ration of sulphatide into the neutral galactocerebroside assemblies gives the microstructure anionic sites for electrostatic binding of Fe(III) polyhydroxy cationic species (which are formed at low pH[20]). These binding sites are the initial foci for nuclei formation such that, under optimal structural and solution conditions, inorganic deposition is confined to the tubule surface. In the case of iron oxide mineralization, no preferential crystallographic orientation with respect to the lipid microstructure was observed, although this does not rule out the possibility of oriented nucleation with more crystalline minerals such as $CaCO_3$ and $BaSO_4$. Moreover, the presence of the iron mineral coating stabilizes the lipid microstructure with respect to hydration so that suspension of the high axial ratio composites can undergo chemical transformations; for example, to produce magnetic tubules. A range of inorganic–organic materials could conceivably be synthesized by this route. We have observed, however, that although amorphous calcium phosphate has a high nucleation affinity for S-Cer-doped HFA-Cer tubules, subsequent phase transformation to crystalline hydroxyapatite is often not associated with the lipid surface (D. Walsh and S.M., unpublished data). Thus, the interplay between interfacial and solution chemistry is critical in dictating the nucleation specificity of these inorganic–organic interfaces.

Finally, we note that although we have been successful in promoting inorganic nucleation on the external surface of the lipid microstructure, we have not yet been able to synthesize reproducibily tubule-based composites in which the inorganic phase resides solely within the 10–30 nm central lumen of the supramolecular assembly. The synthesis of organic-lined inorganic filaments, as well as the production of viscoelastic gels of mineralized S-Cer-doped NFA-Cer unilamellar tubules (Fig. 1, route III) are the principal objectives of current and future work. □

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Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup

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RIFTED continental margins commonly include sections of igneous rock more than twice as thick as normal oceanic crust. Explanations for this voluminous magmatic accretion during rifting include plume models[1–3], which require a deep-seated thermal or chemical anomaly in upwelling mantle, and non-plume models[4–7], which call on broad, shallow thermal anomalies and/or rapid upwelling of mantle through the melting zone. New seismic models from two transects across the continent–ocean transition on the US Atlantic margin[8–10] confirm the presence of a 20–25-km-thick igneous section. Here we argue that the similarity of the crustal structure on these and two previous transects, spanning 1,000 km of the margin, and the association of thick igneous crust with the East Coast magnetic anomaly[11] imply that the thick igneous section extends along the entire margin and may have a volume of as much as 3.2×10^6 km^3. The distribution of volcanic and plutonic rocks, details of the seismic structure, and lack of independent evidence for a hotspot are difficult to reconcile with plume models and suggest that non-plume processes created the thick igneous crust.

Studies of the continental margins of the North Atlantic have shown that voluminous igneous activity, on a scale rivalling the largest continental flood basalt provinces, accompanied the onset of sea-floor spreading[1,12]. Igneous activity on these 'volcanic margins' is shown in seismic data as seaward-dipping reflections beneath the post-rift unconformity on multichannel seismic reflection (MCS) data[1,3,14], and thick, high-seismic-velocity (P-wave velocity 7.2–7.5 $\mathrm{km\,s^{-1}}$) lower crust interpreted from wide-angle seismic data[1,12]. Other margins (such as the Iberia margin), appear to be 'non-volcanic', as evidenced by lower seismic velocities (6.3–6.6 $\mathrm{km\,s^{-1}}$) in the lower crust, lack of seaward-dipping reflections, and block-faulted basement interpreted as thinned continental crust[15,16].

The first indications of significant volumes of volcanic material in the crust of the eastern margin of the United States came from seaward-dipping reflections on MCS data[17] and high velocity (7.2–7.5 $\mathrm{km\,s^{-1}}$) lower crust interpreted from wide-angle seismic data in the Baltimore Canyon[18] and Carolina Troughs[19] (Figs 1, 2). Tréhu *et al.*[19] inferred that the margin was volcanic. Due to limited resolution of those data sets, however, the full thickness and extent of igneous rocks was uncertain, and White and McKenzie[20] concluded that the margin was only mildly volcanic and formed at the distal edge of a hotspot.

Improved images of the geometry and distribution of rift-related igneous rocks have resulted from joint MCS and wide-angle seismic experiments conducted recently in the Carolina and southern Baltimore Canyon troughs[8–10] (Fig. 1). The resulting images show well-developed seaward-dipping reflections together with a thick, high-velocity lower crust (Figs 3, 4). Beneath the seaward-dipping reflections, deep reflections from the Appalachian crust disappear, the Moho shows a striking change in reflective character (Fig. 3), and seismic velocities increase rapidly (Fig. 4). These abrupt lateral changes indicate that very little continental material persists beneath the volcanic wedge, so that the crust there consists almost entirely of new igneous material. The US Atlantic margin is therefore strongly volcanic at least from the Blake Spur fracture zone to offshore New Jersey, and probably along its entire length, as discussed below. The thickness of igneous material added to the crust reaches 25 km in the BA-6 and EDGE transects, exceeding the 18.5 km thickness interpreted on the Hatton Bank[21], which was within 600–700 km of the Iceland hotspot during rifting. Although the inferred igneous material on the US Atlantic margin is buried beneath thick post-rift sediments and is therefore difficult to sample directly, Early Jurassic mafic igneous rocks occur in the Newark-type basins and beneath the coastal plain[22].

Comparison of magnetic anomaly data and the new seismic models shows a first-order spatial correlation between the thick volcanic crust and a broad zone of positive magnetic anomalies that includes the East Coast magnetic anomaly[11] (ECMA, Fig. 4). The landward limit of high-velocity igneous crust is marked by a sharp magnetic gradient near the basement hinge zone. Seaward, the magnetic intensity decreases across the transition from thick volcanic crust to oceanic crust of normal thickness. The peak of the ECMA lies between the thickest part of the seaward-dipping wedge and the landward limit of oceanic basement (Fig. 4). The offset between the thickest igneous section and the ECMA varies from profile to profile, suggesting that crustal magnetization varies laterally and extends into the lower crust[8,23]. The relationship between the magnetic anomalies and inferred extent of thick igneous crust also holds on the LASE and USGS Line 32 profiles (Fig. 2).

We suggest that the similar crustal structure of the Carolina and Baltimore Canyon troughs, together with the association of thick igneous crust with the ECMA, implies that the US Atlantic margin is strongly volcanic along the entire 2,000-km length of the ECMA, between 31° and 44° N (Fig. 1). We refer to the thick rift-related igneous package interpreted to underlie the margin as the East Coast Margin igneous province (ECMIP). The cross-sectional area of igneous material between rifted continental crust and normal oceanic crust is about 1,400 km^2 on transect BA-6 and 1,800 km^2 on EDGE 801. Taking 1,600 km^2 as an average area, we estimate the total volume of igneous material in the ECMIP as 3.2×10^6 km^3. This is probably a maximum estimate, because it ignores the possible presence of intercalated sediments in the seaward-dipping wedge and relict continental crust within the lower crust, as well as possible gaps in the ECMIP. Even if the ECMIP does not extend much north of the LASE profile, the implied volume of 1.6×10^6 km^3 classifies the ECMIP as a large igneous province, comparable in volume to the Deccan province (1.7×10^6 km^3; ref. 24). The deep structure of the conjugate African margin is unknown, but if it is roughly symmetric with the North American margin, the total volume of material erupted during rifting may be twice our estimate.

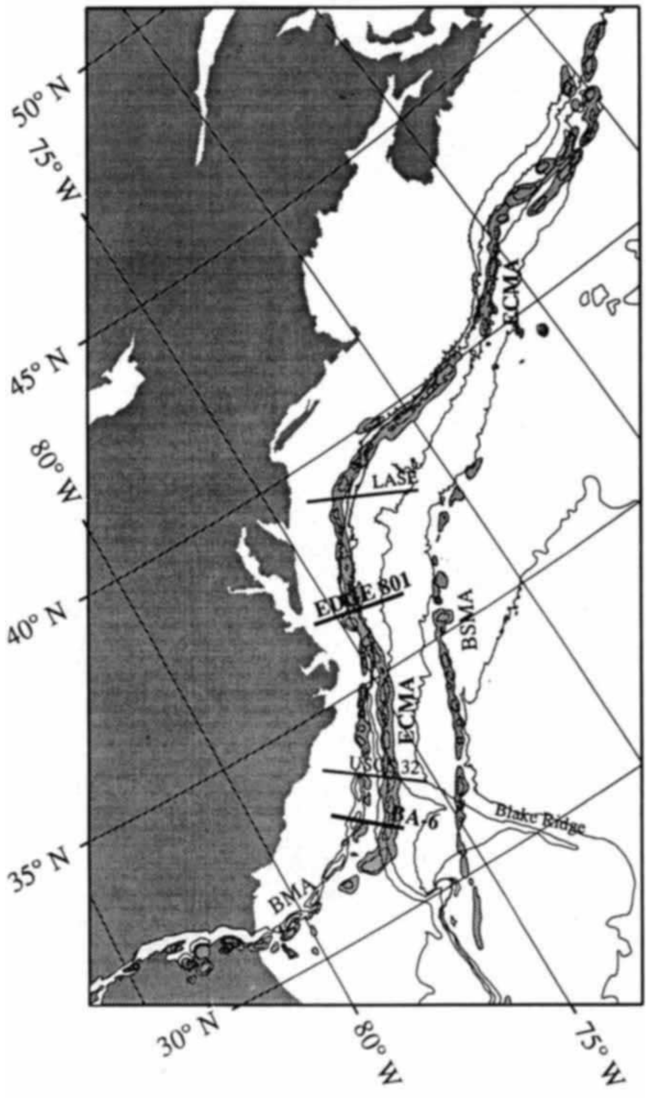

FIG. 1 Location of the US East Coast margin, bathymetry contoured at 1000 m intervals. Magnetic anomalies[11]: ECMA = East Coast magnetic anomaly; BMA = Brunswick magnetic anomaly; BSMA = Blake Spur magnetic anomaly. Seismic transects that contain both reflection and refraction data: LASE [18]; EDGE Line 801[9]; Carolina Trough USGS line 32[19]; Carolina Trough line BA-6[8,10]. The Blake Ridge is a sediment drift deposit[34].

Plume models have been invoked to explain several flood basalt provinces and volcanic margins. In its simplest form the hotspot model[20] predicts that the volume of igneous material emplaced in the crust depends on the temperature of the upper mantle during passive upwelling beneath rifting lithosphere. Rifting over mantle with a normal potential temperature (1,280 °C) produces igneous crust of normal oceanic thickness (7 km), whereas rifting over the warmer mantle near a hotspot produces greater thicknesses[20]. Because the presence of water in the mantle also enhances the volume of melt produced during decompression, some 'hotspots' may be more 'wet' than 'hot'[25]. Other plume models include a dynamic component. In 'plume-head' models the mantle upwelling rate varies with time: the flux of entrained, dynamically upwelling material is large during plume initiation, but decreases once the plume is established. Lateral migration and focusing of melt from a plume to the rift zone may increase igneous accretion without requiring temperature anomalies as large as 150–200 °C (refs 26, 27). Still, these models all require an externally imposed, deep-seated thermal or chemical anomaly in the asthenosphere to explain the formation of thick igneous crust.

Several lines of evidence suggest that the ECMIP was not produced by a long-lived plume. First is the lack of independent evidence for a plume near the margin during rifting. According to plate reconstructions[28] the closest likely hotspot to the central east coast during rifting was the Cape Verde hotspot, which was ~1,000 km northwest of the EDGE transect area 180 Myr ago, assuming a fixed hotspot reference frame. Even if we assume that the Cape Verde hotspot drifted in the necessary direction at 5 mm yr^{-1}, placing it under the margin near Long Island during rifting, there is no hotspot track of appropriate age and orientation. There is no chain of volcanoes, bathymetric swell, nor any known track of anomalously thick crust, leading eastward from the central east coast into the Atlantic. (The New England seamounts and Bermuda Rise are substantially younger than the opening of the margin, with ages of 124–75 Myr and 33 Myr, respectively[29].) A hotspot beneath North Africa might not have left a track on the Atlantic sea floor, but known African hotspots (for example, the Hoggar dome[30]) were too far (at least 1,500 km) from the margin to have created the ECMIP. A 'hot blob' of rising material, lacking an underlying plume, is a possible explanation, but it requires a fortuitous arrival at the time of continental rifting.

In this respect the ECMIP may be similar to the Cuvier margin of northwestern Australia[31] and is clearly different from margins where flood basalts and offshore igneous provinces have been linked to known plumes. In the South Atlantic, for example, the Tristan de Cunha hotspot, which is believed to have caused the Paraná basalts of South America and Etendeka basalts of Southwest Africa, left a distinct bathymetric track in the Walvis

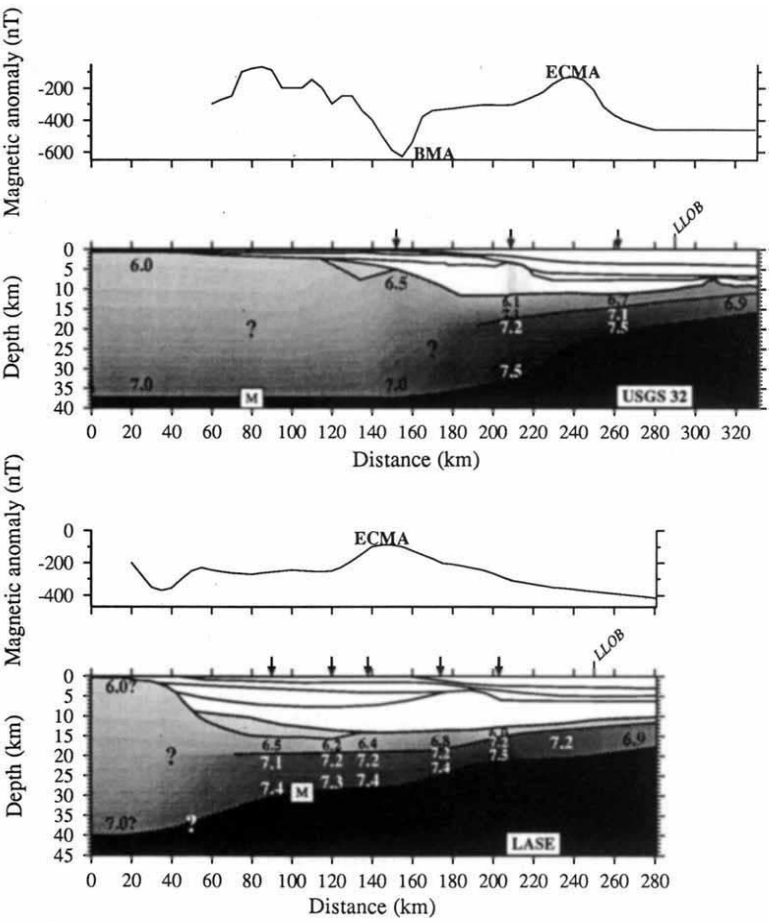

FIG. 2 Magnetic data and crustal velocity structure across (top) USGS Line 32 transect, modified from ref. 19, and (bottom) LASE transect, modified from ref. 18. In the crustal velocity diagrams, shading is proportional to velocity and the numbers are velocities in km s^{-1}. Arrows indicate velocity control points from along-strike ocean-bottom seismometer lines or expanding spread profiles. M = Moho; ECMA = East Coast Magnetic Anomaly; BMA = Brunswick Magnetic Anomaly; LLOB = landward limit of oceanic basement, identified from coincident seismic reflection data.

ridge and Rio Grande rise. Similarly, the Iceland hotspot (North Atlantic Tertiary igneous province) left its mark on the sea floor in the Iceland–Faeroes and Greenland–Iceland rises, as did the Réunion hotspot (Deccan Traps) in the Chagos–Laccadive ridge. No such track exists in the central Atlantic.

Second, the strongly asymmetric distribution of igneous accretion along and across the margin is difficult to reconcile with plume models. The hotspot[20] and plume-head models[2,3,32] imply that mantle temperature should decrease radially from the plume. This in turn predicts that the thickness and magnesium content (and, therefore, seismic velocity) of igneous rocks will decrease radially from the plume. The similarity in thickness and velocity of igneous rocks on the BA-6 and EDGE transects, however, implies that melting did not vary strongly along the margin. Perpendicular to the margin, in contrast, the amount of melting decreased rapidly over a distance of only 60–80 km. From the thick igneous crust to oceanic crust, average igneous crustal velocities decrease from 7.1 to 6.4 km s^{-1}, the total thickness of igneous crust decreases from 25 to 7–8 km, and lower-crustal velocities decrease from 7.4–7.5 to 6.9–7.0 km s^{-1} (Fig. 4). This strong asymmetry in margin structure implies that igneous accretion is controlled by dynamic rift processes, rather than by proximity to a plume.

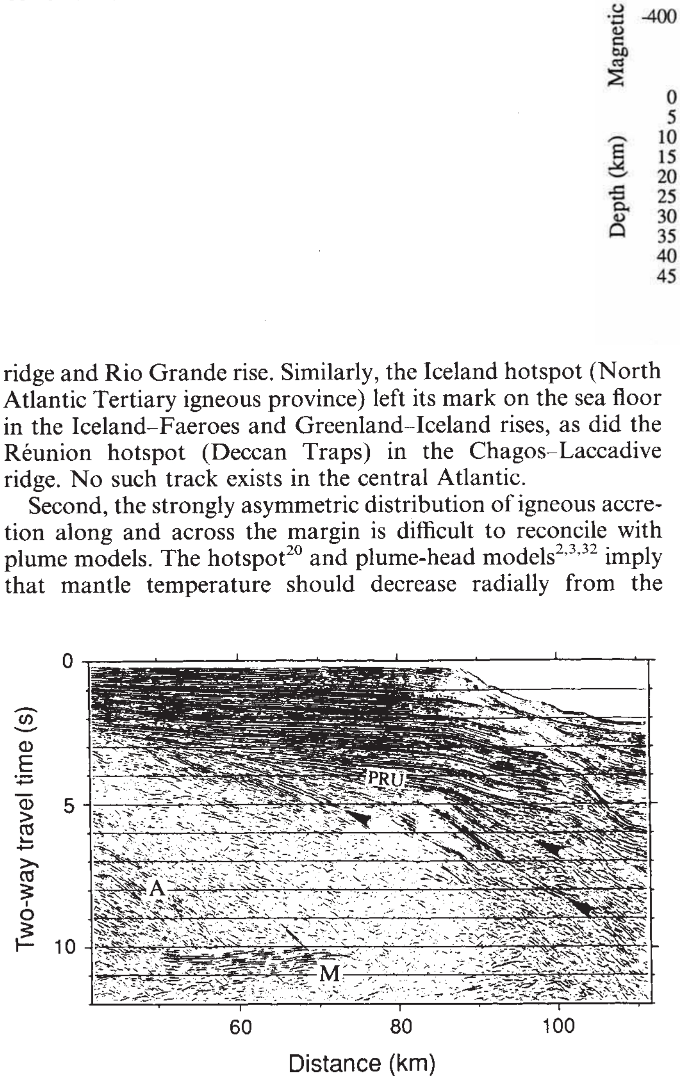

Fig. 3 Seismic reflection data showing seaward dipping reflections (arrows) on line EDGE 801. Strong, dipping lower-crustal reflections in Appalachian crust (A) give way seaward to a more transparent lower crust, whereas the Moho (M) shows high-amplitude laminations before disappearing beneath the thickest seaward-dipping reflections. These observations, together with the coincident velocity model (Fig. 4), indicate an abrupt transition from old continental crust to new igneous crust. PRU = post-rift unconformity.

Third, the observed seismic velocities and crustal thicknesses are difficult to generate with the hotspot model without an unusually large thermal anomaly. The interpreted igneous crustal thickness of 25 km beneath the BA-6 and EDGE transects would require the maximum thermal anomaly (200 °C) considered reasonable by White and McKenzie. The observed lower-crustal velocities of 7.4–7.5 km s^{-1} cannot be generated with their model, which predicts a velocity of ~7.15 km s^{-1} for a 200 °C anomaly[20]. Even if the lower crust comprises olivine-rich cumulates, the average igneous crustal velocities of 7.1 km s^{-1} require a 150 °C anomaly. It seems unlikely that such a high-temperature plume would not leave a hotspot track on the sea floor.

Thus, although plume models may explain some volcanic margins, we do not believe that they apply to the US Atlantic margin, and we must seek other explanations for the prodigious volcanism there. One possibility is that, during rifting, the upper mantle was warm over a broad region, without a deep-seated plume. Surface-wave tomography suggests that such 'hot cells' exist in the upper mantle, perhaps owing to a lack of subduction-related cooling[6]. Alternatively, upper-mantle thermal anomalies

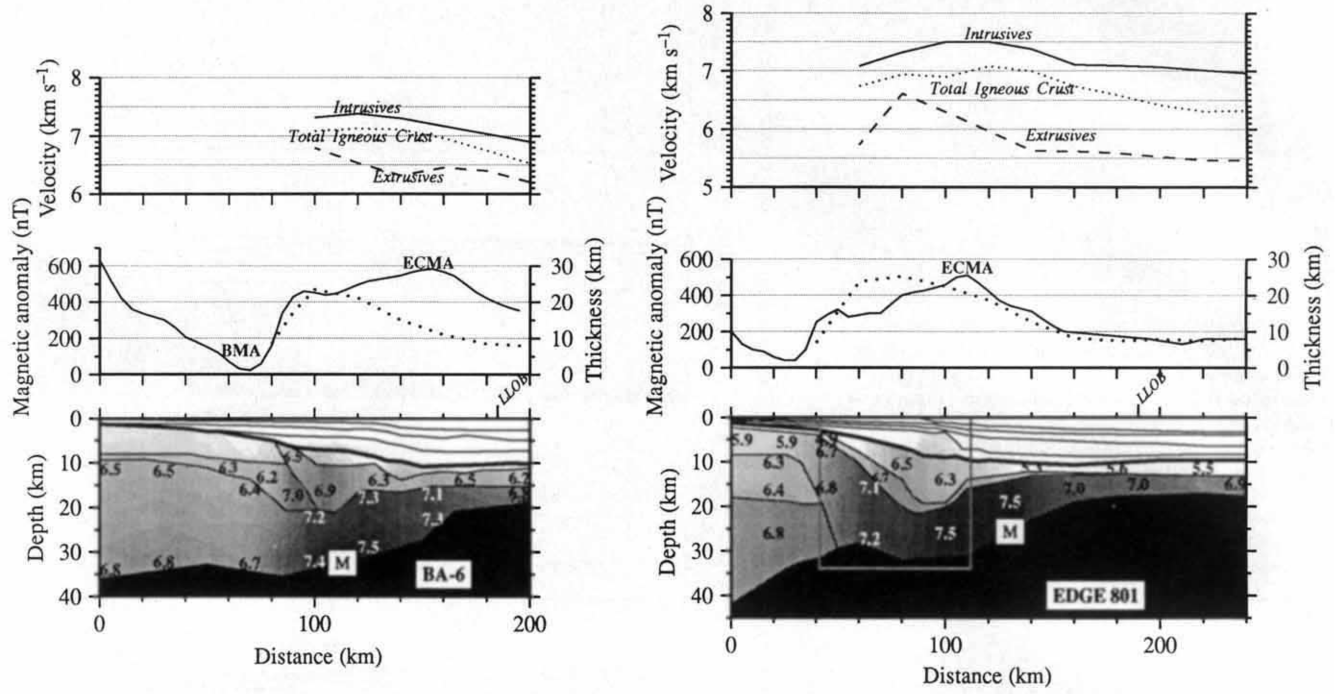

Fig. 4 Structure across Carolina Trough BA-6 profile[35] (left) and southern Baltimore Canyon Trough profile EDGE 801 (W.S.H. *et al.*, manuscript in preparation) (right). Top, velocity across the section of (solid line) intrusives (lower crust), (broken line) extrusives (layer 2) and (dotted line) total igneous crust (extrusives + intrusives). Middle, Magnetic data in nT (solid line) and total thickness of igneous rocks emplaced during rifting, interpreted from seismic sections (dotted line). ECMA = East Coast magnetic anomaly; BMA = Brunswick magnetic anomaly. Bottom, Crustal velocity structure, with shading proportional to velocity; velocities labelled in km s^{-1}. Bold line represents post-rift unconformity. The strong lateral increase in crustal seismic velocity and first occurrence of seaward-dipping reflections correspond to a sharp seaward increase in magnetic intensity. Box outlines location of multichannel seismic reflection data shown in Fig. 3. LLOB = landward limit of oceanic basement.

and consequent asthenospheric upwelling and continental rifting might result from the insulating effect of supercontinents[5]. The thermal anomalies envisioned in these models differ from deep-seated plumes in several ways: they are generated in the upper mantle, they originate over a broad region rather than at a point source, and they can be dissipated by subsequent rifting. Such thermal anomalies would not leave a distinct hotspot track.

We believe that dynamic mantle upwelling during rifting—in which the asthenospheric upwelling rate exceeds the lithospheric extension rate—contributes to the accumulation of thick igneous crust. Secondary convection, induced by temperature contrasts across an abrupt lithospheric rupture beneath the rift, may also enhance melting during continental breakup[4,31,33]. Similarly, abrupt variations in the thickness of lithospheric domains juxtaposed by continental collision may lead to significant lateral temperature gradients which nucleate secondary convection before and during rifting[7]. The dynamics of these models, however, are poorly understood.

If dynamically upwelling mantle lacks a strong thermal anomaly, the liquid produced will initially consist of small melt fractions formed at high average pressure from a very large volume of peridotite. Such a process would explain the thick, high-velocity lower crust of the ECMIP. This hypothesis can be tested by geochemical analysis of new basalt samples from drilling of volcanic margins. We tentatively predict that such basalts will be found to be derived from relatively low-degree, high-pressure melting of the upper mantle, as found for basalts from the Vøring margin[33]. ☐

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