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Abstract: Continental break-up in the northern North Atlantic was accompanied by massive volcanism. This produced sequences of basalt flows erupted close to sea-level, which are imaged as seaward-dipping reflectors on seismic reflection profiles. They comprise the upper 4–5 km of transitional crust in both the Edoras Bank and Hatton Bank areas of the Rockall continental margin. Detailed surveys show that the reflectors are convex-upward on dip lines but are sub-horizontal on strike lines. They are probably produced by aerially extensive basalt flows extruded from linear fissure vents aligned parallel to the rift axis. Along the Rockall margin two sequences of seaward-dipping reflectors occur, separated by an 'outer high' near the foot of the continental margin. The landward set of basalt flows are emplaced above stretched and intruded continental crust, while the seaward set span the region from highly distended continental crust to fully oceanic crust. The outer high is capped by basalt flows but exhibits little coherent internal reflectivity. We discuss possible origins of the outer high as a residual block of thinned and intruded continental crust or as a central volcano cut by fissure vents similar to those found in the neovolcanic zones of Iceland.

Keywords: volcanism, rifting, continental margin, seismic profiles.

Seaward-dipping reflectors were first recognised on the continental margins in the Norwegian Sea (Hinz & Weber 1976). Subsequently they have been imaged using multichannel seismic data on volcanic rifted margins throughout the world. They were drilled on the Rockall margin during DSDP leg 81 (Roberts *et al.* 1984), on the Vøring Plateau margin during ODP leg 104 (Eldholm *et al.* 1989) and more recently on the SE Greenland margin during ODP legs 152 and 163 (Larsen *et al.* 1994; ODP Shipboard Scientific Party 1996), and were found to be produced by sequences of basaltic lava flows. Interbedded sediments and weathered flow tops in many of the sequences indicate that much of the basalt was extruded above sea-level. The seaward dip on continental margins is a feature thought to be acquired through differential subsidence caused by loading (e.g., Hinz 1981; Mutter *et al.* 1982), in a similar manner to that postulated by Pálmason (1980) for the lavas extruded from the rift zones on Iceland.

We report results from two detailed studies of seaward-dipping reflector sequences on the Rockall continental margin that allow us to establish their three-dimensional geometry. They were formed as the NE Atlantic opened just prior to anomaly 24B time (*c.* 55 Ma, Berggren *et al.* 1995). One dataset is from the Edoras Bank area on the south-western edge of Rockall Plateau, and the other is from the Hatton Bank area 200 km to the northeast (Fig. 1).

Edoras Bank margin

Intra-basement seaward dipping reflectors are imaged in two sets along the Edoras Bank dip-profile (Fig. 2a). The geometry of the dipping reflectors in each of the sets is similar, although the reflectors are more broken and less continuous in the oceanward set. Reflectors are arcuate and convex-upward with dips steepening from sub-horizontal at shallow crustal levels to 9–18° toward their base. Individual reflectors can be traced for up to 11 km down-dip. The upper sequence boundary is generally overlain conformably by a series of sedimentary reflectors, which also exhibit arcuate seaward dips over the landward set (Fig. 2a). The steeply dipping reflectors disappear into a noisy reflection pattern at 5–6 s two-way travel time (twtt), obscuring base-lap relationships. The thickness of the imaged dipping reflectors, converted from twtt using the seismic velocities reported by Barton & White (1995, in press), reaches a maximum of 4–5 km. Both sets of dipping reflectors appear to wedge out in a landward direction into thin sequences. The oceanward termination is abrupt, passing from coherent dipping reflectors into seismically more opaque basement where intra-basement reflections are shorter and more discontinuous, and are often obscured by diffractions. In plan view the seaward dipping reflectors occupy a band 50–100 km wide, parallel to the bathymetric trend of the margin. The majority of the dipping reflectors lie landward of the oldest identifiable seafloor spreading magnetic anomaly.

On intersecting margin-parallel profiles (Fig. 3), the reflectors appear as sub-horizontal, sub-parallel features that are continuous along strike for distances of up to 12 km. This is particularly clear on strike profiles Cam79 and Cam80 (Fig. 3), which intersect the upper set of dipping reflectors. It is also illustrated by the block diagrams in Fig. 4 showing relationships between the reflectors on the dip profile Cam77 and the strike profiles Cam79 and Cam80.

On strike-line Cam81 (Fig. 3), which crosses the main dip profile in the middle of the outer high between the two sets of reflectors (Fig. 2), much of the profile exhibits the same rough basement topography and lack of coherent crustal reflectors that is apparent on the dip-line. However, there is one area of dense sub-horizontal reflectors about 15 km wide and 4–5 km thick, centred at 60 km along Cam81 (Fig. 3); this shows that the outer high is not continuous along strike, but is broken by segments of strongly reflective sequences that look the same as the along-strike expression of the dipping reflectors.

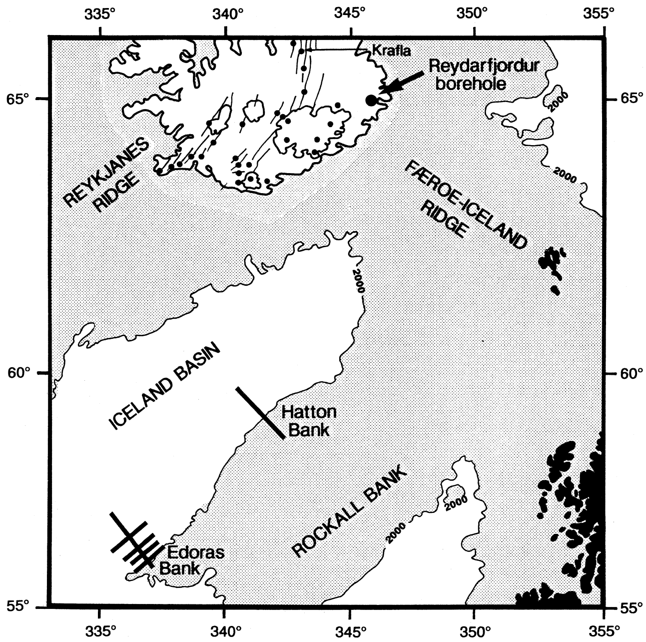

Fig. 1. Locations of the Hatton Bank and Edoras Bank surveys in the NE Atlantic. Areas shallower than 2000 m are shaded. Bold lines are locations of the multichannel seismic reflection profiles shown in this paper. On Iceland the dots and fine lines show locations of central volcanoes and associated fissure systems, which may provide an analogue for the continental margin architecture in the final stages of break-up.

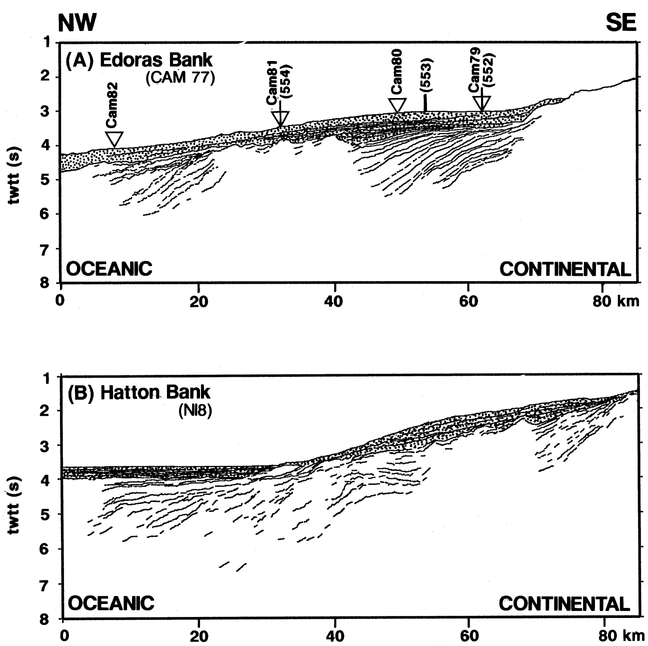

Fig. 2. Line drawings of migrated normal-incidence seismic reflection data from dip profiles: (**a**) Cam77 in Edoras Bank area; (**b**) NI8 in Hatton Bank area (see Fig. 1 for locations). Intersections with strike profiles are shown by triangles, and DSDP holes 552, 553 and 554 are marked by lines. Seaward dipping reflectors are imaged in two segments of each profile: 5–25 km and 45–70 km on Cam77 (**a**); and 5–50 km and 70–80 km on NI8 (**b**). The sedimentary section is stippled.

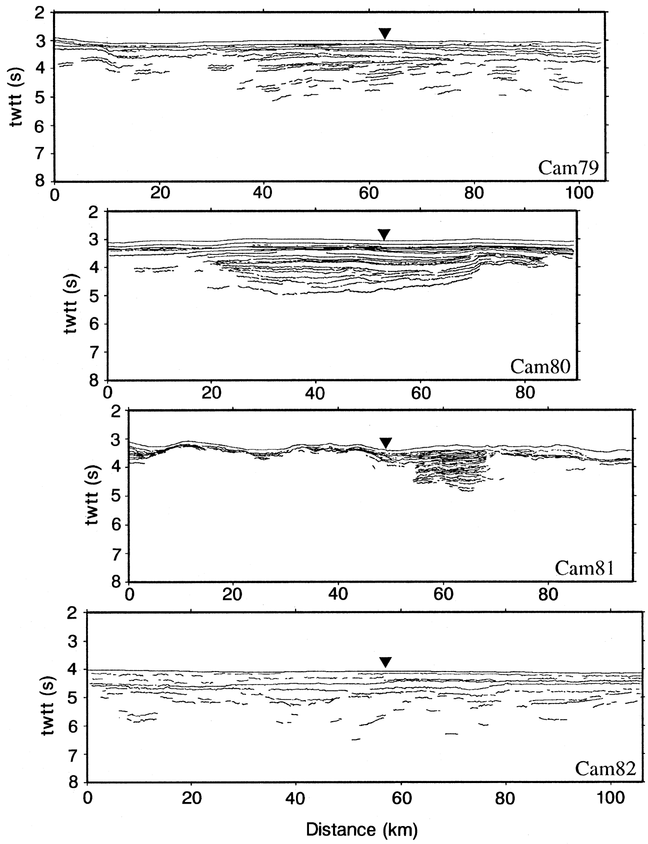

Fig. 3. Line drawings of migrated seismic reflection profiles from margin-parallel lines in the Edoras Bank area. Intersections between these strike lines and the main dip profile Cam77 are marked by triangles on this figure and on Fig. 2a.

Hatton Bank margin

The shallow structure of the Hatton Bank margin has been described previously (e.g., White *et al.* 1987; Morgan *et al.* 1989; Spence *et al.* 1989). For this study the multichannel data were migrated to establish structural relationships and to provide a dataset directly comparable to that from the Edoras Bank margin.

In general the seaward dipping reflectors are less clearly imaged at Hatton Bank than at Edoras Bank. This may be due, in part, to the smaller airgun array used at Hatton Bank. Again there are two distinct dipping reflector sequences (Fig. 2b). Individual reflectors imaged at Hatton Bank show a similar geometry to those at Edoras Bank. The landward sequence consists of 8–10 km long reflectors that are often planar and oceanward divergent. Using seismic velocities derived from two-ship wide-angle experiments (Spence *et al.* 1989), conversion from twtt to depth shows that the sequence reaches a maximum thickness of 4–5 km. As on Edoras Bank, the dipping reflectors wedge out landward, and in an oceanward direction pass abruptly into a seismically opaque zone with rough basement topography. The seaward dipping reflectors at the foot of the continental slope exhibit lower reflection amplitudes, but have the same convex-upward geometry as those imaged in the same setting at Edoras Bank. Weak reflectors can be traced to depths as great as 6–7 km beneath the basement. Sub-horizontal reflectors are imaged toward the oceanic end of the dip profile in a region exhibiting readily identifiable seafloor spreading anomalies (Spence *et al.* 1989).

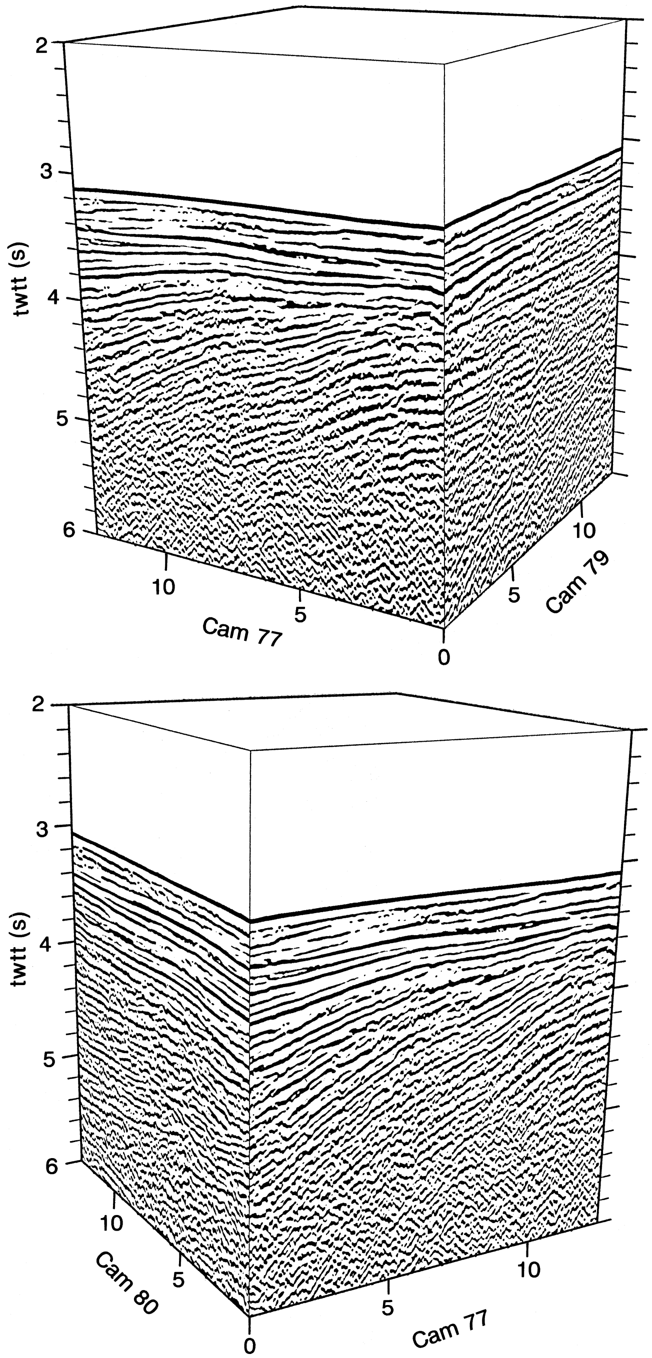

Fig. 4. Perspective views of unmigrated seismic reflection data from the Edoras Bank margin close to the intersection of the dip profile, Cam77 (Fig. 2a) with (**a**) strike profile Cam79 (Fig. 3), viewed from the south; and (**b**) strike profile Cam80 (Fig. 3), viewed from the west. In each case the length of the side of the cube is approximately 12.5 km.

The three-dimensional geometry of the Hatton Bank seaward-dipping reflectors determined from a grid of seismic profiles is remarkably similar to that imaged in the Edoras Bank area. Seaward-dipping reflectors on the dip-profile are imaged on margin-parallel profiles as sub-horizontal reflectors that are continuous for up to 10 km along strike. The along-strike expression of the outer high between the two dipping reflector sequences is limited, the chaotically or non-reflective crustal material of the outer high passing abruptly into a further region of sub-horizontal reflectivity 20 km to the NE of the main dip-profile.

To summarize, at both Hatton Bank and Edoras Bank the seaward-dipping reflectors are extremely two-dimensional in their expression. Individual reflectors map out surfaces that are remarkably uniform along strike and that strike parallel to the bathymetric trend of the margin. The geometry of the reflectors is fairly uniform across the Rockall margin, but their along-strike extent is more variable. In many areas dipping reflectors are uniformly distributed over distances in excess of 100 km, but elsewhere they may be imaged as discrete packets of less than 20 km lateral extent.

Causes of reflectivity

At DSDP site 553 on the Edoras Bank margin (see Fig. 2a for location), where a 181.5 m section of the seaward dipping reflector sequence was drilled, individual flow thicknesses average *c.* 6 m. This is too thin for seismic profiling to resolve as individual reflectors. The highly reflective dipping sequence is likely, therefore, to represent a complex interference pattern between closely spaced basalt flows. The impedance contrast required to produce such strong reflections comes from the interbedding of the lava flows with volcaniclastic sediments and tuffs in addition to impedance contrasts within the flows themselves, as for example between the massive centres of the flows and the weathered margins (Planke 1994; Planke & Eldholm 1994). However, where sufficiently thick (i.e., >50 m) individual flows are present, they could produce discrete individual reflectors on the seismic profiles.

The discontinuous reflectors imaged in the upper crust at the oceanic end of profile Cam77 (Fig. 2a) and the intersecting strike profile Cam82 (Fig. 3) have a different character to that of the coherent packages of seaward dipping reflectors. Explanations for similar isolated sub-horizontal reflectors seen elsewhere in oceanic crust include hydrothermal alteration fronts, or the residue of melt intrusions as sills (White *et al.* 1994; Henstock *et al.* 1996).

Volcanism during continental break-up: comparison with Iceland

The arcuate seaward dips of the oceanward set of basalt flows on the Rockall continental margin are consistent with a down-dip (i.e., oceanward) melt source, with subsequent tilting of the crust as it is loaded by further volcanic flows. The three dimensional shape of the basalt flows is of sheets of lava that now dip in an oceanward direction. The most probable source of the originally flat-lying sheet flows is linear fissure vents aligned parallel to the line of break-up, with similar lateral dimensions to the along-strike extent of the basalt flows imaged as reflector sequences. However, if the terrain over which the lavas flowed was flat-lying and subaerial, then extensive sheet flows could also have spread laterally from large eruptions fed by central-vent volcanoes, particularly if the central volcanoes themselves fed fissure eruptions. Whether the eruptive sources were concentrated, as in central vent volcanoes, or lineated, as in fissure systems, the landward decrease in thickness and the present seaward dip of the reflectors point to an oceanward source, in a similar manner to that postulated by Pálmason (1980) for the thick sequences of dipping lavas on Iceland.

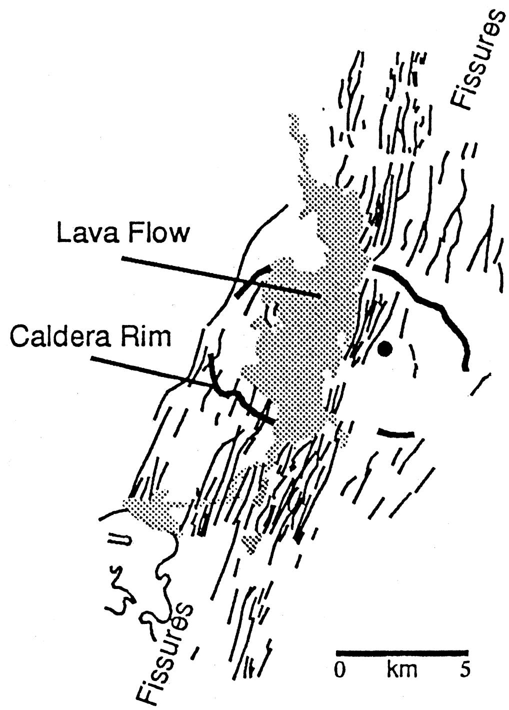

Fig. 5. Outline geological map of the Krafla caldera in NE Iceland, showing the associated fissure swarm and the lava flows of the 1725–29 eruption (after Björnsson *et al.* 1977; Brandsdóttir *et al.* in press). This caldera lies on a segment of the rift system which cuts across NE Iceland. It may provide a good analogue for the formation of an outer high on a rifted continental margin.

The present active zones of Iceland are characterized by dominant mafic fissure volcanism (Gibson & Gibbs 1987), and by 40–100 km long swarms of tension fractures, normal faults and volcanic fissures, which extend over regions 5–20 km wide (Gudmundsson 1995). The 40–100 km long volcanic segments on Iceland are each fed by a central volcano which is cut by fissure swarms (e.g., Björnsson *et al.* 1977) (Fig. 1). The central volcanoes are sub-circular in plan and typically 15–40 km in diameter (Fig. 5). The style of rifting found in the neovolcanic zones on present-day Iceland may provide a good analogue for the architecture of the rift systems and volcanic sources on the rifted continental margin during the later stages of break-up, since both develop on 15–20 km thick lithosphere in the presence of abnormally hot asthenosphere fed from a mantle plume. The extent of flows imaged on the Rockall margin are of the same order as those reported from Iceland.

The thicknesses of individual lava flows drilled on the Edoras Bank margin average 6.2 ± 4.1 m, similar to those drilled on the Vøring Plateau margin where thicknesses are 6.8 ± 3.6 m in fine-grained flows and 3.8 ± 1.9 m in medium-grained flows (Planke 1994). The lava pile at Reydarfjordur, E. Iceland (Robinson *et al.* 1982) exhibits similar flow thicknesses ranging from 1.2 to 19.7 m (average 7.1 m) in the borehole and 1 to 30 m (average 5.2 m) in exposed nearby cliffs. Lava in each of these areas was extruded subaerially, dips gently towards the rift axis and exhibits flow thicknesses and lengths of similar sizes. We estimate lava extrusion rates for the Rockall margin that are similar to published estimates for the lava pile of eastern Iceland (Table 1). Such observations support the notion that lavas extruded during continental break-up on the Rockall margin formed in a manner analogous to those on Iceland.

Table 1. *Lava deposition rates on the Rockall margin and northeast Iceland*

	Duration (Ma)	Average thickness of lava pile (km)	Lava deposition rate (m Ma^{-1})
Hatton Bank	3*	4.0	1300
	0.5 − 1†	4.0	5000
Edoras Bank	3*	3.0	1000
	0.5 − 1†	3.0	4000
Reydarfjordur			1620–2580‡

Average thickness of lava pile at Hatton and Edoras Banks was calculated assuming (i) interbedded clastic material has volcanic origin; and (ii) the porosity of interbedded material is constant throughout the section. The values given represent minimum values since the base of the pile is not imaged.
*Basalts extruded at a constant rate over 3 Ma.
†Two-thirds of basalt emplaced within first 0.5–1 Ma of a 3 Ma rift period (Eldholm & Grue 1994).
‡Hall *et al.* (1982).

Origin of the outer high

At both Hatton and Edoras Banks the seaward dipping reflectors are imaged as two distinct sequences (Fig. 2). The region between the sequences imaged on each margin is characterised by a bumpy acoustic basement underlain by seismically non-reflective or chaotically reflective crust, *c.* 20 km wide at Edoras Bank and *c.* 15 km wide at Hatton Bank. A similar division of the seaward dipping reflectors into two sequences is also found on other margins in the North Atlantic, including the Vøring Plateau margin and areas off NE Greenland (e.g., Mutter & Zehnder 1988).

The age relationship between the landward and oceanward sets of dipping reflectors is not well known, due to lack of suitable sampling and insufficient high-precision dating. However, it appears that the syn-rift basalts on the nearby Faeroe Islands were extruded in two distinct episodes separated by a hiatus of up to a few million years. A similar hiatus separates the sets of dipping reflectors drilled on ODP legs 152 and 163 off NE Greenland (ODP Shipboard Party 1996). The oldest, landward set preceded the onset of seafloor spreading by several million years, while the oceanward set was produced contemporaneously with the initiation of seafloor spreading. So it is possible that the two sets of basaltic sequences imaged on the Rockall margin also correspond to volcanism in two distinct phases, with the landward set being the oldest.

We propose two main possibilities for the origin of the outer high. These are: first, that it represents a dominantly intrusive igneous feature, either emplaced at a late stage through an earlier continuous series of basalt flows, or generated as a central volcano cut by eruptive fissures during the rifting; or, second, that it represents a continental fault block generated during break-up and heavily intruded by igneous activity. If there was, indeed, a hiatus between the extrusion of the landward and oceanward sequences of basalts, then it is possible that this, too, could have played a role in shaping the outer high, which lies in the transition between the two sequences.

The outer high at Hatton Bank has the appearance of a late-stage igneous intrusion cutting into the pre-existing reflector sequences, and has been described as such by White *et al.* (1987). It also exhibits high seismic velocities and densities

(Morgan *et al.* 1989). These are features characteristic of the deep structure of central volcanoes in Iceland, both in the neovolcanic zones (Brandsdóttir *et al.* in press), and in other areas of older crust (Staples *et al.* in press).

The central volcanoes in Iceland feed segments 40–100 km long through dykes which extend at shallow crustal levels away from the central volcanoes before erupting from fissure systems aligned parallel to the rift zones. The calderas in the central volcanoes are often filled at shallow levels with intermingled hyaloclastites and lava flows, as for example in the case of the active Krafla system in NE Iceland (Fig. 5). Hyaloclastites are generated when large volumes of basaltic magma are injected into shallow water: such explosive deposits could account for the chaotically reflective or unreflective nature of the outer high. A similar explanation has been proposed for the outer high observed on seismic reflection profiles across the Cuvier, Western Australia and the Namibian margins (S. Planke pers. comm. 1996). If this is the correct explanation, we would expect to find the outer high formed at the foot of the continental slope in the region where the margin first started to form in a submarine rather than a subaerial environment. We would also expect rift-parallel fissures to transect the outer high in the same way as fissures cut the active central volcanoes on Iceland (Fig. 5), and for them to act as sources for sheet flows adjacent to the outer high.

At Edoras Bank the outer high appears more like a block of residual, intruded continental crust. It does not exhibit anomalous velocities or densities (Barton & White 1995, in press), and is bounded along strike by sharp boundaries abutting against thick reflector sequences (Fig. 3). Subsidence modelling and drilling of the Edoras Bank margin suggests that the pre-rift depth of the outer high may have been close to sea-level, while the pre-rift depth immediately landward of the outer high was *c.* 500 m below sea level (Barton & White in press). This suggests that a basin may have existed landward of the outer high prior to, or during break-up.

If the lavas that now form the seaward-dipping reflectors landward of the outer high flowed into a syn-rift basin bounded by a continental fault block, then they could have attained their dip by loading stretched continental crust as accommodation occurred along a landward-dipping normal fault (see cartoon in Fig. 6). This could explain the observed abrupt termination of the seaward dipping reflectors against the landward side of the outer high (Fig. 2a), and also the continued seaward dip of layers of sediment deposited above the basaltic flows. The along-strike dimension of the inferred fault block that forms the outer high is a few tens of kilometres (Fig. 3): similar dimensions for fault blocks are observed on so-called non-volcanic margins such as those found on the Goban Spur and the Iberian margins (White 1992). We would expect any heavily extended continental region to break up into fault blocks that rotate along normal faults, but such fault blocks are presumably rarely imaged on volcanic margins because the huge volumes of melt injected into the stretched region both weakens and partially melts and remobilizes it. So the evidence of any syn-rift fault blocks on the margin may have been obscured by the continued volcanism. If there was a hiatus in volcanism, then it is possible that the outer high survived as a relatively more coherent continental block, though drilling shows that it is covered by basalt flows, and we would expect it to be heavily intruded.

A similar explanation for the seaward dips of the lava flows as due to loading in the hanging wall of a fault has been postulated for the Vøring margin by Gibson & Love (1989) and by Eldholm *et al.* (1995). The landward set of seaward-dipping reflectors on the NE Greenland margin also lie in a setting between fault blocks of continental crust, so may have a similar origin.

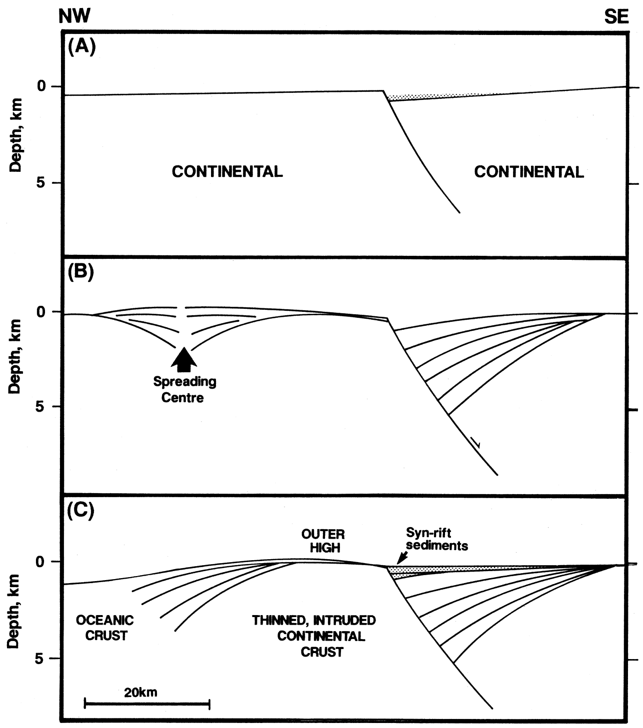

Fig. 6. Cartoon showing a possible scenario for the development of seaward dipping reflector sequences at Edoras Bank. (**a**) A basin bounded by a normal fault formed landward of the continental fault block as the region was stretched. (**b**) As continental break-up progressed the basin was filled with lava flows, with dips caused by loading of successive lava flows and reactivation of the normal fault. To the NW a sub-aerial spreading centre formed and seaward dipping reflectors developed as the source region was loaded by extrusives in the manner envisaged by Hinz (1981). (**c**) Following continental break-up, oceanic crust formed and two sequences of seaward-dipping reflectors remained on the rifted continental margin.

Conclusion

Basalt fissure volcanism resulted in the emplacement of lava piles at least 4–5 km thick on the Rockall continental margin during continental break-up. The nature of volcanism is similar at both the Edoras Bank area of the margin and at Hatton Bank 200 km to the NE, and is similar to that found on Iceland at the present day. The sheet flows that cause the dipping reflector sequences are aerially extensive, and sub-horizontal in a direction parallel to the rift margin. In each of the study areas two distinct sequences of basalt flows are imaged, separated by the seismically non-layered crust of the outer high. At Hatton Bank, the outer high may represent a central volcano which fed melt via fissure systems to the adjacent parts of the rift, in a manner similar to the central volcanoes formed in the rift zones on Iceland. At Edoras Bank the outer high is most probably a heavily intruded continental block bounded on its landward side by a large eastward-dipping normal fault which was active during continental break-up. A thick sequence of lavas was accommodated in the submarine basin to the east of this block prior to break-up, and a younger sequence of seaward-dipping reflectors was formed to the west as seafloor spreading commenced.

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References

Barton, A.J. & White, R.S. 1995. The Edoras Bank margin; continental break-up in the presence of a mantle plume. *Journal of the Geological Society* **152,** 971–974.

—— & —— 1997. Crustal structure of the Edoras Bank margin and mantle thermal anomalies beneath the North Atlantic. *Journal of Geophysical Research*, **102,** in press.

Berggren, W.A., Kent, D.V., Swisher, III, C.C. & Aaubry, M.-P. 1995. A revised Cenozoic geochronology and chronostratigraphy. *In*: Berggren, W.A., Kent, D.V., Aaubry, M.-P. & Hardenbol, J. (eds) *Geochronology, Time Scales and Global Stratigraphic Correlation*. Society for Sedimentary Geology, Special Publications, **54**, 129–212.

Björnsson, A., Saemundsson, K., Einarsson, P., Tryggvason, E. & Grönvold, K. 1977. Current rifting episode in north Iceland. *Nature* **266,** 318–323.

Brandsdóttir, B., Menke, W., Einarsson, P., White, R.S. & Staples, R.K. 1997. Faroe-Iceland Ridge Experiment—II. Crustal structure of the Krafla central volcano. *Journal of Geophysical Research*, **102,** in press.

Eldholm, O. & Grue, K. 1994. North Atlantic volcanic margins: Dimensions and production rates. *Journal of Geophysical Research* **99,** 2955–2968.

——, Skogseid, J., Planke, S. & Gladczenko, T.P. 1995. Volcanic margin concepts. *In*: Banda, E., Torne, M. & Talwani, M. (eds) *Rifted Ocean-Continent Boundaries*. Kluwer Academic Publishers, London, 1–16.

——, Thiede, J. & Taylor, E. 1989. Evolution of the Vøring volcanic margin. *In*: Eldholm, O., Thiede, J., Taylor, E., *et al.* (eds) *Proceedings of the Ocean Drilling Program, Scientific Results*, **104**. College Station, TX (Ocean Drilling Program), 1033–1065.

Gibson, I.L. & Gibbs, A.D. 1987. Accretionary volcanic processes and the crustal structure of Iceland. *Tectonophysics* **133,** 57–64.

—— & Love, D. 1989. A Listric Fault Model for the formation of the dipping reflectors penetrated during the drilling of Hole 642E, ODP Leg 104. *In*: Eldholm, O., Thiede, J., Taylor, E., *et al.* (eds) *Proceedings of the Ocean Drilling Program, Scientific Results*, **104**. College Station, TX (Ocean Drilling Program), 979–984.

Gudmundsson, A. 1995. Infrastructure and mechanics of volcanic systems in Iceland. *Journal of Volcanological and Geothermal Research* **64,** 1–22.

Hall, J.M., Walls, C. & Hall, S.L. 1982. On inclined features in the Iceland Research Drilling Project drill core, Reydarfjordur, eastern Iceland. *Journal of Geophysical Research* **87,** 6605–6618.

Henstock, T.J., White, R.S. & McBride, J.H. 1996. Along-axis variability in crustal accretion at the Mid-Atlantic Ridge: Results from the OCEAN study. *Journal of Geophysical Research* **101,** 13 673–13 688.

Hinz, K. 1981. A hypothesis on terrestrial catastrophes. Wedges of very thick oceanward dipping layers beneath passive continental margins—their origin and paleoenvironmental significance. *Geologisches Jahrbruch* **E22,** 2–28.

—— & Weber, J. 1976. Zum geologischen aufbau des Norwegischen kontinentalrandes und der Barents-See nach reflexionsseismischen Messungen, Petrochemie, Erdol und Kohle. *Erdgas*, 3–28.

Larsen, H.C., Saunders, A.D., Clift, P.D., *et al.* 1994. *Proceedings of the Ocean Drilling Program, Initial Reports*. College Station, TX (Ocean Drilling Program), **152**.

Morgan, J., Barton, P.J. & White, R.S. 1989. The Hatton Bank continental margin—III. Structure from wide-angle OBS and multichannel seismic refraction profile. *Geophysical Journal International* **89,** 367–384.

Mutter, J.C. & Zehnder, C.M. 1988. Deep crustal structure and magmatic processes: the inception of seafloor spreading in the Norwegian-Greenland Sea. *In*: Morton, A.C. & Parson, L.M. (eds) *Early Tertiary Volcanism and the Opening of the NE Atlantic*. Geological Society, London, Special Publications, **39**, 35–48.

——, Talwani, M. & Stoffa, P.L. 1982. Origin of seaward dipping reflectors in oceanic crust off the Norwegian margin by ‘‘sub-aerial sea-floor spreading’’. *Geology* **10,** 353–357.

ODP Shipboard Scientific Party 1996. Exploring the volcanic-rifted margins of the North Atlantic. *EOS* **77,** 165–168.

Pálmason, G. 1980. A continuum model of crustal generation in Iceland: kinematic aspects. *Journal of Geophysics* **47,** 7–18.

Planke, S. 1994. Geophysical response of flood basalts from analysis of wireline logs: ODP site 642, Vøring volcanic margin. *Journal of Geophysical Research* **99,** 9279–9296.

—— & Eldholm, O. 1994. Seismic response and construction of seaward dipping reflectors in flood basalts: Vøring volcanic margin. *Journal of Geophysical Research* **99,** 9263–9278.

Roberts, D.G., Schnitker, D., *et al.* 1984. *Initial Reports of the Deep Sea Drilling Project*, **81**. US Government Printing Office, Washington.

Robinson, P.T., Hall, J.M., Christensen, N.I., Gibson, I.L., Fridleifsson, I.B., Schmincke, H.-U. & Schönharting, G. 1982. The Iceland research drilling project: synthesis of results and implications for the nature of Icelandic and oceanic crust. *Journal of Geophysical Research* **87,** 6657–6667.

Spence, G.D., White, R.S., Westbrook, G.K. & Fowler, S.R. 1989. The Hatton Bank continental margin—I. Shallow structure from two-ship expanding spread seismic profiles. *Geophysical Journal International* **96,** 273–294.

Staples, R.K., White, R.S., Brandsdóttir, B., Menke, W.H., Maguire, P.K.H. & McBride, J. 1997. Faroe-Iceland Ridge Experiment—I. The crustal structure of north-eastern Iceland. *Journal of Geophysical Research*, **102,** in press.

White, R.S. 1992. Magmatism during and after continental break-up. *In*: Klewin, B.C., Alabaster, T. & Pankhurst, R.J. (eds) *Magmatism and the Causes of Continental Break-Up*. Geological Society, London, Special Publications, **68**, 1–16.

——, Westbrook, G.K., Fowler, S.R., Spence, G.D., Barton, P.J., Joppen, M., Morgan, J., Bowen, A.N., Prescott, C. & Bott, M.H.P. 1987. Hatton Bank (northwest UK) continental margin structure. *Geophysical Journal of the Royal Astronomical Society* **89,** 265–272.

——, McBride, J.H., Henstock, T.J. & Hobbs, R.W. 1994. Internal structure of a spreading segment of Mesozoic oceanic crust. *Geology* **22,** 597–600, plus foldout.

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