated at the deep Sites 917 and 642, where they represent subaerially erupted and emplaced volcanics. The Lava Delta unit has not been penetrated by any drill holes but is interpreted to represent a volcaniclastic lava delta formed as subaerially erupted lavas reached a paleo-shoreline. This interpretation is compatible with the hypothesis that the Faeroe-Shetland Escarpment is a coastal feature (Smythe et al., 1983). Hydroclastite lava delta constructions are found exposed, for example, on Nuussuaq Island off western Greenland (Pedersen et al., 1996), and are well developed along the coastline of Hawaii (Moore et al., 1973). The Inner Flows are interpreted as dominantly hydroclastite deposits consisting of a mixture of massive and fragmented basalts. Together, the three facies units form a coarse-grained Gilbert-type clastic delta, where the Landward Flows, Lava Delta, and Inner Flows represent the top-set, fore-set, and bottom-set facies of the delta.

Two SDR units are identified on the transect across the Møre Margin, where the seaward one is overlaid by an internally stratified Outer High. Based on the drilling results elsewhere in the northeast Atlantic, the SDRs are interpreted as dominantly subaerially emplaced and erupted basalts, while the stratified Outer High is interpreted as consisting of shallow-marine volcaniclastics. The deeper landward-dipping reflectors are not drilled anywhere but are interpreted as feeder dikes that likely followed weakness zones such as fault planes. The dikes may originally have been emplaced as near-vertical feeders but have acquired their landward dip by synconstructional margin flexuring and subsidence.

On the Jan Mayen Ridge, the conjugate seismic profile is located near the southernmost part of the mapped SDR (Fig. 9B) (Åkermoen, 1989). A thin SDR unit is identified here, terminating near a broad Outer High. The apex of the SDR was later faulted, probably occurring when the Jan Mayen Ridge broke off East Greenland during the mid-Tertiary (Gudlaugsson et al., 1988; Eldholm et al., 1990). Landward-dipping reflector segments below the SDR, similar to those found on the Møre Margin, have been interpreted as a feeder dike system on the Jan Mayen Ridge (Åkermoen, 1989).

DISCUSSION

Nature of Seismic Reflectivity

The nature of the intrabasement reflectivity on volcanic rifted margins is largely unconstrained (Planke and Eldholm, 1994; Barton and White, 1997b; Smallwood et al., 1998). Currently, only the Landward Flows unit has been sampled by several deep drill holes. Only a few, very shallow holes have been drilled into the SDR, and only one hole has recovered material from the Outer High. None of the other seismic facies units have been sampled. Moreover, none of the northeast Atlantic drill holes have penetrated any well-defined intrabasalt reflectors, with the exception of reflector K, representing the lower boundary of the SDR on the Vøring Margin.

Internal reflectors in the SDR may represent ponded or thick lava units, interference phenomena between several flows of similar thickness, or very fragmented or hydroclastic units deposited in a shallow-marine environment. It has further been suggested that deep marine-emplaced flood-basalt constructions may be imaged as SDR (Planke et al., 1995), but this hypothesis cannot be addressed by the existing borehole data. Our preferred interpretation of the nature and emplacement environments for the main seismic facies units is summarized in Table 1. However, the interpretational freedom in these volcanic provinces is large. Field observations and data from other volcanic provinces are therefore essential information necessary to integrate into the interpretation of volcanic complexes on rifted margins.

Comparison of Conjugate Margin Transects

Mapping of seismic facies units on margin segments with relatively dense profile coverage shows that the intrabasement reflectors are continuous for several kilometers along strike (e.g., Barton and White, 1997a) and that the facies units are clearly three-dimensional features (Alvestad, 1997). The Outer High is commonly only mappable several tens of kilometers along strike, and the individual SDR seismic facies units are often discontinuous along a margin segment. It is therefore difficult to assess how representative a margin transect is without a relatively dense seismic grid. The Jan Mayen Ridge and Møre Margin transects are the best constrained conjugate margin pair, but the seismic facies interpretation of the Hatton Bank and EG63 transects are also constrained by nearby profiles (Fig. 9).

The conjugate margin transects are symmetric in the sense that SDR are present on both sides of the ocean, but the structure of the volcanic complexes is quite different. On the Jan Mayen Ridge profile, a relatively small extrusive complex is identified, consisting mainly of one SDR, whereas an extensive volcanic complex is interpreted on the Møre Margin profile, consisting of two SDR units and various other volcanic seismic facies units (Fig. 9B). A somewhat different asymmetry is found on the EG63-Hatton Bank conjugate transects. Here, the thickness and width of the SDR is much larger on the EG63 transect than on the Hatton Bank Margin. In contrast, the total width of the volcanic zone is much greater on the Rockall Margin extending almost 1000 km landward of the SDR (e.g., Joppen and White, 1990).

Several different models have been proposed for the formation of the breakup-related volcanic extrusive complexes. These models can be divided into two main categories—those that relate the construction of the volcanic complex to infilling and capping of a rifted terrain (e.g., Hinz, 1981; Eldholm, Thiede, Taylor, et al., 1989; Planke and Eldholm, 1994) and those that are focused on the volcanics being formed during a phase of subaerial seafloor spreading (e.g., Mutter et al., 1982; Larsen and Saunders, 1998). The drilling data have not been able to distinguish between these end-member models, and both processes may actually form constructions imaged as SDR. Sites 642 and 917 provide direct evidence that the Landward Flows are underlain by extended continental crust (Eldholm, Thiede, Taylor, et al., 1989; Larsen and Saunders, 1998). The seaward continuation of the deep reflector patterns below the SDR suggests that at least the inner parts of the SDR are underlain by continental material (Figure 9B). However, the Site 918 results suggest that the entire crust below the Inner SDR on the Southeast Greenland Margin is of igneous nature (Larsen and Saunders, 1998). Volcanic margin models need to satisfactorily explain the conjugate margin asymmetry and lateral variation in volume and reflection characteristics of the breakup volcanic complexes as revealed by Figure 9. Models further must explain the consistent seaward dip of the SDR packages, even in provinces where ridge-axis jumps are inferred such as on the Vøring Margin (e.g., Skogseid and Eldholm, 1987) and the discontinuous, segmented magnetic anomaly pattern along the margin. We believe that the variations in the seismic reflection pattern of the volcanic complexes point toward a structural control for the emplacement of a major part of the extrusive volcanics. However, voluminous volcanic episodes during seafloor spreading can locally form subaerial or deep marine basaltic sheet-flow constructions also imaged as SDR.

The conjugate margin seismic reflection profiles provide little direct evidence about the nature of the deep crust and the location of the continent-ocean boundary as a reflection Moho is not identified and almost no deep crustal reflectors are present. Magnetic data are of limited use in determining the exact location of the continent-ocean boundary as the oldest magnetic lineations are discontinuous and segmented in the vicinity of the transects and located seaward of the main breakup-related volcanic complex (Figs. 1, 9). On the conjugate margin transects, the oldest magnetic anomalies, 24A and 24B, are both located seaward of the SDR on the Jan Mayen Ridge and Møre Margin profiles (Figs. 1, 9). Similarly, Anomaly 24n.3n is located near the seaward termination of the SDR on transect EG63, whereas the outer part of the SDR is questionably related to Anomaly 23 on the Hatton Bank Margin (Fig. 9A). Magnetic modeling on the Vøring Margin shows that a 4- to 5-km-thick volcanic cover is sufficient to explain the magnitude of the magnetic anomalies (Schreckenberger, 1997). Magnetic data, thus, may not provide any direct information about the nature of the deeper crust, which may be entirely igneous or extended and intruded continental fragments.

CONCLUSIONS

The extrusive volcanic complex in the northeast Atlantic is characterized by the presence of SDR along the majority of the rifted margin segments, while numerous other volcanic seismic facies units are also regionally mappable. Available drill holes show the presence of extensive subaerially emplaced basaltic constructions, but the well sites have a strong bias toward sampling the Landward Flows and the inner part of the SDR. Many second-order features are still poorly constrained by the existing database. The drilling has not yet been able to confidently resolve important scientific questions regarding the nature of the intrabasalt reflectivity, the eruption and emplacement environment of the bulk part of the extrusive complex, and the relative importance of tectonic and magmatic processes during construction of the volcanic piles (Table 2). The significant asymmetry of the volcanic complexes revealed by studies of conjugate margin transects suggests that tectonic control may initially play an important role during the construction of the extrusive volcanic sequences. Both improved seismic and borehole data and improved models are required to resolve important scientific questions related to volcanic margin formation.

Table 2. Interpretational problems on volcanic rifted margins resolvable by scientific drilling.

Problem	Feasible interpretations
Nature of SDR reflectivity	Thick flow Interference phenomena Hydroclastites
Large-scale presence of volcanic facies other than subaerial basalts	Deep-marine flood-basalts Shallow-marine hydroclastites Volcaniclastics Dikes
Constructional processes for SDR	Infill of rift-basins Subaerial seafloor spreading

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