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Fixity of the Iceland "hotspot" on the Mid-Atlantic Ridge: Observational evidence, mechanisms, and implications for Atlantic volcanic margins

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ABSTRACT

The Iceland anomaly has been attributed to a deeply rooted and fixed mantle plume, and Early Tertiary magmatism in the North Atlantic Igneous Province (NAIP) has commonly been interpreted to relate to an ancient expression of the same plume. We challenge these concepts. A major problem with attributing the Iceland anomaly to a fixed plume is the lack of evidence for a hotspot track. Although the Greenland-Faeroe Ridge has been suggested to be the hotspot track, its symmetric and continuous construction instead suggests in situ development on the plate boundary. Magmatism in the NAIP occurred in two phases, distributed in approximately perpendicular belts. The first phase (ca. 62–58 Ma) occurred along a north-west belt through the British Volcanic Province to west Greenland. We relate this phase to a transient and failed rift, intermediate in time and space between seafloor spreading in the Labrador Sea and the northeast Atlantic. The second phase (ca. 56–53 Ma) followed the incipient northeast Atlantic plate boundary. Both magmatic phases can therefore be associated with plate tectonics. Likewise, the north Atlantic–Arctic breakup can be explained as a natural outcome of plate tectonics and lithospheric strength distribution. We follow other recent research in suggesting that the voluminous magmatism during NAIP phase 2 is related to reactivation and opening along the Caledonian orogen. Specifically, we point to a close correspondence between the reactivated orogen and the north Atlantic volcanic passive margins, and suggest that the extreme magmatism could stem from the melting of eclogitic material, either residing in remnants of the Caledonian-Appalachian orogenic root or within a delaminated root. Extending this idea, we postulate as a testable hypothesis that volcanic margins are the natural products of the Wilson Cycle (i.e., opening of sutures). We have tested the hypothesis on the north, central, and south Atlantic Ocean and have found a broad correlation between volcanic margin segments and reopened Late Neoproterozoic–Phanerozoic fold belts.

Keywords: Iceland, Atlantic, plume, hotspot, fold belt, eclogite, volcanic margin

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INTRODUCTION

In the northeast Atlantic region, the Iceland "plume" has been the suggested cause of a wide range of Tertiary-to-Recent geologic phenomena, features, and processes, such as:

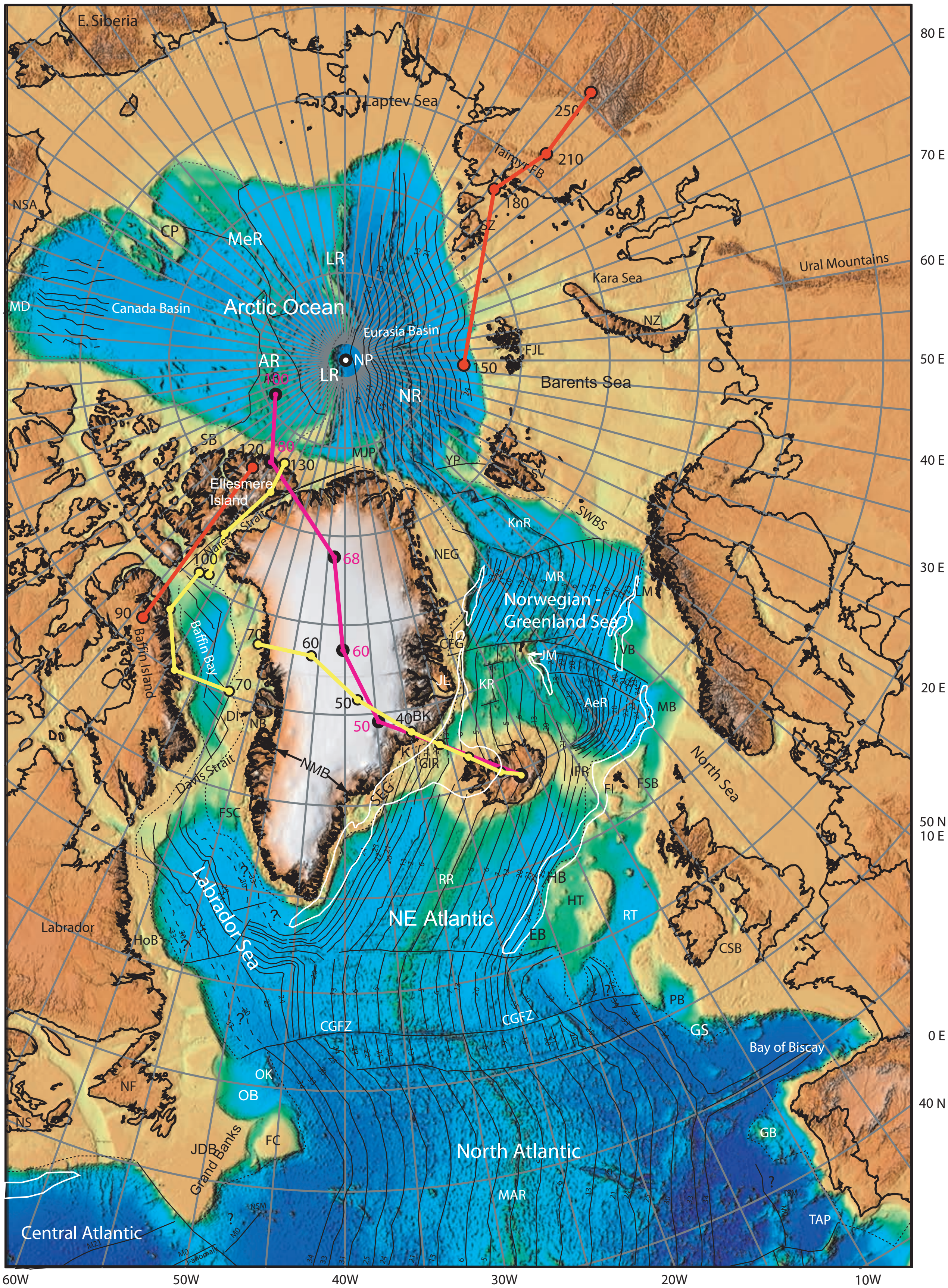
1. Lithospheric weakening, facilitating Early Eocene breakup (e.g., Morgan, 1981; White and McKenzie, 1989);
2. North Atlantic Igneous Province (NAIP) magmatism (including its full range of magmatic features) (e.g., White and McKenzie, 1989; Saunders et al., 1997);
3. Regional uplift forming a continental land bridge between North America and Eurasia (Ziegler, 1988);
4. Transient regional dynamic Paleocene uplift (Nadin et al., 1995);
5. Episodic Paleocene uplift and associated sand distribution (White and Lovell, 1997);
6. Gradually increasing Tertiary uplift related to partial lithospheric delamination (Nielsen et al., 2002);
7. A ridge jump from the Aegir to the Kolbeinsey ridge (Talwani and Eldholm, 1977);
8. Microcontinent separation from east Greenland (Müller et al., 2001);
9. Stress inversion, including development of mid-Tertiary inversion features (Lundin and Doré, 2002);
10. Widely spaced, broad areas of Neogene uplift (Rohrman and van der Beek, 1996);
11. Oligocene-to-Recent V-shaped ridges (e.g., Vogt, 1971; Jones et al., 2002a);
12. Abnormally thick and bathymetrically shallow Greenland-Faeroe ridge (GFR) (e.g., Bott, 1983);
13. Anomalously shallow north Atlantic bathymetry (e.g., Vogt, 1983); and
14. Positive north Atlantic geoid anomaly (e.g., Marquart, 1991).

Interpreted indirect effects of the Iceland plume likewise include a wide range of phenomena, ranging from changes in oceanic circulation (e.g., Wright and Miller, 1996) to major submarine slides off the mid-Norwegian margin (e.g., Storegga Slide) (Berndt, 2000). The above list of phenomena, attributed to the Iceland plume, does not necessarily represent the current view, but serves to illustrate the breadth of its implied influences.

The concept of a plume beneath Iceland dates back to the definition of the plume hypothesis (Morgan, 1971), which proposed that plumes originate in the deep mantle, remain fixed with respect to one another, and drive plate tectonics. The plume concept has, since its inception, seen several changes (e.g., Campbell and Griffiths, 1990; Hill, 1991; Sleep, 1992; Malamud and Turcotte, 1999; Courtillot et al., 2003). Although some of the plume models have become increasingly complex in geometry (e.g., Smallwood and White, 2002) and in internal composition (e.g., Kempton et al., 2000), it is noteworthy that with respect to Iceland Courtillot et al. (2003) reached the same conclusion as did Morgan 30 yr earlier—that Iceland is underlain by a fixed plume, rooted in the deep mantle.

Following Morgan (1971), other workers have refined the fixed hotspot framework (e.g., Müller et al., 1993), and the concept remains applied in modern plate reconstructions (e.g., Torsvik et al., 2001a; Lawver et al., 2002) (Fig. 1). In parallel with the definition of the fixed hotspot framework, however, the stability of plumes was contested (e.g., Molnar and Atwater, 1973). Since the early work by Molnar and Atwater (1973), several workers have estimated that Indo-Atlantic and Pacific hotspot groups have moved relative to one another at rates of ~20 mm/yr (e.g., Norton, 2000 and references therein). More recently, it has been shown that individual Pacific hotspots drift relative to one another (e.g., Koppers et al., 2001; Tarduno et al., 2003) at rates of 10–60 mm/yr (Koppers et al. 2001). Notably, Iceland's "hotspot track," the GFR, does not correspond to the motion of either the Indo-Atlantic or the Pacific hotspot families, and Norton (2000) therefore placed Iceland in a one-member family. If the rates of hotspot drift estimated in the Pacific apply to Iceland, hotspot drift could probably keep up with the rates of lithospheric drift, as discussed by Vogt (1983). However, to form the essentially linear GFR, an underlying plume would have to drift in the same direction as, and in concert with, the overriding plates. Such behavior requires coincidence or that the location of surface magmatism was governed by plate tectonic processes.

Figure 1. North Atlantic and Arctic location map (polar stereographic projection). Shaded relief bathymetry and topography image, based on data from Smith and Sandwell (1997) and Jakobsson et al. (2000), overlain by our interpreted magnetic anomalies, fracture zones, and spreading axes. Hotspot tracks proposed by Forsyth et al. (1986) (magenta dots/lines), Lawver and Müller (1994) (yellow dots/lines), and Lawver et al. (2002) (red dots/lines). Seaward-dipping reflector sequence outlines: Northwest European margin from Eldholm et al. (2000); southeast Greenland from Larsen and Saunders (1998). AR—Alpha ridge; AeR—Aegir ridge; BK—Blosseville Kyst; CEG—central east Greenland; CGFZ—Charlie Gibbs Fracture Zone; CP—Chukchi Plateau; CSB—Celtic Sea Basins; DI—Disco Island; EB—Edoras Bank; FC—Flemish Cap; FSC—Fylla Structural Complex; FI—Faroe Islands; FJL—Franz Josef Land; FSB—Færoe Shetland Basin; JDB—Jeanne D'Arc Basin; GIR—Greenland-Iceland ridge; GB—Galicia Bank; GS—Goban Spur; HB—Hatton Bank; HoB—Hopedale Basin; HT—Hatton Trough; IFR—Iceland-Faeroe ridge; JL—Jameson Land; JM—Jan Mayen microcontinent; K—Kangerlussuaq; KnR—Knipovich ridge; KR—Kolbeinsey ridge; LM—Lofoten Margin; LR—Lomonosov ridge; MAR—Mid-Atlantic Ridge; MD—McKenzie Delta; MB—Møre Basin; MeR—Mendelev ridge; MJP—Morris Jesup Plateau; MR—Mohns ridge; NB—Nuussuaq Basin; NEG—northeast Greenland; NL—Newfoundland; NP—North Pole; NR—Nansen ridge; NS—Nova Scotia; NSA—north slope of Alaska; NZ—Novaya Zemlya; OB—Orphan Basin; OK—Orphan Knoll; PB—Porcupine Basin; RR—Reykjanes ridge; RT—Rockall Trough; SB—Sverdrup Basin; SEG—southeast Greenland; SV—Svalbard; SWBS—southwest Barents Sea margin; SZ—Severnaya Zemlya; TAP—Tagus abyssal plain; VB—Vøring Basin; YP—Yermak Plateau.



E. Siberia
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210
180
SZ
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NSA
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MeR
LR
Canada Basin
Arctic Ocean
Eurasia Basin
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AR
NP
LR
NR
FJL
Barents Sea
Kara Sea
NZ
Ural Mountains
SB
120
130
MJP
YP
SV
Ellesmere Island
Nares Strait
KnR
SWBS
100
NEG
68
MR
Norwegian - Greenland Sea
LM
90
Baffin Island
Baffin Bay
70
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North Sea
Davis Strait
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NE Atlantic
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40W
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Despite increasing indications that hotspots are not fixed, many papers on the northeast Atlantic, including work by us, have made the a priori assumption that the Iceland plume is fixed (e.g., Lawver and Müller, 1994; Nadin et al., 1995; Clift, 1996; Saunders et al., 1997, 1998; Tegner et al., 1998; Larsen and Saunders, 1998; Naylor et al., 1999; Ritchie et al., 1999; Skogseid et al., 2000; Müller et al., 2001; Torsvik et al., 2001a; Lawver et al., 2002; Lundin and Doré, 2002; Mosar et al., 2002; Scott et al., 2005). In this paper, we question this assumption. We also refer to independent work that demonstrates that the seismic velocity anomaly beneath Iceland is confined to the upper mantle. Together, these arguments question the presence of a deeply rooted and fixed plume beneath Iceland. However, a thermal anomaly in the shallow mantle is not ruled out.

Following White (1988), most workers have sought to explain the Early Tertiary volcanism in the NAIP in terms of impingement of a mantle plume, an early manifestation of the present Iceland anomaly. However, the recognition that NAIP magmatism can be grouped into two separate temporally and geographically constrained events (Saunders et al., 1997) has created problems for Iceland plume adherents. Gradually more complex plume models have evolved to explain the magmatic record. Rather than relating these magmatic events to a plume, we investigate alternative origins as consequences of plate tectonics.

A substantial body of geochemical and petrological papers related to the proposed Iceland plume have followed early work (by e.g., Schilling, 1973). In the early work, plumes were often considered to originate at the core-mantle boundary and to be enriched in incompatible trace elements and Sr/Nd concentrations (e.g., Campbell and Griffiths, 1990). Mid-ocean ridge basalts (MORB) were thought to be derived from a depleted upper mantle, whereas ocean-island basalts (OIB) were envisioned to be derived from the hot and enriched plume tail, tapping the lowermost mantle. The enrichment was thought to originate from oceanic crust and sediments brought down via subduction to the core-mantle boundary (the so-called "D" layer) from which the enriched material eventually recycled to Earth's surface via plumes (e.g., Hofmann and White, 1982).

Picrites and komatiites are generally considered strong evidence for elevated mantle temperatures associated with a hot plume tail. However, many geochemical and petrological observations on Iceland contradict this classic plume model (e.g., Campbell and Griffiths, 1990; Herzberg and O'Hara, 2002). For instance, the dominance of tholeiites on Iceland and, likewise, the subordinate presence of picrites (Foulger et al., 2003; Natland, 2003; Presnall, 2003) contradict the general assumption that a plume tail is very hot and a prime source of picrites, or that such a tail is present under Iceland. That the Iceland basalts are depleted rather than enriched also goes against the same general plume model. As a result, "modern" geochemical/petrological models for the Iceland plume have required modifications of the early models. For instance, Kempton et al. (2000) maintain that the Iceland plume is derived from the lower mantle, but point out that the depleted nature of Iceland basalts conflicts with the view of the lower mantle as being an enriched reservoir. Hence, their plume model was provided with a depleted sheath, added to the outside of the rising plume during a temporary stall at the lower-upper mantle transition zone. Notably, the core of the plume stem (derived from the lower mantle) is suggested to be heterogeneous and to contain "enriched streaks or blobs dispersed in a more depleted matrix" (Kempton et al., 2000, p. 255). This geochemically based plume model has the appearance of an ad hoc solution, tailor-made to match observations that conflict with the older general models (e.g., Campbell and Griffiths, 1990).

A viable alternative approach is to question the basic physical and chemical Earth model on which these ideas are based. There is, in fact, no general consensus on a compositional Earth model (compare, e.g., Campbell and Griffiths, 1990, with Kerr, 1995). A comparison between "plumist" and "nonplumist" schools of thought clearly reveals that fundamentally different Earth models exist, such as one invoking a completely reversed sequence of mantle layering with an enriched but heterogeneous upper mantle (typically the upper 660 km) above a depleted lower mantle (e.g., Anderson, 1996; Hamilton, 2003). Depending on the view taken, the same data may support fundamentally different models. At the very least, claims of distinctive geochemical or petrological "plume signatures" must be separated from evidence for a lower mantle origin or for plumes emanating from this level, because the rare element distribution in the mantle is not known for certain. Related to these arguments, recent publications (Anderson, 1989, 2003, this volume; Sheth, 1999: Foulger, 2003a; Hamilton, 2003) have suggested that the plume concept as used by many adherents is fundamentally impossible to disprove using the scientific method. Because plumes are not observed directly, their supposed nature and variability can be, and have been, adapted ad hoc to fit the evidence (regional, geodynamic, associated with hotspot tracks, geochemical, petrological, and geophysical) in any given instance.

PRESENT-DAY ANOMALIES IN THE NORTH ATLANTIC—INDICATORS OF A PLUME?

On Earth, the north Atlantic stands out because of its vast topographic and free air gravity anomaly that starts near the Azores in the south, peaks over Iceland, and extends north to the Arctic gateway (e.g., Sandwell and Smith, 1997; Andersen and Knudsen, 1998). Although a portion of the northeast Atlantic uplift can be accounted for by permanent uplift from overthickened oceanic crust (cf. Holbrook et al., 2001), a significant part (1.5–2 km centered on Iceland) has been ascribed to dynamic uplift (Jones et al., 2002b). The excess mass of this large topographic anomaly is judged too large to be supported by the strength of the lithosphere and is suggested to be supported by mantle upwelling (Vogt, 1983).

The larger north Atlantic region is characterized by a superregional ~60 m positive geoid anomaly (Fig. 2). This geoid

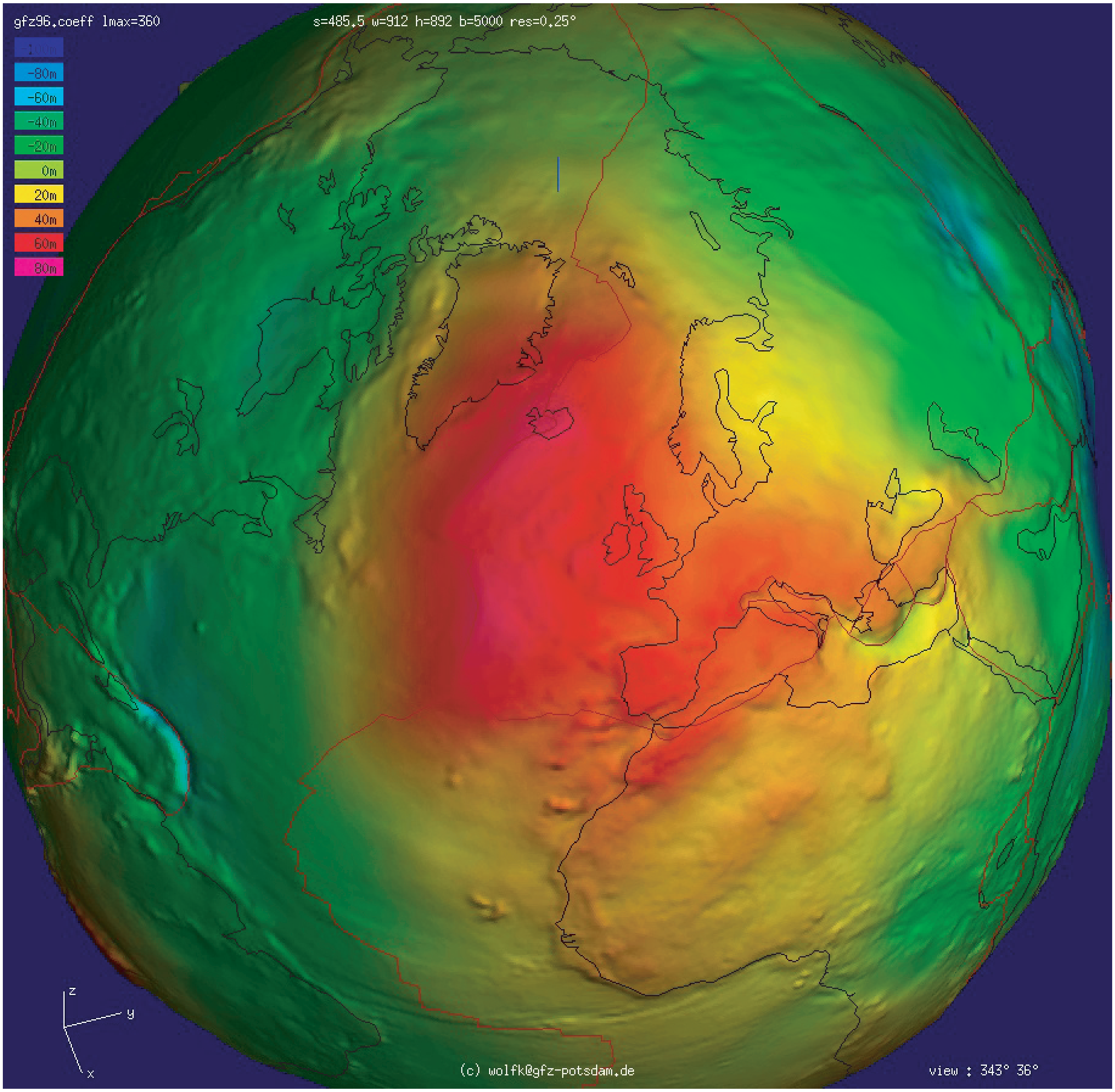

Figure 2. North Atlantic geoid anomaly (from Köhler, 2004). This prominent geoid anomaly is one of two such large positive anomalies on Earth; the other being located in Indonesia. Note the vast size of the anomaly, spanning the entire north Atlantic and extending across much of northwest Europe into northwest Africa. The geoid anomaly coincides approximately with the extent of the north Atlantic topographic-bathymetric anomaly (e.g., Smith and Sandwell, 1997) but is more widespread than the upper mantle low-velocity anomaly (e.g., Ritsema et al., 1999). The Indonesian positive geoid anomaly overlies a positive upper mantle velocity anomaly, and partly overlies a negative lower mantle velocity anomaly (Ritsema et al., 1999). lmax—maximum degree of Legendre functions; s—scaling; w and h—width and height of image; b—vertical exaggeration; res—grid resolution; view—viewpoint angles.

anomaly, which extends well into North Africa, Western Europe and eastern North America, has been interpreted as indicating upper mantle upwelling and the cause of the low mean ocean depths in the north Atlantic (Marquart, 1991). In general terms, it has been suggested that there is "considerable observational evidence that the topography of hotspot swells is directly associated with a geoid anomaly" and that this is "strong evidence that the excess topography and mass of the swell are compensated at depth by anomalously light (possibly hot) mantle material" (Malamud and Turcotte, 1999, p. 117). Nonetheless, the magnitude and vast extent of the north Atlantic geoid anomaly (~3000–4000 × 2000 km) is an order of magnitude larger than those of other hotspot swells (e.g., Monnereau and Cazenave, 1990). Actually, there are very few such large geoid anomalies on Earth, and there is thus no one-to-one correlation between them and other proposed plumes, deeply rooted or otherwise (compare, e.g., Courtillot et al., 2003, with Köhler, 2004).

The remarkable time-transgressive V-shaped ridges in the northeast Atlantic (e.g., Vogt, 1971) are "centered" on Iceland and extend up to 1000 km south along the Reykjanes ridge and several hundred km north along the Kolbeinsey ridge (Jones et al., 2002a). The expression along the Kolbeinsey ridge is considerably more subdued than along the Reykjanes ridge, possibly as a function of thicker sediment cover. These topographic ridges, which appear to be related to ~2-km thickness variations in the oceanic crust (e.g., White et al., 1995), are limited to oceanic crust ranging in age from approximately earliest Oligocene to Recent (e.g., Jones et al., 2002a). Various suggestions for the origin of the V-shaped ridges have been put forth, such as: (1) passage of hotter than normal asthenosphere traveling at high rates away from the Iceland plume (Vogt, 1971; White et al., 1995; Jones et al., 2002a; Smallwood and White, 2002), (2) plume pulses of constant temperature but increased flux (Ito, 2001), and (3) compositional changes in the mantle (cf. Jones et al., 2002a). Alternatively, it has been suggested that it is the troughs between the ridges that represent the anomalies (Hardarson et al., 1997) and that reduced melt production of the troughs relates to ridge migrations on Iceland. As far as we are aware, the V-shaped ridges around Iceland are not a general characteristic of ridge-centered "hotspots" elsewhere in the world. The only possible analog known to us is the Miocene seafloor south of the Azores (e.g., Cannat et al., 1999), which is a subdued example by comparison. Notably, the Tristan da Cunha hotspot and its presumed ancient predecessor responsible for the Walvis ridge–Rio Grande Rise (as well as the Paraná-Etendeka flood basalt provinces) have no reported V-shaped ridges.

Whole-mantle and teleseismic tomography reveals an upper mantle anomaly (velocity reduction) beneath Iceland (e.g., Ritsema et al., 1999; Megnin and Romanowicz, 2000; Foulger et al., 2001). Although some previous work (e.g., Bijwaard and Spakman, 1999) has suggested that the anomaly extends to the core-mantle boundary, this idea has been refuted by subsequent studies (Ritsema et al., 1999; Foulger et al., 2001; Montelli et al., 2003).

NAIP MAGMATISM—INDICATIONS OF A PLUME IN THE PAST?

Magmatism in the NAIP has been divided into two phases (e.g., Saunders et al., 1997). The first is the "Middle" Paleocene (ca. 62–58 Ma), mainly continent-based magmatism in the British Volcanic Province (BVP), eastern Baffin Island, and west Greenland. This first phase of magmatism followed a linear north-west trend that has been referred to as the "Thulean Volcanic Line" (Hall, 1981). The second phase took place in the latest Paleocene to earliest Eocene (ca. 56–53 Ma) along the northeast Atlantic margins (Fig. 3). This second phase of magmatism closely followed the northeast-trending margins of the northeast Atlantic, implying a strong relationship to plate tectonics. Volume estimates for the second phase lie in the range of 5–10 × 10^6 km^3, and the duration of the event may have been as short as 2–3 m.y. (White et al., 1987). If above-normal oceanic crust thickness is used as a measure of melt production, the event probably lasted until ca. 48 Ma, spanning ca. 6 m.y. (Holbrook et al., 2001).

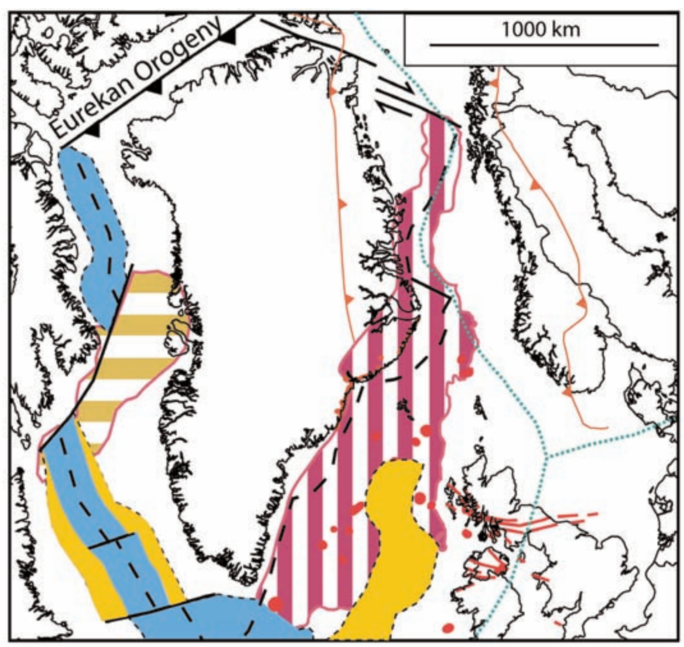

Figure 3. North Atlantic plate reconstruction to the Early Eocene (ca. 54 Ma) with the distribution of basalt flooded over the margins during breakup. The lava in west Greenland (brown striping) is older (ca. 62–58 Ma) than the lava along the northeast Atlantic margins (purple striping; ca. 56–53 Ma). Light blue marks Late Paleocene seafloor (ca. 61–54 Ma). Orange areas are transitional crust (probably serpentinized mantle). Red blobs are seamounts and central igneous complexes, largely of Paleocene age (e.g., Stoker et al., 1993). Red lines are simplified Early Paleocene dike swarms. Black dashed lines are existing or incipient axes of seafloor spreading. Green dotted lines mark Iapetus sutures. Red barbed lines are Caledonian thrust fronts. Note that shortening related to the Eurekan orogeny in the Canadian Arctic Islands has not been palinspastically reconstructed. Modified after Lundin and Doré (2005).

Regardless of the duration, the second phase was considerably more voluminous than the first.

Following the work by White et al. (1987) and White (1988), many workers have explained the NAIP magmatism as a result of the "Iceland plume." However, the lack of general agreement on how the plume has appeared in space and time has led to a variety of proposed models, ranging from a single point whose position can be mapped on the overriding plates (e.g., Lawver and Müller, 1994) to a super-regional phenomenon simultaneously affecting areas 2000 km apart (e.g., Smallwood and White, 2002). One proponent of the first school of thought has suggested a very long-lived (ca. 250 m.y.) Iceland plume, responsible for the earliest Triassic Siberian traps, Early Cretaceous magmatism in and around the Amerasia Basin, Early Paleocene magmatism in west Greenland, the Late Paleocene–Early Eocene magmatism during the northeast Atlantic breakup, and, of course, Iceland today (Lawver et al., 2002). As the Amerasia Basin and surrounding region has recently been proposed to represent a large igneous province (LIP) (Maher, 2001), the same plume is viewed to have caused three LIPs: (1) the Siberian traps (ca. 250 Ma), (2) the Arctic LIP (ca. 120 Ma), and (3) the NAIP LIP (ca. 62–53 Ma). There is no evidence for a hotspot track between these LIPs.

As shown in the introduction to this chapter, a voluminous literature refers to the migration of the hotpot position on the lithosphere across Greenland during the Paleocene. This literature, however, presupposes the fixity of the plume, and relies on calculations of where the plume "ought to have been," such that lithospheric drift can have brought the constructional plate boundary to its present position directly above the plume (i.e., associating the Iceland "hotspot" with the plume). There is, however, no convincing a priori regional, petrological, or geophysical evidence for such a hotspot trail across Greenland (Lundin and Doré, 2005). The foundation of so many derivative geological interpretations resting on a presumptive and unproven model—one not even supported by some plume advocates—should be a concern to all those studying north Atlantic geological history.

It has been argued that support for plate drift over a fixed Iceland plume is provided by proposed eastward jumps of the rift zone on Iceland in the Miocene (Saemundsson, 1979; Björnsson, 1983). However, the eastern rift zone in Iceland has dominantly shifted westward (Helgason, 1984), making the importance of rift zone shifts unclear (cf. Foulger, 2003b).

The division of the NAIP magmatism into two different regions, oriented approximately orthogonally to one another, has created geometric problems for plume models. Onset of basaltic magmatism in west Greenland and the BVP (Ritchie et al., 1999; Jolley and Bell, 2002) was essentially simultaneous, which is difficult to explain, considering that the plume supposedly was located near the northwestern limit of this magmatic province. Such a location would have been a comparatively short distance from the already existing spreading axis in the nonmagmatic Labrador Sea, necessitating the adoption of a special case for lithosphere geometry to explain why this margin was not volcanic (e.g., Gill et al., 1992). The proposal of Smallwood and White (2002) that the early NAIP was caused by a major (2000-km) northwest-southeast sheetlike plume represents an attempt to explain the geologically instantaneous onset of magmatism across the area in terms of a plume model. If true, it would invalidate all other hypotheses that characterize the "plume" as a point across which the lithosphere has migrated since (perhaps) the Triassic. Our problem with this model stems mainly from the fundamental geometric changes through time that would have to be displayed by such a plume to satisfy all the NAIP data. The plume would have had to consist of several intersecting sheets to explain its distribution in the early NAIP; to have refocused into a northeast-southwest sheet to explain the later NAIP phase along the new passive margin; and at some time during the Cenozoic, would be required to have collapsed into a narrow stem beneath the constructional plate boundary (i.e., into the present Iceland "plume"). Furthermore, such a stem would have to have been "captured" by the spreading ridge (or vice versa) to explain why lithospheric drift has not at the present day placed northwest Britain above the plume (see also discussion in Lundin and Doré, 2005).

We consider it likely that the linear zone of magmatism constituting the early NAIP was associated with a transient rift attempt, intermediate in time and space between the Late Cretaceous Labrador Sea and the Early Eocene northeast Atlantic, an idea previously suggested by Dewey and Windley (1988) and developed in more detail by Lundin and Doré (2005) (Fig. 4). In the BVP, this proposed rift is characterized by northwest-trending mafic dike swarms, whose frequency and consistent trend clearly indicate a northeast-southwest extensional stress field (England, 1988). Other potential expressions of this extension are:

1. The northwest-trending fjord and dike trends of the Faeroes;
2. The northwest-trending fissures and feeder dikes penetrating the Faeroe lower series basalts and sourcing the middle series lavas (Waagstein, 1988);
3. The so-called "transfer trend" that crosses and segments the Faroe-Shetland Basin and other parts of the northeast Atlantic seaboard (Rumph et al. 1993);
4. The fjord trend of east Greenland and recently reported northwest-trending half-graben structures containing Upper Cretaceous and Paleogene shallow marine sediments east of Kangerlussuaq (see Fig. 1) (Larsen and Whitham, 2005); and
5. The fjord trend and a set of northwest-trending Paleocene extensional faults in the volcanic area of west Greenland (Nøhr-Hansen et al., 2002).

This transient extensional arm was consistent with the propagation direction of the southern north Atlantic and Labrador Sea in the latest Cretaceous and Paleocene (e.g., Johnston et al., 2001), and can be viewed as responding to the same far-field stresses. It probably represents an attempt to find a new and more direct extensional pathway from southern Europe to newly developed

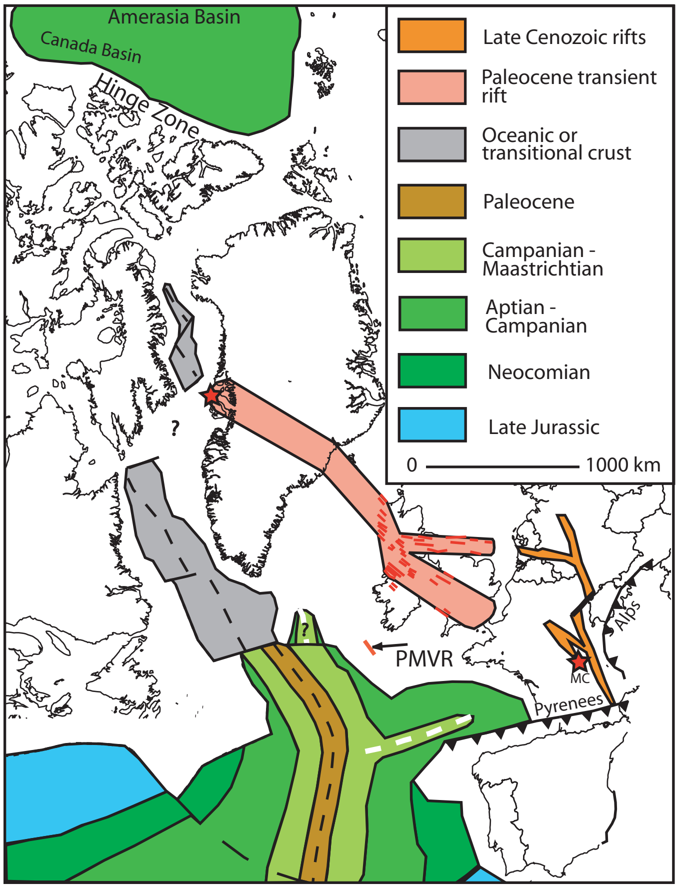

Figure 4. Simplified north Atlantic plate reconstruction to 60 Ma, illustrating the proposed transient rift, along the main dike trend in the British Volcanic Province to west Greenland, and possibly linking with early spreading centers in Baffin Bay. Note the consistency of this northwest-trending extensional-magmatic belt with plate separation vectors that had been active from mid-Cretaceous times. The Late Cenozoic European rift system (from Ziegler, 1992) is included out of age context on this map to illustrate later, more evolved fragmentation of the European plate, with associated magmatism, occurring approximately normal to the Alpine compressive front. Note that shortening related to the Eurekan orogeny in the Canadian Arctic Islands has not been palinspastically reconstructed. MC—Massif Central; PMVR—Porcupine Median Volcanic ridge. The red star denotes the west Greenland Paleocene magmatic area. Equal area stereographic projection. Reproduced from Lundin and Doré (2005).

spreading centers in Baffin Bay, which were otherwise separated from the Labrador Sea spreading by a major continental transform in the present Davies Strait (Fig. 4).

The transient northwest-southeast extensional arm of the early NAIP was abandoned during the Late Paleocene–Early Eocene as seafloor spreading was initiated through the northeast Atlantic, essentially by exploitation of the Caledonian fold belt. We consider the initiation of northeast Atlantic spreading and the Caledonian reactivation to be critical factors in initiation of the second, voluminous phase of NAIP magmatism. This concept is further developed in succeeding sections.

PALEOCENE VERTICAL MOTIONS IN THE NORTHEAST ATLANTIC

Paleocene regional extension preceding northeast Atlantic breakup is observed on the Vøring margin, but is otherwise faintly expressed or absent (e.g., Doré et al., 1999; Roberts et al., 1999). A common explanation is that a central rift zone may have become masked by landward-flowing flood basalts during incipient spreading (e.g., Roberts et al., 1999; Skogseid et al., 2000), and/or that faulting in areas not masked by basalts may be below seismic resolution or diffusely accommodated (e.g., Dean et al., 1999; Skogseid et al., 2000). Another possible explanation for the faint signs of extension may be that the seismically visible upper crust is thinned considerably less than the whole lithosphere, a phenomenon termed *depth dependent stretching* (e.g., Davis and Kusznir, 2004).

Paleocene uplift of the landmasses bordering the northeast Atlantic margins appears common. The northern British Isles were uplifted and acted as an important provenance area for Late Paleocene and Eocene sands shed southeast into the North Sea (e.g., Den Hartzog Jager et al., 1993) and northwest into the Faroe-Shetland Basin (e.g., Mitchell et al., 1993; Lamers and Carmichael, 1999). This uplift has been described as a permanent effect related to magmatic underplating caused by the Iceland plume (e.g., Brodie and White, 1994). Uplift and erosion of the Norwegian mainland took place throughout the entire Paleocene, based on sediment distribution on the mid-Norwegian margin (Henriksen et al., 2004). Particularly, the presence of Danian sandstones is worth emphasizing, as they reveal a comparatively early onset of uplift. Although the deltaic portions of the Danian system have been removed by erosion, it appears clear that these sandstones entered the mid-Norwegian margin along major tectonic boundaries; a northern input was located in the Vestfjord Basin, inboard of the Lofoten Islands, and demonstrates uplift of northern Norway. The Norwegian mainland has not been proposed to be permanently uplifted by underplated material, largely due to lack of contemporaneous igneous activity. The seismically observed high-velocity lower crustal layer (typically interpreted as underplated material) ends south of the Bivrost Lineament (i.e., south of the Lofoten Islands) (Mjelde et al., 2005). Thus the northern Norway uplifted area was located beyond the generally assumed radial limitation of the Iceland plume (e.g., White and McKenzie, 1989; Mjelde et al., 2005). Various suggestions exist for the cause of Early Tertiary uplift of the Norwegian mainland, including: (1) rift shoulder uplift (Riis, 1996), and (2) convective removal of a basal part of the lithospheric mantle by a Rayleigh-Taylor mantle instability related to the Iceland plume (Nielsen et al., 2002).

Forward and reverse 2D modeling of syn- and post-rift stratigraphy along geoseismic profiles in the northern North Sea permitted interpretation of a transient Paleocene uplift phase (Nadin and Kusznir, 1995; Nadin et al., 1997). These models converged at the time of the Late Jurassic rifting, but the reverse modeling revealed anomalous water depth in Paleocene time, which was interpreted as an effect of dynamic uplift from the Iceland plume. The modeling constrained the uplift no more precisely than to the Paleocene. Prograding Late Paleocene deltaic sequences provided constraints on palaeobathymetry. In both the northern North Sea and Faroe-Shetland Basin, turbidites derived from the uplifted northern British Isles and East Shetland Platform started entering the basins in the Early Paleocene. By the Late Paleocene (Thanetian), the prograding deltas had reached the central parts of the Faroe Shetland Basin (e.g., Lamers and Carmichael, 1999; Naylor et al., 1999). In the northern North Sea, the southeastward prograding deltas are of latest Paleocene age (e.g., Den Hartog Jager et al., 1993; Morton et al., 1993).

Transient uplift has subsequently been assumed for the mid-Norwegian margin (Roberts et al., 1997; Kusznir et al., 2005), on the assumption of a ~2000 km axisymmmetric plume-related uplift (cf. White and McKenzie, 1989). However, such uplift is more uncertain in this region because of the uncertainty in timing and magnitude of earlier Mesozoic rifting, as well as the palaeobathymetry of the earlier syn-rift sequences (if imaged at all). It is, nevertheless, clear from industry wells and Ocean Drilling Project (ODP) (Eldholm et al., 1989) borehole data that the Vøring Marginal High and local structural highs (e.g., Gjallar ridge, Vema Dome) were uplifted and eroded in the Paleocene. Uplift of the outer margins is also revealed by the presence of seaward-dipping reflector sequences (SDRS), which are generally accepted to have formed during subaerial spreading.

Clift and Turner (1998) could neither confirm nor exclude the presence of transient uplift in the Rockall and Faroe-Shetland areas, or in the Moray Firth, whereas Nadin et al. (1997) concluded that the transient Paleocene uplift also affected the Faroe-Shetland Basin. It is clear from the deltaic sequences in the basin that the southern part of the basin was at wavebase in the Late Paleocene. Transient uplift has also been proposed for the Porcupine Basin area (Jones et al., 2001), and has been related to the build-out of middle-to-earliest Late Eocene deltas into the basin (McDonnel and Shannon, 2001). Jones et al. (2001) interpreted this uplift event to be coeval with the interpreted transient uplift event in the northern North Sea and Faroe-Shetland Basin (Nadin and Kusznir, 1995; Nadin et al., 1997). However, the Porcupine Basin deltas are considerably younger than those in the northern North Sea and Faroe-Shetland Basin, and considerably younger than the Danian sandstones off northern Norway. If they formed because of the same uplift event, there is considerable diachronicity between the different areas (ca. 20 m.y.). The northern North Sea and Faroe-Shetland Basin deltas relate to uplift predating the northeast Atlantic breakup, whereas the middle-to-earliest Late Eocene age of the deltas in the Porcupine Basin must post-date breakup. Hence, while the northern North Sea and Faroe-Shetland Basin areas were subsiding rapidly, supposedly due to breakup-related collapse of the dynamic plume uplift, the northern Porcupine Basin area was being uplifted. If the ages of the observed deltas are correct, one cannot easily propose the same mechanism for the different areas.

The uplift and subsidence history of the Kangerlussuaq area in east Greenland (see Fig. 1) is pertinent to the issue of an ancient Iceland plume, because this is the region into which the plume is supposed to have migrated from underneath Greenland (e.g., Lawver and Müller, 1994). This area experienced gentle subsidence in the Late Cretaceous, but the subsidence pattern was reversed in the Paleocene, with peak uplift after 65 Ma, followed by renewed subsidence ca. 61 Ma, just prior to deposition of the main thick flood basalt sequence on the Blosseville Kyst. Thus the uplift event lasted from the onset of the Paleocene to the Late Paleocene. Remnants of Lower-Middle Eocene marine strata demonstrate that the area subsided below wavebase after breakup. Apatite fission track analysis (AFTA) reveals that the Kangerlussuaq area subsequently was uplifted and eroded ~4–6 km. This uplift clearly post-dates the Lower-Middle Eocene, and may have started in the Early Oligocene (Clift et al., 1998) and accelerated through the Neogene (Hansen and Brooks, 2002). Regardless of the precise onset of this permanent uplift, which often is assumed to reflect addition of underplated material, it considerably post-dated the northeast Atlantic breakup. Clift et al. (1998) associated the uplift with the arrival of the Iceland plume, but also recognized that AFTA (Hansen, 1996) precluded a plume migrating eastward to the Kangerlussuaq area from the interior of Greenland. More recent work by Hansen and Brooks (2002) has confirmed the work of Hansen (1996), that is, precluding a "migrating" plume.

AFTA (Hansen, 2000) reveals that southeast Greenland experienced many phases of uplift and erosion since the Caledonian, with enhanced rates in the Neogene. There are no signs of relaxation following the northeast Atlantic breakup. North of Kangerlussuaq, the Jameson Land Basin (see Fig. 1) subsided rapidly during extrusion of the Early Eocene lava sequences (Larsen and Marcussen, 1992). The basin reached a maximum burial depth between ca. 55 and 20 Ma and exhumation clearly post-dates the northeast Atlantic breakup (Hansen, 2000).

The Nussuaq Basin area in west Greenland (see Fig. 1) underwent short-lived middle Paleocene uplift and erosion, followed by significant rapid subsidence during basalt extrusions (Japsen et al., 2005). This volcanism occurred during Chron 27 (ca. 61 Ma), when the Labrador Sea was either opened or undergoing opening (cf. Roest and Srivastava, 1989; Chalmers and Pulvertaft, 2001).

Clift and Turner (1998) backstripped a number of wells in the North Sea, Faroe-Shetland Basin, and Rockall Trough and calculated underplating thicknesses from discrepancies between modeled and measured depths to basement. This work suggested that underplating reached ~900 km into Great Britain from the northeast Atlantic margin. Notably, heatflow estimates based on AFTA and vitrinite reflectance (VR) in the Faroe-Shetland Basin are considerably smaller than those predicted from estimated underplating thicknesses. Green et al. (1999) also reported that areas close to the British Atlantic margin lack evidence for significantly elevated Early Tertiary basal heatflow, despite the proximity to the continent-ocean boundary and the extensive Early Tertiary igneous activity. Clift and Turner (1998) suggested the lack of evidence for increased Paleocene heatflow could relate to gradual emplacement of underplated material, but also opined the possibility that the estimated underplating thicknesses could be too large. The effects of elevated mantle temperatures related to a plume, addition of underplated material to the base of the crust, and depth-dependent stretching should all increase the heatflow. It is therefore surprising that indirect measures of heatflow, such as AFTA and VR, are not more dramatic.

Early Tertiary subsidence without significant observable extensional faulting is a general characteristic for many basins along the northwest European seaboard (see Fig. 1 for locations), such as mid-Norwegian Lofoten, Vøring, and Møre basins (Roberts et al., 1997; Davis and Kusznir, 2004; Kusznir et al., 2005); Faroe-Shetland Basin (Turner and Scrutton, 1993; Dean et al. 1999); northern North Sea (e.g., White and Latin, 1993); Porcupine Basin (Tate, 1993; Jones et al., 2001); and Orphan Basin off Newfoundland (Keen et al., 1987). As noted by Joy (1992), the northern North Sea, Porcupine Basin, and Orphan Basin are not located adjacent to the northeast Atlantic and therefore cannot easily be associated with pre-breakup extension of the northeast Atlantic. Rather, these basins were rifted in the Late Jurassic and Early Cretaceous and were well into their post-rift thermal subsidence phases. This type of anomalous subsidence is not a phenomenon exclusive to the northeast Atlantic, however, and has also been reported from the southern north Atlantic (nonvolcanic) margins (e.g., Driscoll and Karner, 1998; Davis and Kusznir, 2004), the south Atlantic (Karner et al., 2003), and from other margins worldwide (Driscoll and Karner, 1998; Davis and Kusznir, 2004). There are also indications of such anomalous subsidence in abandoned continental rifts (Bois, 1992).

Some workers have reported anomalous Paleocene subsidence in the northern North Sea and Faroe-Shetland Basin (e.g., White and Latin, 1993; Hall and White, 1994) whereas others claim transient uplift for the same time period (e.g., Nadin and Kusznir, 1995; Nadin et al., 1997). The latter group claims that the first group's results were in error due to applying the 1D Airy backstripping technique. We agree that 2D forward and reverse modeling of syn- and post-rift stratigraphy, including flexural strength to the crust, is a superior method to 1D Airy backstripping, but also note that the timing and magnitude of rifting, as well as the palaobathymetry of syn-rift strata of earlier rift events, are not always well constrained. Depending on which subsidence analysis one selects, significant differences in Paleocene uplift and subsidence are apparent between adjacent areas, both radially away from the presumed plume center (Faroe-Shetland Basin versus northern British Isles) and tangentially to it (e.g., East Shetland Platform versus northern North Sea).

In summary, explanations of Paleocene uplift and subsidence patterns in terms of mantle plume impingement are only feasible in microcosm. On a broad, regional scale, their complexity in both time and space argues against a super-regional phenomenon, such as plume impingement, and points instead to a wide variety of causes.

Post-breakup vertical motions are also prominent along the northeast Atlantic margins, including epeirogenic uplift. These motions depart from theoretical thermal subsidence patterns (e.g., Steckler and Watts, 1978). A full discussion is beyond the scope of this paper, but may be found in Stoker et al. (2005).

SYMMETRIC GFR

The aseismic GFR (see Fig. 1) forms a bridge between Greenland and northwest Europe, and consists of abnormally thick oceanic crust, of the order of 30 km thick (Bott, 1983; Richardson et al., 1998; Smallwood et al., 1999; Holbrook et al., 2001). Although it is clear that the GFR has formed from anomalous melt production, the cause is less certain. One view is that the above-normal thickness (>7 km) results from elevated temperatures associated with a mantle plume (e.g., White and McKenzie, 1989; Smallwood et al., 1999). However, alternative views exist for the cause of the excessive melting, such as melting of a fertile upper mantle (e.g., Anderson, 1996; Foulger, 2002, 2003a).

A problem with the assumption that the Iceland "plume" is fixed is that there is no proven time-transgressive hotspot track away from Iceland. The GFR has been suggested to be all or part of such a track (e.g., Morgan, 1971, 1981; Holbrook and Keleman, 1993; Lawver and Müller, 1994; Eldholm et al., 2000). However, a problem with such an interpretation is that to a first order, the GFR is a symmetric construction. And although the ridge becomes younger toward Iceland, it is not time-transgressive in a classic way (i.e., one direction) for hotspots, such as the Hawaii–Emperor Seamount Chain (e.g., Wilson, 1965; Morgan, 1971).

The hot-plume-tail explanation for generating the above-normal GFR crustal thickness is difficult to accept if at the same time the plume is fixed with respect to the deep mantle. A corollary to the fixed hotspot framework, which predicts that the Iceland "plume" was located somewhere under south-central Greenland in the Paleocene (see Fig. 1), is that the plume can never have been located east of its current position. Thus the hot plume tail can never have been directly underneath the eastern half of the ridge (the Iceland-Faeroe ridge). Vink (1984a) recognized this problem and suggested a model whereby a fixed plume under Greenland fed hot mantle material laterally to the nearest spreading axis (Reykjanes ridge) and thereby generated the GFR. However, palaeomagnetic data (e.g., Torsvik et al., 2001b) reveals that both Greenland and Eurasia have moved significantly northward since breakup, implying that the plume-fed plateau should be distinctly V-shaped, which it is not.

Although several hotspots are documented to be unstable positionally, (e.g., Koppers et al., 2001; Tarduno et al., 2003), coincidence or plate tectonic control must be invoked to make the Iceland "plume" drift in the same direction and at a similar rate as the overriding plates to form the linear GFR. Such behavior seems unlikely for a plume emanating either from the core-mantle boundary or the 660-km discontinuity, and whose rise toward the surface is neither affected by convection in the upper mantle nor by the overriding plates. Notably, some models now permit plumes to sway and be tilted in the lower mantle (e.g., Steinberger and O'Connell, 1998). At the very least, if Iceland and the GFR are associated with a mantle plume, then the fixed hotspot framework cannot apply to Iceland.

OPENING OF THE NORTH ATLANTIC AND ARCTIC—FINAL BREAKUP OF PANGEA

The final breakup of Pangea relates to opening and linkage between the northeast Atlantic and the Arctic Eurasia Basin and is often considered to have started synchronously in the Early Eocene (Chron 24b, ca. 54 Ma). A relatively common perception is that the northeast Atlantic breakup was triggered by the Iceland plume (e.g., White, 1988; White and McKenzie, 1989; Hill, 1991; Skogseid et al., 2000). In this section, we use regional geologic and plate tectonic considerations to argue that the northeast Atlantic and Arctic breakup was a natural consequence of lithospheric strength distribution and plate kinematics rather than having been governed by lithospheric weakening from a plume.

The Labrador Sea margins were rifted in the Early Cretaceous (ca. Barremian) (Balkwill, 1987; Chalmers and Pulvertaft, 2001), and seafloor spreading may have started in the Late Cretaceous (Chron 33, ca. 81 Ma; Figs. 1 and 4) (Roest and Srivastava, 1989; Srivastava and Roest, 1999) or at least no later than by the Early Paleocene (Chron 27) (Chalmers and Laursen, 1995; Chalmers and Pulvertaft, 2001). Although the onset of spreading is disputed, there is no dispute about the Chron 27–13 anomalies in the Labrador Sea, or about the orientation of fracture zones associated with the two phases of opening (pre-and post-Chron 24).

Ziegler (1988) suggested that rifting in the Labrador Sea and Baffin Bay extended into the Canadian Arctic Islands, rather than being accommodated by significant lateral motion in Nares Strait (see Fig. 1). This view is consistent with the apparent continuity of geologic features across Nares Strait (e.g., Dawes and Kerr, 1982; Okulitch et al., 1990). Recently, magnetic anomalies correlating to Chron 26n or Chron 25n (Middle Paleocene) have been suggested to exist in Baffin Bay (Oakey et al., 2003), but the nature of the anomalies, seafloor or otherwise, is uncertain. From seismic refraction data, it seems clear that seafloor, at least, never propagated beyond the northern tip of Baffin Bay (e.g., Reid and Jackson, 1997).

We argue that when the northward propagating seafloor in the Labrador Sea had reached the northern tip of Baffin Bay, possibly in the Middle Paleocene, it was approaching the hinge zone to the Amerasia Basin passive margin (Figs. 1 and 4). Although the age of the Amerasia Basin is not firmly established, a Hauterivian age (ca. 120 Ma) of inception appears reasonable (e.g., Grantz et al., 1990). The Amerasia Basin hinge zone was therefore on the order of 60 Ma old when approached by the Labrador Sea–Baffin Bay rift. The strength of this hinge zone may have acted as a barrier to further propagation and triggered plate reorganization, analogous to the way the Neo-Tethyan hinge zone is suggested to have hindered further propagation of the Red Sea–Gulf of Suez rift (Steckler and ten Brink, 1986).

Linkage between the Labrador Sea–Baffin Bay and the Eurasia Basin may have already been achieved in the Middle Paleocene (Brozena et al., 2003). A magnetic anomaly predating Chron 24 in the Eurasia Basin (Vogt et al., 1979) is now proposed to be Chron 25 (ca. 56 Ma) (Brozena et al., 2003). Regardless of whether the Eurasia Basin started to open at Chron 25 or 24, the site of opening must have been dictated by the strength of the Amerasia Basin (Vink, 1984b) and followed its shear margin (cf. Grantz et al., 1990), from which the Lomonosov ridge (a microcontinent) was split off (see Fig. 1). Soon thereafter (in the Early Eocene, Chron 24), the northeast Atlantic opened along the Caledonian fold belt and the associated Mesozoic rift system.

During the following ca. 20 m.y. (i.e., until the earliest Oligocene; Fig. 5), simultaneous spreading occurred along two arms of the north Atlantic: the Labrador Sea–Baffin Bay and the northeast Atlantic. This simultaneous spreading was linked at a triple junction south of Greenland (Kristoffersen and Talwani, 1977), and the northward motion of Greenland induced the Eurekan Orogeny (Oakey, 1994). Oakey's (1994) study of west-central Ellesmere Island and East Axel Heiberg Island revealed a dominant structural transport direction of ~N60°W, corresponding almost perfectly with the calculated N67°W convergence direction between Greenland and North America (Roest and Srivastava, 1989; Srivastava and Roest, 1999). The angle of convergence was thus very high, preventing significant lateral motion along the Wegner Transform (located in Nares Strait–trending ~N40°E), and providing a possible explanation for why the Labrador Sea–Baffin Bay was not a favorable link between the Atlantic and Arctic. The end of the Eurekan Orogeny has been associated with the termination of seafloor spreading in the Labrador Sea and Baffin Bay near Chron 13 (ca. 35 Ma) (Oakey, 1994).

Despite the difficulty in confidently determining the youngest magnetic anomaly in the Labrador Sea (P. Vogt, 2004, personal comun.), Oakey's (1994) suggestion that spreading in the Labrador Sea ended at Chron 13 seems reasonable. This timing coincides with the marked change in relative plate motions that tranformed the southwest Barents Sea shear margin to a rift margin (e.g., Faleide et al., 1993), thereby initiating the successful linkage between the Arctic Eurasia Basin and the northeast Atlantic (see Fig. 1). Further support is provided by Chron 13 being the first continuous anomaly along the western side of the Reykjanes ridge, in the area previously occupied by the triple junction south of Greenland (Kristoffersen and Talwani, 1977). It can therefore be argued that initiation of the continuous Eurasia Basin–northeast Atlantic ridge system made the existence of the Labrador Sea–Baffin Bay arm of the north Atlantic redundant. Likewise, on a smaller scale, linkage between the Kolbeinsey and Mohns ridges near Chron 13 has been proposed to have terminated spreading along the Aegir ridge (Lundin and Doré, 2005).

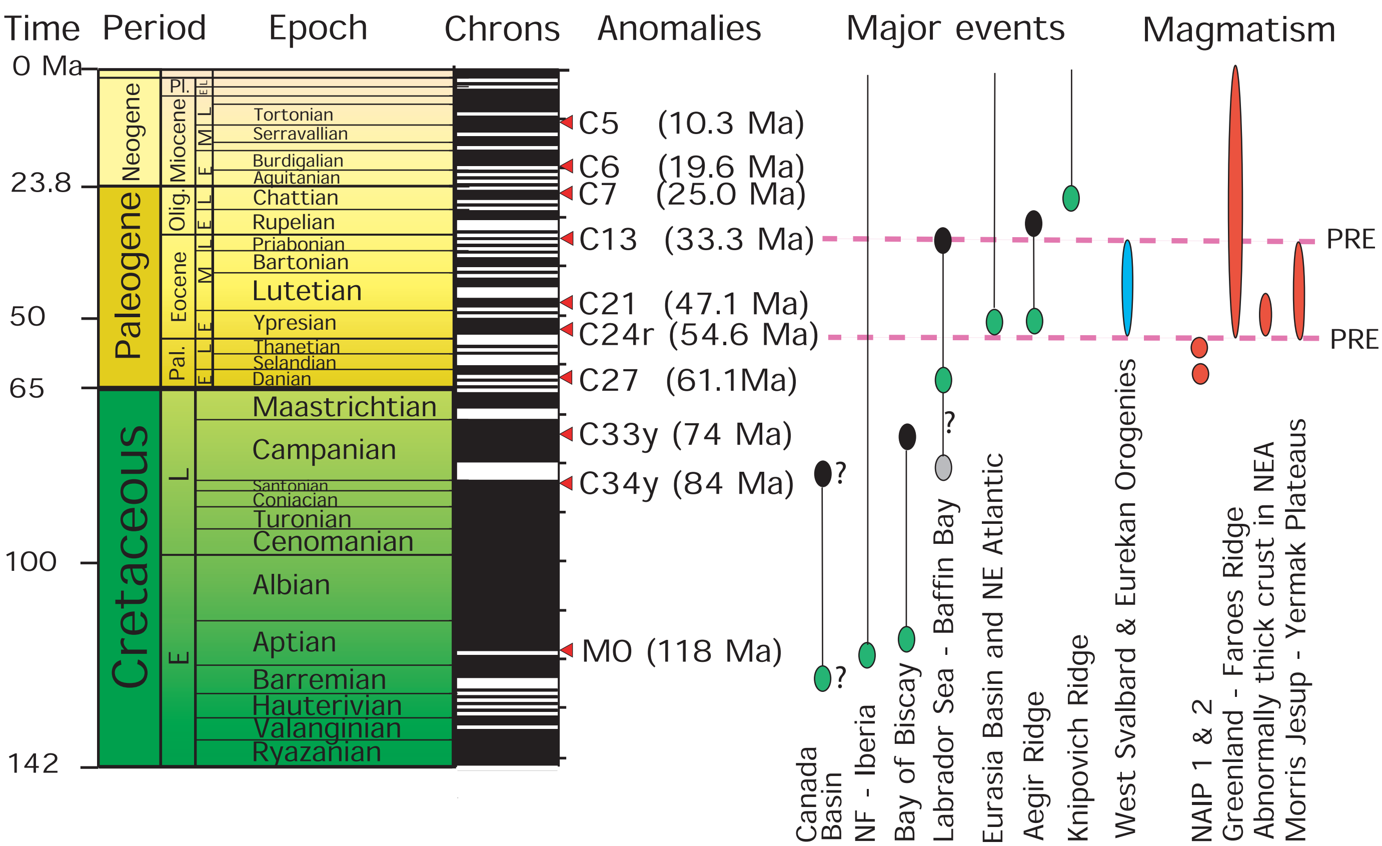

Figure 5. Chronologic events diagram showing the relationship between major tectonic and magmatic events. NAIP—north Atlantic Igneous Province; NEA—northeast Atlantic; NF—Newfoundland; PRE—Plate reorganization event. Reproduced from Lundin and Doré (2005).

In summary, while far-field stresses in the latest Cretaceous to the "middle" Paleocene were attempting to rupture Laurasia along northwest-southeast lines, it seems that continued northwest propagation of the Labrador Sea and Baffin Bay was hindered by the Amerasia Basin hinge zone. The suggested transient BVP–west Greenland rift (see Fig. 4) was probably abandoned for the same reason. Continued rupture of Pangea became focused on the Caledonian fold belt. Survival of the northeast Atlantic at the expense of the Labrador Sea–Baffin Bay is attributed to the high angle of convergence across the Wegner Transform, making lateral motion difficult, and to the relative change in plate motion at Chron 13. Notably, it was Eurasia that changed direction (Torsvik et al., 2001a), and hence the linkage between the Eurasia Basin and the northeast Atlantic became natural. Lithospheric weakening by an "Iceland plume" need not be invoked to explain opening of the northeast Atlantic.

EXTENT OF CENTRAL ATLANTIC, SOUTH ATLANTIC, AND ARCTIC VOLCANIC PASSIVE MARGINS/LIPS

NAIP magmatism can be subdivided into two phases that occurred in zones oriented perpendicular to one another. If viewed together, these crossing magmatic belts can be interpreted as spokes of a circle ~2000 km in diameter, which in turn has been suggested to reflect a typical plume head size (e.g., White and McKenzie, 1989). Northeast Atlantic volcanic passive margins are confined between the southern tip of Greenland and northeast Greenland–Lofoten Islands (see Fig. 1), a distance of ~2000 km. To evaluate the entire Atlantic, we briefly describe the central and south Atlantic.

The Early Jurassic Central Atlantic Magmatic Province (CAMP; see also http://www.auburn.edu/academic/science_math/res_area/geology/camp/CAMPindex.html) is approximately three times wider than the NAIP, with dike swarms extending from north-central Brazil well into Iberia, a distance of ~6000 km. The reconstructed width of the region affected by dike swarms is ~2000 km (Figs. 6 and 7). These dike swarms and flood basalts are of similar age (ca. 201–198 Ma) and occur in eastern North America (McHone, 1996, 2000), northwest Africa (e.g., Sebai et al., 1991), and Brazil (Marzoli et al., 1999; De Min et al., 2003). The CAMP event predated the central Atlantic breakup by ca. 25 m.y. but occurred synchronously with the rifting (e.g., Schlische, 1993) that ultimately led to continental separation in the Middle Jurassic (ca. 175 Ma) (Klitgord and Schouten, 1986).

SDRS and an associated high-velocity lower crust are well defined along the North American margin, where they coincide with the so-called "East Coast Magnetic Anomaly" (ECMA) (Oh et al., 1995). A high-velocity layer at the base of the crust is typically interpreted as underplated material added during the final phase of rifting and early breakup, analogous to the interpretation of similar bodies in the northeast Atlantic. Volumes estimated for the high-velocity layer are ~3.2×10^6 km^3 (Holbrook and Keleman, 1993). In addition, an area on the order of 5×10^5 km^2 is proposed to have been flooded by continental flood basalts (McHone, 1996). Volume estimates for the Brazilian part of the CAMP are 2×10^6 km^3, and the total area affected by CAMP magmatism is estimated to be ~7×10^6 km^2, making it one of the largest continental flood basalt provinces (see http://www.largeigneousprovinces.org/record.html).

We are unaware of reports of corresponding SDRS along the conjugate northwest African margin, but the so-called "S1 anomaly" off Morocco (Roeser, 1982) is a candidate for an equivalent anomaly to the ECMA (our basis for the outline of SDRS in Fig. 6). A lack of SDRS on the northwest African margin would imply asymmetry between the central Atlantic conjugate margins (as suggested by e.g., Eldholm et al., 1995), but if one accepts the model of SDRS development (e.g., Pálmason, 1980; Mutter et al., 1982), SDRS should form symmetrically on conjugate margins.

Traditionally, CAMP magmatism has been attributed to a

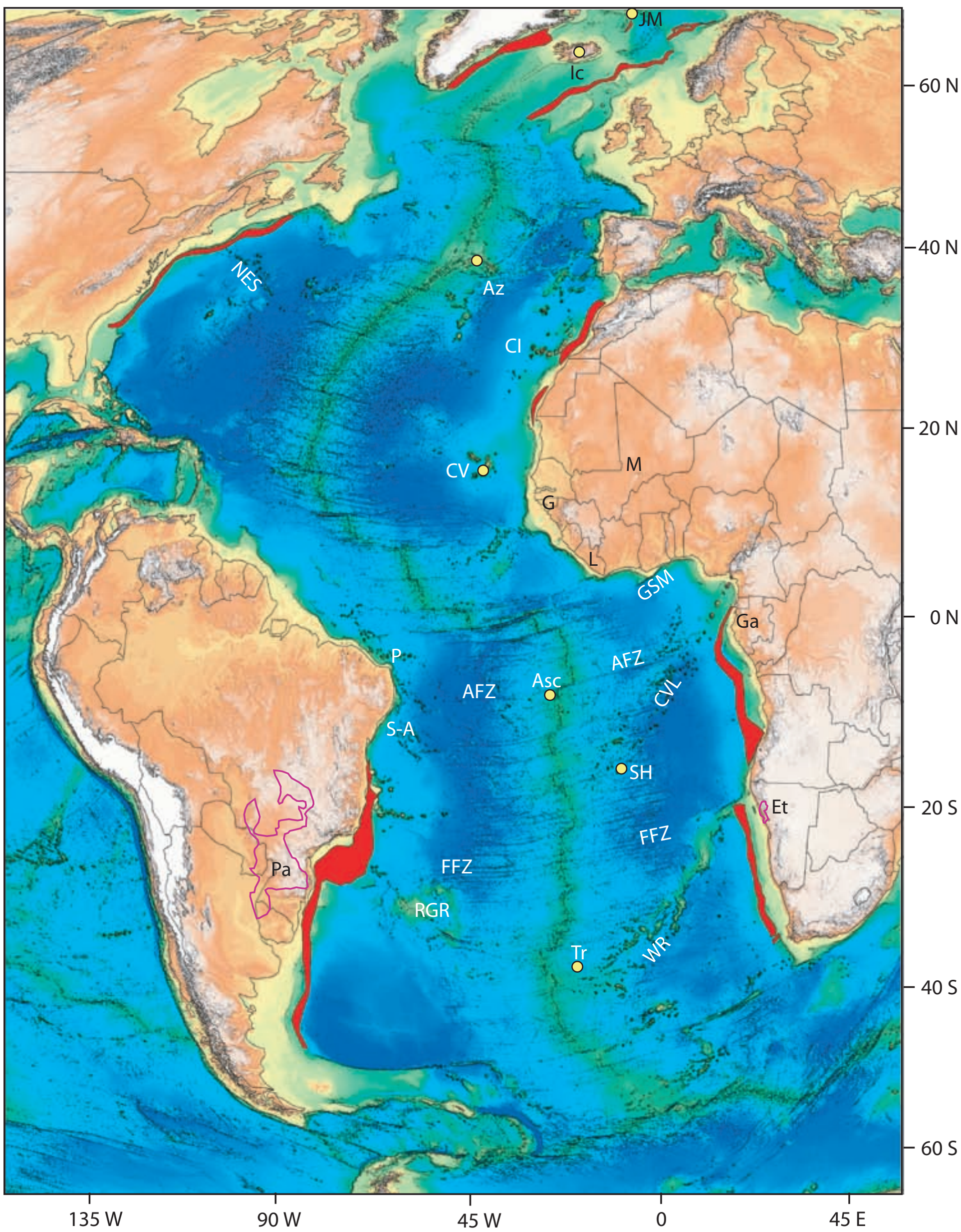

Figure 6. General location map for the southern north Atlantic, central Atlantic, and south Atlantic (Mollveide projection). Red outlines mark seaward dipping reflectors (i.e., volcanic margins). AFZ—Ascension Fracture Zone; Asc—Ascension Island; AZ—Azores; CI—Canary Islands; CV—Cape Verde; CVL—Cameron Volcanic Line; Et—Etendeka flood basalts; FFZ—Florianopólis Fracture Zone; G—Gambia; Ga—Gabon; GSM—Ghana shear margin; Ic—Iceland; JM—Jan Mayen; L—Liberia; M—Mali; NES—New England Seamounts; P—Potiguar; Pa—Paraná flood basalts; RGR—Rio Grande Rise; S-A—Sergipe-Alagoas; SH—St. Helena; Tr—Tristan da Cuhna; WR—Walvis ridge.

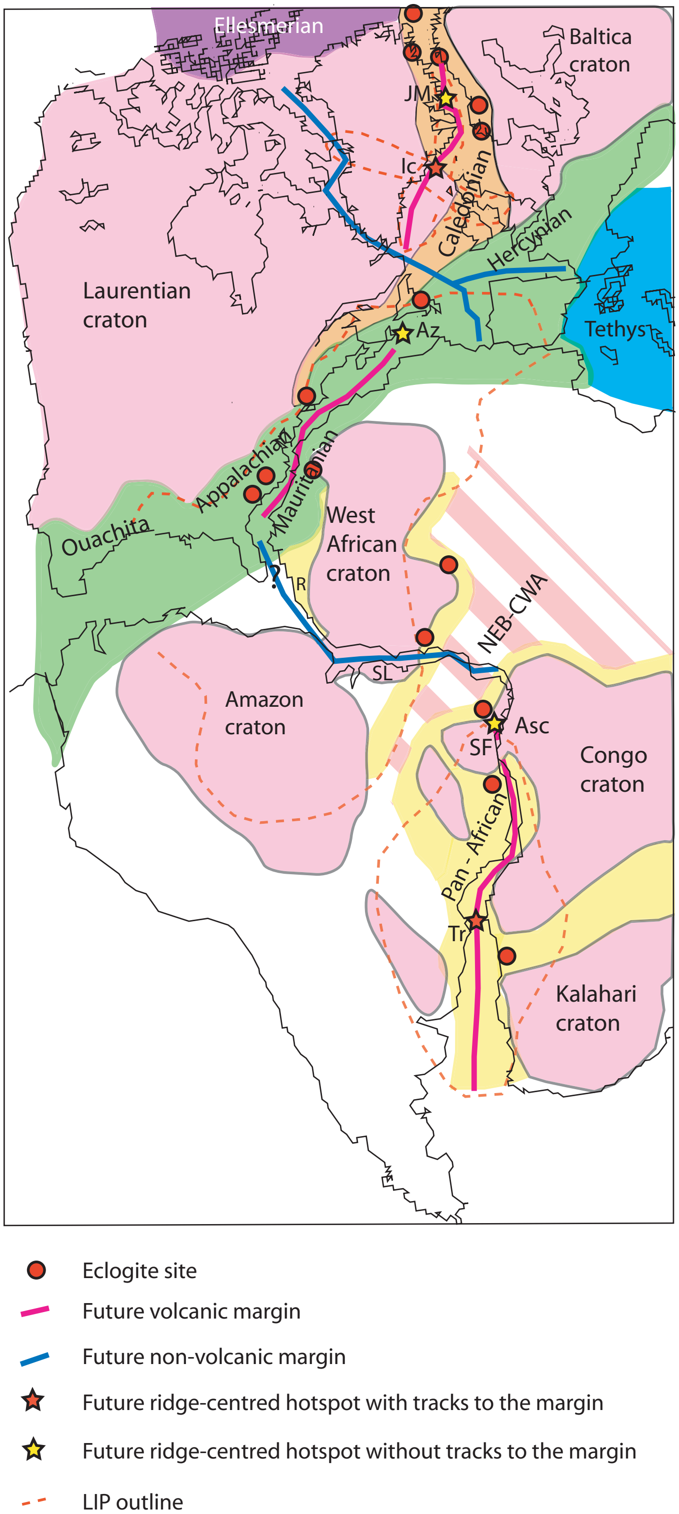

Figure 7. Compilation map of Atlantic part of Pangea 180 Ma, illustrating the location of Late Proterozoic–Phanerozoic fold belts, sites of exposed eclogites, and future Atlantic volcanic and nonvolcanic margins, large igneous provinces, and hotspots. The Pan-African fold belts are only shown toward the future Atlantic, whereas they in reality wrap around all Gondwana cratons. Fold belt sources: Pan-African after Trompette (1997), Caledonian after McKerrow et al. (2000), Ellesmerian after Trettin (1991), Mauritanides after Rousell et al. (1984), Ouachitas after Arbenz (1989), Hercynian after Ziegler (1988). Eclogite sources: after Steltenpohl et al. (2003), Goff et al. (2001), Jahn et al. (2001), Maruyama and Liou (1998). Volcanic margins: northwest European margin from Eldholm et al. (2000); central Atlantic from Coffin and Eldholm (1992) and Roeser (1982); south Atlantic from Talwani and Abreau (2000), Gomes et al. (2000), and Jackson et al. (2000). Equal area stereographic projection. Modified from Lundin and Doré (2005).

plume. However, there is no consensus on the position of this supposed plume during the development of the dike swarms or during breakup. The plume position is variously suggested to have been located in the vicinity of Florida (e.g., Hill, 1991), ~1000 km northwest of the New England coast (Coney, 1971; Morgan, 1971; White and McKenzie, 1989), under Mali (Wilson, 1997), and in the triangle between North America, South America, and Africa (Ernst and Buchanan, 1997). Early proposals of a plume related to the New England seamounts (Fig. 7), governing breakup (Coney, 1971; Morgan, 1971), was refuted by Vogt (1973). More recently, several authors (e.g., White and McKenzie, 1989; Sebai et al., 1991; Kelemen and Holbrook, 1995) have pointed out that the CAMP magmatic event does not appear to have been associated with significantly elevated mantle temperatures. McHone (2000) and McHone et al. (this volume) emphasize that CAMP dikes do not radiate out from a common center, in contrast to the view advocated by numerous workers since the first proposal by May (1971). Rather, the dikes follow the trend of the rifts that ruptured Pangea in the central Atlantic and equatorial south Atlantic.

Several workers (e.g., Holbrook and Keleman, 1993; Hames et al., 2000; McHone, 2000; De Min et al., 2003) argue against a plume origin for the CAMP magmatism. Major points raised against a plume origin are the lack of km-scale uplift prior to breakup (cf. Farnetani and Richards, 1994) and the absence of a hotspot track (e.g., Holbrook and Keleman, 1993; McHone, 2000). Another characteristic that is problematic with respect to a plume model is that CAMP tholeiites have internally consistent geochemical signatures within a given region but vary between regions (Marzoli et al., 1999; De Min et al., 2003). For instance, North American CAMP basalts are of at least three distinct types, and each type can be associated with very long (250–700 km) dike swarms. It is difficult to reconcile distinct individual dike swarm geochemistry and the differences between dike swarms with a plume model. As an alternative, De Min et al. (2003) suggested that the melts were sourced from a geochemically heterogeneous lower part of the lithospheric thermal boundary layer. Certainly the wide distribution of the CAMP would require a far larger plume head than what is suggested to be normal (White and McKenzie, 1989), which of course could simply be solved by advocating a larger plume.

The south Atlantic is also bordered by a LIP, consisting of the Paraná and Etendeka continental flood basalt provinces and the volcanic passive margins. This part of the Atlantic opened in segments from south to north (Gibbs et al., 2003), predominantly along Pan-African fold belts (Fig. 7). According to Trompette (1997) the Pan-African Orogeny consisted of an older event (ca. 600 Ma), largely involving oceanic closure, and a younger event (ca. 520 Ma) characterized by internal deformation between already assembled cratons and fold belts. In the northernmost south Atlantic, the propagating ocean intersected the once-continuous Saõ Fransisco–Congo craton and broke it in two, and likewise, along the equatorial shear margin, the once-continuous West Africa–Saõ Luis–Amazon craton was separated (Trompette, 1997). Even if the Africa–Saõ Luis–Amazon craton had already been broken during the late Pan-African event (marked by the Rokelides), this area did not contain sutures.

The ca. 132-Ma Paraná-Etendeka continental flood basalt provinces, the ~200-km-wide area of SDRS in the Santos and Walvis basins, the Walvis ridge–Rio Grande Rise, and the Tristan da Cunha hotspot are commonly attributed to a single long-lived plume (e.g., O'Connor and Duncan, 1990; Talwani and Abreau, 2000). Notably, however, the north side of the Rio Grande Rise is limited by the Florianopólis Fracture Zone, as is the first formed ~500–700 km of the Walvis ridge (Fig. 6). The small circle projection of this fracture zone into South America coincides with the marked scarp and ~600-km lateral step in the southern limit to the Paraná flood basalt province, and with a postulated dextral transform required to close the south Atlantic. Together, these features suggest a considerable plate tectonic control on the location of the initial pulse of Paraná-Etendeka flood basalt magmatism and early development of the oceanic plateau.

South Atlantic SDRS are well expressed south of the Walvis ridge–Rio Grande Rise (e.g., Talwani and Abreau, 2000), and are mapped intermittently at least as far north as the Sergipe-Alagoas Basin off northeast Brazil (Gomes et al., 2000) and the Gabon margin of West Africa (e.g., Jackson et al., 2000) (Fig. 6). Allochtonous salt in the Aptian salt basin probably masks SDRS locally. The northernmost part of the northeast-southwest Brazilian margin (between Potiguar and Sergipe-Alagoas basins) is reported to lack SDRS (Gomes et al., 2000). Thus the south Atlantic volcanic margin, when defined by the presence of SDRS, extends approximately from the southernmost south Atlantic to the Gabon–Sergipe-Alagoas Basin region. The Ghana shear margin is nonvolcanic (e.g., Sage et al., 2000; Bird, 2001). Likewise, the Liberia-Gambia margin segment appears to be nonvolcanic, based on a lack of SDRS off Senegal-Gambia (G. Tari, 2004, personal commun.). These nonvolcanic segments correspond mainly to areas where cratons were ruptured.

CORRESPONDENCE BETWEEN ATLANTIC NEOPROTEROZOIC-PHANEROZOIC FOLD BELTS AND VOLCANIC PASSIVE MARGINS?

The northeast, central, and south Atlantic are dominated by volcanic margins, which in turn constitute major portions of LIPs. Each of these LIPs has been proposed to be associated with a plume; notably, the Iceland plume for the northeast Atlantic (e.g., White et al., 1987), the CAMP plume for the central Atlantic (e.g., Hill, 1991), and the Tristan plume for the south Atlantic (e.g., O'Connor and Duncan, 1990). In this section, we investigate the possible correlation between Late Neoproterozoic–Phanerozoic fold belts (hereafter simply referred to as "Phanerozoic") and Atlantic volcanic passive margins (Fig. 7).

A broad empirical correlation is found between reopened Phanerozoic fold belts and Atlantic-Arctic volcanic margins (Fig. 7). A key question is whether there is any reason to expect voluminous magmatism along the margins of oceans that have utilized Phanerozoic fold belts. It has already been proposed that magmatism at Iceland and along the Greenland-Faeroe ridge may relate to melting of a steep or imbricated slab of Iapetus oceanic crust trapped in the suture (i.e., the Caledonian fold belt) (Foulger, 2002). Petrological support for such a model was presented by Natland (2003). A more widespread and voluminous source could be eclogitic orogenic roots (e.g., Ryan and Dewey, 1997; Ryan, 2001). Along the northeast Atlantic seaboard, eclogite-bearing rocks are well exposed in the Bergen Arcs of the Western Gneiss Region, southwest Norway (e.g., Austrheim, 1987, 1994). In a ~50 km^2 area in the Bergen Arcs, the eclogite content is estimated to be 30–45% (Austrheim, 1987), reaching up to 50% in smaller areas (Austrheim and Mørk, 1988). The Western Gneiss Region, which contains mainly granulitic, felsic rocks with scattered mafic dolerite lenses locally transformed to eclogite (e.g., Austrheim, 1994), is interpreted to have been exhumed during postorogenic extensional collapse in the Late Devonian (e.g., Andersen and Jamtveit, 1990). The process of postorogenic collapse and associated exhumation has in turn been proposed to relate to eclogitization of the orogenic root and subsequent delamination (e.g., Austrheim, 1994; Ryan and Dewey, 1997; Ryan, 2001). Austrheim (1991, 1994) speculated that the shallower and less dense felsic granulites and subordinate eclogites (now exposed in, e.g., the Western Gneiss Region) are the remnant upper portion of the orogenic welt that previously floated on top of mafic eclogites deeper in the root. These deeper mafic eclogites were suggested to have been lost into the upper mantle through delamination.

Eclogites in the Bergen Arcs and Western Gneiss Region provide good evidence that eclogitization has occurred in the deeper parts of the Caledonian orogen. Caledonian eclogites are also well known in several other localities in Norway (e.g., Robinson, 1991). Recent Ar^{39}/Ar^{40} age dating of eclogites in the Lofoten area suggests that these eclogites are also Caledonian in age (Steltenpohl et al., 2003). In addition to the eclogite outcrops, geophysical data permit interpretation of such rocks at the base of the crust directly west and northwest of the Western Gneiss Region (Olafsson et al., 1992; Christiansson et al., 2000). Eclogites are also interpreted further basinward, in the Vøring Basin on the mid-Norwegian margin (Olesen et al., 2002; Gernigon et al., 2003; Mjelde et al., 2005), based on seismic velocities and gravity data.

Structural work (e.g., Braathen et al., 2002) has shown that the extensional collapse of the Norwegian Caledonian orogen occurred perpendicular to the direction of orogenic shortening (i.e., in an orogen-parallel direction). The extensional collapse resulted in exhumation of large northeast-southwest elongated basement windows spaced ~500 km apart on the Norwegian mainland, explaining why the eclogites are concentrated in the basement windows. Integration of geophysical methods (gravity and magnetics) with on-shore geological mapping has permitted extension of the detachments bounding the basement windows northwestward onto the Norwegian margin (Olesen et al., 2002). These geophysically defined detachments have in turn been correlated with similar detachments in east Greenland (Olesen et al., 2004), where undated eclogites are interpreted to be of Caledonian age (e.g., Ryan, 2001; Steltenpohl et al., 2003).

Eclogites exist intermittently along the entire Caledonian-Appalachian orogen (Steltenpohl et al., 2003), as well as in the northern Mauritanides (Goff et al., 2001), and more sparsely in Pan-African fold belts of Africa and South America (Maruyama and Liou, 1998; Jahn et al., 2001) (Fig. 7). The volcanic margins of the Atlantic correspond broadly to reopened Phanerozoic fold belts, which show signs of having been eclogitized at depth.

South Atlantic nonvolcanic margin segments occur in the northernmost South Atlantic and along the equatorial shear margin, including Liberia-Gambia (see Fig. 6). However, the central Atlantic margins are volcanic. In the north Atlantic, the empirical relationship between the nonvolcanic Labrador Sea–Baffin Bay margins and the utilized Archean Rinkean mobile belt suggests that such old mobile belts provide a different deep protolith than do Phaneorozoic sutures. Does this imply a fundamental difference between Archean mobile belts and Phanerozoic fold belts? Work by Maruyama and Liou (1998) and Jahn et al. (2001), among others, suggests that this may be the case.

Pan-African (ca. 625 Ma) ultra-high pressure (UHP) eclogites on the southeast side of the West African craton in Mali are claimed to be the world's oldest (Jahn et al., 2001). UHP eclogitic rocks occur mainly in Phanerozoic fold belts and are only rarely found in Precambrian terranes. Although older eclogites are reported from, for example, the Grenville Province (ca. 1.4–1.0 Ga) and from Tanzania (ca. 2 Ga), these did not form under UHP conditions and their eclogite facies metamorphic ages are not well constrained (Jahn et al., 2001 and references therein). The Earth was probably too hot prior to the Late Proterozoic to "sustain the formation and preservation of deeply subducted UHP metamorphic rocks" (Jahn et al., 2001, p. 143). Higher geothermal gradients during the earlier Earth history lowered the strength of the lithosphere and made it difficult to form deep crustal roots (Maruyama and Liou, 1998; Ryan, 2001). Thus a fundamental difference may exist between Late Proterozoic–Phanerozoic and older fold belts. The older fold belts and mobile belts probably never contained eclogitized roots.

It has been shown experimentally (Yaxley, 2000) that a relatively modest component (tens of percent) of eclogitic or pyroxenitic material in mantle peridotite will lower the melting temperature and enhance melt production. Numerical modeling (Cordery et al., 1997) has also emphasized the important role of eclogite on melt productivity and rate. Both Cordery et al. (1997) and Yaxley (2000) proposed that such eclogites were derived from subducted oceanic material, recycled from the base of the mantle via plumes. This idea is similar to the proposal by Hofmann and White (1982), who proposed that subducted oceanic crust, returned from the core-mantle boundary, induces ocean island basalt magmatism. An alternative is a much shorter route of recycling from eclogites trapped in the lithospheric mantle immediately beneath Phanerozoic orogens. Cordery et al. (1997) considered it unlikely that eclogites residing in the lithospheric mantle can contribute significantly to flood basalt provinces because of the long timescale required to transfer sufficient heat between the mantle and lithosphere through conduction. Nevertheless, the apparent correlation between Phanerozoic fold belts and Atlantic volcanic passive margins (and hence LIPs; Fig. 7) is suggestive of a causal relationship. For plumes to by chance selectively impinge upon reopened Phanerozoic fold belts would be unlikely.

A testable alternative hypothesis based on the Atlantic is that reopening of Phanerozoic fold belts generates volcanic margins during the final extension phase leading to breakup. In particular, eclogitized orogenic roots incorporated into the upper mantle may be instrumental in lowering the melting temperature and enhancing melt productivity. For these eclogites to be available as a fertile source during breakup, they must remain present under the incipient ocean during breakup, rather than becoming "lost to the system" (i.e., asthenosphere) during postorogenic collapse (e.g., Ryan, 2001). Conceivably, delamination during orogenic collapse is a partially successful process, permitting the root to remain weakly coupled to the lithospheric mantle and to travel with the drifting plates. At least beneath some orogens, such as the Carpathians, seismic tomography suggests that the torn-off slab resides in the upper mantle (Wortel and Spakman, 2000). However, the torn-off slab in this region is a comparatively young phenomenon (ca. 16 Ma) and does not indicate whether orogenic roots can travel with the plates. It is plausible that raised geotherms during final lithospheric thinning result in complete delamination of the root and incorporation of it into the asthenosphere. As long as individual eclogitic bodies are on the order of 0.1–1 km in size, they should be able to heat up well within the timeframe of 2–3 m.y. typical for volcanic margin magmatism (Cordery et al., 1997).

Presence of eclogite in an orogenic root is, by itself, unlikely to be sufficient to cause voluminous magmatism. If a relationship exists, we suspect that the root first becomes incorporated into an asthenospheric melt upon substantial lithospheric thinning when the combined pyrolite-eclogite mixture is brought above its solidus, thereby producing voluminous melting. We support the view of Anderson (this volume) that the mantle is close to its solidus, and that melt anomalies arise from tectonic thinning, causing the mantle rocks to cross the solidus. We thus favor a passive model involving tapping of a locally fertile upper mantle to an active plume model that requires originally subducted material to be recycled from the base of the mantle.

DISCUSSION

In Table 1, we have assembled various arguments for and against a plume origin for Iceland, the NAIP, and the Atlantic volcanic passive margins. Arguments against an Iceland plume are the lack of a hotspot track, and the symmetry of the GFR construction. If the GFR formed above a plume, then such a plume has at least not been fixed with respect to other Indo-Atlantic hotspots (e.g., Norton, 2000). Rather, such a plume would have had to migrate in concert with, and in the direction of, plate drift, implying a plate tectonic control. Thus the concept that plumes are fixed and unrelated to plate tectonics cannot easily be applied to Iceland. The dominance of depleted tholeiites on Iceland (e.g., Presnall, 2003) argues against plume models that imply that plume tails are exceptionally hot (e.g., Campbell and Griffiths, 1990). This dominance could mean that the common perception that Iceland is underlain by a narrow plume stem or tail is wrong, or that the concept of hot plume tails is incorrect.

The MORB signature of the northeast Atlantic SDRS (Fitton et al., 1997) is inconsistent with a lower mantle enriched source, according to the general plume model by Campbell and Griffiths (1990). Whereas Fitton et al. (1997) proposed an upper mantle source, Kempton et al. (2000) modified the Campbell and Griffiths (1990) model to explain why the observations on Iceland depart so fundamentally from the early model. Other plume models involve dramatic shape changes to explain the magmatic distribution (Smallwood and White, 2002). As discussed earlier, these shape changes are here seen as supporting tectonic control on the location of magmatism. If the pre- and post-breakup Cenozoic vertical motions in and around the northeast Atlantic were related to the Iceland plume, they add another

TABLE 1. PROS AND CONS FOR THE ICELAND ANOMALY, NAIP, AND ATLANTIC VOLCANIC MARGINS RELATING TO MANTLE PLUMES

Feature	Pro versus con plume	Inconclusive	Comment
NEA topographic anomaly		X	Must relate to mantle phenomenon but probably not to the Iceland anomaly
NEA positive geoid anomaly		X	Much larger amplitude and area than for other hotspots; must relate to mantle phenomenon but probably not to the Iceland anomaly
V-shaped ridges around Iceland	Pro		Strongly suggests at least upper mantle upwelling; curious why no V-shaped ridges formed in Eocene when melt anomaly occurred in NAIP; not a universal observation for ridge-centered hotspots
Symmetric GFR construction	Con		Implies plate tectonic control on mantle upwelling and related melting
GFR crustal thickness		X	Requires melt anomaly, but not necessarily high temperature
Paleocene uplift		X	Regional and related to NEA opening, but not a simple axisymmetric phenomenon around a center
Geochemistry		X	Interpretations are model dependent; Iceland geochemistry requires elaborate model
Petrology		X	Nondefinitive pattern of, for example, picrite distribution; Iceland is dominated by depleted tholeiite
NEA breakup	Con		Readily explained by plate tectonics and lithospheric strength constraints; no plume weakening required
NAIP magmatic events		X	Difficult to explain with a plume; requires very elaborate shape changes; appears to be governed by plate tectonics
NAIP melt volume	Pro		Requires excessive melting; a plume explanation is possible but alternative explanations exist (e.g., fertile upper mantle, delaminated Caledonian orogenic root)
Iceland hotspot track	Con		Problematic with GFR symmetry, lack of track across Greenland, no uplift inboard of Kangerlussuaq, nonvolcanic margins in Labrador Sea
Eastward shifts of rift zone on Iceland		X	Both eastward and westward shifts have occurred for rift zones on Iceland
Upper mantle low-velocity anomaly beneath Iceland	Pro?		Could relate to hot upper mantle, but temperature anomaly need not exceed 50–100 °C; Could also relate to partial melting; no evidence for a deeply rooted plume
Correspondence between Atlantic volcanic passive margins and Palaeozoic fold belts	Con		Broad correlation is observed; could indicate that fertile upper mantle is important for volcanic margin development; needs further testing
Young ridge-centered hotspots in Atlantic	Con		Those lacking hotspot tracks can hardly be related to pre- and syn-breakup "plume" magmatism; locations near ridge/fracture zones suggest plate tectonic control on location

Note: GFR—Greenland-Faeroes ridge; NAIP—North Atlantic Igneous Province; NEA—northeast Atlantic.

dimension of complexity. A plume model satisfying geochemistry, magmatic distribution, and geographically variable syn- and post-breakup uplift remains to be proposed.

The reduced mantle velocity in the northeast Atlantic, as observed from seismic tomography, may signify elevated mantle temperatures as commonly proposed, but alternatively could stem from a partial melt (e.g., Goes et al., 2000; Foulger et al., 2001) or at least partially from compositional heterogeneity; a less than ~1% partial melt with no temperature anomaly can cause the velocity reductions observed under Iceland (see Foulger et al., 2001, for a fuller discussion). In any event, it appears clear that the northeast Atlantic velocity anomaly is restricted to the upper mantle (Ritsema et al., 1999), and the presence of a deeply rooted Morgan-type plume can probably be excluded (cf. Morgan, 1971; Courtillot et al., 2003).

NAIP melt volumes associated with breakup (i.e., magmatic phase 2) are large and have traditionally been related to a model of hot plume head impingement at the base of the lithosphere (e.g., Campbell and Griffiths, 1990; Skogseid et al., 2000), or to rifting above a mantle plume (White and McKenzie, 1989). The requirement for significant lithospheric thinning to generate the large melt volumes in White and McKenzie's model (1989) or alternatively, the need for very hot plumes, led Cordery et al. (1997) to propose a ~15% component of eclogites in the mantle source as a means for generating voluminous melts (see also Yaxley, 2000).

The broad empirical relationship between the Atlantic volcanic passive margins and the reopened eclogitized Late Neoproterozoic and Phanerozoic fold belts is suggestive of a causal relationship. This hypothesis, which involves supply of eclogite to the upper mantle from delaminated orogenic roots, needs to be tested on other passive margins in the world. An obvious area to investigate is the Arctic, where an Early Cretaceous LIP has been proposed (e.g., Maher, 2001; see http://www.largeigneousprovinces.org), possibly contemporaneous with the opening of the Amerasia Basin (cf. Grantz et al., 1990; Weber and Sweeney, 1990), and where the Alpha-Mendelev ridge (see Fig. 1) is strikingly analogous to the Greenland-Faeroe ridge (Weber, 1990). This basin may have reopened the northwest continuation of the Caledonian fold belt (Gee, 2004; Gee and Tebenkov, 2004) and its possible continuation into the latest Devonian to Early Carboniferous Ellesmerian fold belt (Trettin, 1991). It is unclear to us whether the Amerasia Basin margins are volcanic, and we are not aware of any published work that firmly establishes their nature.

The presence of continental eclogites at the base of an orogen is suggested to weaken the lithosphere and be the reason for Wilson Cycle reopening of sutures (Ryan and Dewey, 1997; Ryan, 2001). Ryan and Dewey (1997) proposed that heat from nonexhumed (and nondelaminated) eclogite phase transitions in an orogenic welt, together with already existing radiogenic heat production, will weaken the orogen by a factor of two or three after ca. 300 m.y. In the area investigated, we observe a considerable variation in the time span between orogeny and breakup: South Atlantic ca. 400 m.y., northeast Atlantic ca. 350 m.y., and central Atlantic ca. 150–225 m.y.

Conceivably, build-up of heat beneath a supercontinent like Pangea (Anderson, 1994) may have played a role for magmatism during breakup. Because the central Atlantic represents the first Atlantic portion of Pangean breakup, it is possible that this rupture of the supercontinent bled off a comparatively larger volume of warm mantle, reflected by the widespread and voluminous CAMP magmatism. However, if such heat did build up in the upper mantle due to insulation under the supercontinent, it probably occurred over a wide region, which we regard as a different phenomenon than the rise of a narrow plume emanating from the core-mantle boundary or, for example, the 660-km transition.

Although it is conceivable that eclogitic orogenic root material may have fertilized the upper mantle and led to volcanic margins upon breakup, it is more difficult to explain the continuously subaerial construction of the GFR as a result of tapping the same source. We acknowledge that mantle upwelling of a diapir-like shape may be taking place underneath Iceland; this is at least a possible interpretation based on seismic tomography (cf. Foulger et al., 2001). Such a diapiric mantle upwelling may have initiated at the intersection between the suggested northwest-trending Early Paleocene transient rift and the Late Paleocene northeast Atlantic rift. The rift intersection should be marked by increased extension, which ought to induce diapiric behavior of a plastic material (the asthenosphere) below a brittle material (crust and lithoispheric mantle). If one accepts passive diapiric upwelling under Iceland, it appears likely that the V-shaped ridges represent an axial flow phenomenon as originally proposed by Vogt (1971).

We have formulated some testable predictions of the hypothesis involving eclogitized orogenic roots in volcanic margin development. According to the hypothesis:

1. Volcanic passive margins should predominantly follow reopened Late Proterozoic–Phanerozoic high-pressure fold belts (presumed to contain eclogitized roots); and
2. Conversely, volcanic margins should not exist along Archean mobile belts, nor where cratons have been split.

CONCLUSIONS

The common assumption that Iceland is underlain by a fixed (and deeply rooted) mantle plume is challenged. There is no a priori evidence for a hotspot track away from Iceland. Specifically, the hotspot track across Greenland adopted as the basis for numerous papers is founded on presumption rather than regional, petrological, or geophysical evidence.

The Iceland anomaly is proposed to have formed in situ on the plate boundary, during and as a consequence of the northeast Atlantic opening. The GFR represents symmetrical subaerial construction of seafloor on either side of the Iceland anomaly during continuous widening of the northeast Atlantic. The GFR is thus not a classic hotspot track, because it is not diachronous in one direction.

Evidence is presented suggesting that a northwest-trending transient rift caused the first phase of NAIP magmatism (ca. 62–58 Ma) in an area between the BVP and west Greenland. Exploitation of the Caledonian fold belt is the suggested cause of the second and more voluminous phase of NAIP magmatism (ca. 56–53 Ma) focused on the newly developing northeast Atlantic passive margin.

The final breakup of Pangea (north Atlantic–Arctic linkage) was a natural result of plate tectonics and lithospheric strength distribution. In particular, the strong Amerasia Basin and the weak Caledonian fold belt were decisive factors in the abandonment of: (1) the transient Paleocene northeast-southwest extensional field across Britain and Greenland, and (2) the Labrador Sea–Baffin Bay axis, in favor of NE Atlantic spreading. Lithospheric weakening by a plume need not be invoked.

The south, central, and north Atlantic volcanic passive margins formed along reopened Late Neoproterozoic–Phanerozoic fold belts. As an alternative to plume-induced magmatism, we suggest as a testable hypothesis that delaminated eclogitic roots of such orogens generated a fertile source for voluminous magmatism when mixed with upper mantle peridotite. Lithospheric thinning caused adiabatic melting of the fertilized mantle. If correct, volcanic passive margins are the expected outcome of reopened Late Neoproterozoic–Phanerozoic sutures (i.e., a natural outcome of the Wilson Cycle).

Atlantic nonvolcanic passive margins occur where cratons were split, Late Neoproterozoic–Phanerozoic fold belts were cut at a high angle, and Archean mobile belts were utilized. The apparently nonfertile Archean mobile belts may result from the Earth's thermal gradient having been too high to permit build-up of thick orogenic welts, in turn excluding the possibility of developing eclogitized orogenic roots.

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REFERENCES CITED

Andersen, O.B., and Knudsen, P., 1998, Gravity anomalies from ERS-1 and Geosat Geodetic Missions: Copenhagen, Denmark, Kart og Matrikelstyrelsen.

Andersen, T.B., and Jamtveit, B., 1990, Uplift of deep crust during orogenic extensional collapse: A model based on field studies in the Sogn-Sunnfjord region of western Norway: Tectonics, v. 9, p. 1097–1111.

Anderson, D.L., 1989, Theory of the Earth: Boston, Blackwell Scientific Publications, 366 p.

Anderson, D.L., 1994, Superplumes or supercontinents?: Geology, v. 22, p. 39–42, doi: 10.1130/0091-7613(1994)022<0039:SOS>2.3.CO;2.

Anderson, D.L., 1996, Enriched asthenosphere and depleted plumes: International Geology Review, v. 38, p. 1–21.

Anderson, D.L., 2003, The plume hypothesis: Geoscientist, v. 13, no. 8, p. 16–17.

Arbenz, K.J., 1989, The Ouachita system, *in* Bally, A.W., and Palmer, A.R., eds, The geology of North America—An overview, The geology of America, v. A: Boulder, Colorado, Geological Society of America, p. 371–396.

Austrheim, H., 1987, Eclogitization of lower crustal granulites by fluid migration through shear zones: Earth and Planetary Science Letters, v. 81, p. 221–232, doi: 10.1016/0012-821X(87)90158-0.

Austrheim, H., 1991, Eclogite formation and dynamics of crustal roots under continental collision zones: Terra Nova, v. 3, p. 492–499.

Austrheim, H., 1994, Eclogitization of the deep crust in continent collision zones: Comptes Rendus de l'Académie des Sciences, Serie II, Sciences de la Terre et des Planètes, v. 319, p. 761–774.

Austrheim, H., and Mørk, M.B.E., 1988, The lower continental crust of the Caledonian mountain chain: Evidence from former deep crustal sections in western Norway, *in* Kristoffersen, Y., ed., Progress in studies of the lithosphere in Norway: Norwegian Geological Survey Special Publication 3, p. 102–113.

Balkwill, H.R., 1987, Labrador Basin: Structural and stratigraphic style, *in* Beaumont, C., and Tankard, A.J., eds., Sedimentary basins and basin-forming mechanisms: Canadian Society of Petroleum Geologists, Memoirs, v. 12, p. 17–43.

Berndt, C., 2000, Continental breakup volcanism on the Norwegian margin [Ph.D. dissertation]: Oslo, University of Oslo, 105 p.

Bijwaard, H., and Spakman, W., 1999, Tomographic evidence for a narrow whole-mantle plume below Iceland: Earth and Planetary Science Letters, v. 166, p. 121–126, doi: 10.1016/S0012-821X(99)00004-7.

Bird, D., 2001, Shear margins: Continent-ocean transform and fracture zone boundaries, Leading Edge, February, p. 150–159.

Björnsson, S., 1983, Crust and upper mantle beneath Iceland, *in* Bott, M.H.P., Saxov, S., Talwani, M., and Thiede, J., eds., Structure and development of the Greenland-Scotland ridge; new methods and concepts, NATO Conference Series IV, Marine Sciences 8: New York, Plenum Press, p. 31–61.

Bois, C., 1992, The evolution of the layered lower crust and the Moho through geological time in Western Europe: Contribution of deep seismic reflection profiles: Terra Nova, v. 4, p. 99–108.

Bott, M.H.P., 1983, The crust beneath the Iceland-Faroe ridge, *in* Bott, M.H.P., Saxov, S., Talwani, M., and Thiede, J., eds., Structure and development of the Greenland-Scotland ridge: New methods and concepts: New York, Plenum Press, p. 63–75.

Braathen, A., Osmundsen, T.T., Nordgulen, Ø., Roberts, D., and Meyer, G.B., 2002, Orogen-parallel extension of the Caledonides in northern Central Norway: An overview: Norwegian Journal of Geology, v. 82, p. 225–242.

Brodie, J., and White, N., 1994, Sedimentary basin inversion caused by igneous underplating: Northwest European continental shelf: Geology, v. 22, p. 147–150, doi: 10.1130/0091-7613(1994)022<0147:SBICBI>2.3.CO;2.

Brozena, J.M., Childers, V.A., Lawver, L.A., Gahagan, L.M., Forsberg, R., Faleide, J.I., and Eldholm, O., 2003, New aerogeophysical study of the Eurasia Basin and Lomonosov ridge: Implications for basin development: Geology, v. 31, p. 825–828, doi: 10.1130/G19528.1.

Campbell, I.H., and Griffiths, R.W., 1990, Implications of mantle plume structure for the evolution of flood basalts: Earth and Planetary Science Letters, v. 99, p. 79–93, doi: 10.1016/0012-821X(90)90072-6.

Cannat, M., Briais, A., Deplus, C., Escartín, J., Georgen, J., Lin, J., Mercouriev, S., Meyzen, C., Muller, M., Pouliquen, G., Rabain, A., and da Silva, P., 1999, Mid-Atlantic Ridge–Azores hotspot interactions: Along-axis migration of a hotspot-derived event of enhanced magmatism 10 to 4 Ma ago: Earth and Planetary Science Letters, v. 173, p. 257–269, doi: 10.1016/S0012-821X(99)00234-4.

Chalmers, J.A., and Laursen, H.K., 1995, Labrador Sea: The extent of continental and oceanic crust and the timing of the onset of seafloor spreading:

Marine and Petroleum Geology, v. 12, p. 205–217, doi: 10.1016/0264-8172(95)92840-S.

Chalmers, J.A., and Pulvertaft, T.C.R., 2001, Development of the continental margins of the Labrador Sea: A review, *in* Wilson, R.C.L., et al., eds., Non-volcanic rifting of continental margins: A comparison of evidence from land and sea: London, Geological Society of London Special Publications 187, p. 77–105.

Christiansson, P., Faleide, J.I., and Berge, A.M., 2000, Crustal structure in the northern North Sea: An integrated geophysical study, *in* Nøttvedt, A., et al., eds., Dynamics of the Norwegian margin: London, Geological Society of London Special Publications 167, p. 15–40.

Clift, P., 1996, Plume tectonics as a cause of mass wasting on the southeast Greenland continental margin: Marine and Petroleum Geology, v. 13, p. 771–780, doi: 10.1016/0264-8172(96)00021-9.

Clift, P.D., and Turner, J., 1998, Paleogene igneous underplating and subsidence anomalies in the Rockall-Faeroe-Shetland area: Marine and Petroleum Geology, v. 15, p. 223–243.

Clift, P.D., Carter, A., and Hurford, A.J., 1998, The erosional and uplift history of NE Atlantic passive margins: Constraints on a passing plume: Journal of the Geological Society of London, v. 155, p. 787–800.

Coffin, M.F., and Eldholm, O., 1992, Volcanism and continental break-up: A global compilation of large igneous provinces, *in* Storey, B.C., Alabaster, T., and Pankhurst, R.J., eds., Magmatism and the causes of continental break-up: London, Geological Society of London Special Publications 68, p. 17–30.

Coney, P.J., 1971, Cordilleran tectonic transitions and motions of the North American plate: Nature, v. 223, p. 462–465.

Cordery, M.J., Davies, G.F., and Campbell, I.H., 1997, Genesis of flood basalts from eclogite-bearing mantle plumes: Journal of Geophysical Research, v. 102, B9, p. 20,179–20,197.

Courtillot, V., Davaille, A., Besse, J., and Stock, J., 2003, Three distinct types of hotspots in the Earth's mantle: Earth and Planetary Science Letters, v. 205, p. 295–308, doi: 10.1016/S0012-821X(02)01048-8.

Davis, M., and Kusznir, N.J., 2004, Depth-dependent lithospheric stretching at rifted continental margins, *in* Karner, G.D., ed., Proceedings of NSF Rifted Margins Theoretical Institute: New York, Columbia University Press, p. 92–136.

Dawes, P.R., and Kerr, W.J., 1982, The case against major displacement along Nares Strait: Meddelser om Grønnland: Geoscience, v. 8, p. 369–386.

Dean, K., McLachlan, K., and Chambers, A., 1999, Rifting and the development of the Faroe-Shetland Basin, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum geology of northwest Europe: Proceedings of the 5th conference: London, Geological Society of London, p. 533–544.

De Min, A., Piccirillo, E.M., Marzoli, A., Bellieni, G., Renne, P.R., Ernesto, M., and Marques, L.S., 2003, The Central Atlantic Magmatic Province (CAMP) in Brazil: Petrology, geochemistry, ^{40}Ar/^{39}Ar ages, palaeomagnetism and geodynamic implications, *in* Hames, W., ed., The Central Atlantic Magmatic Province: Insights from fragments of Pangea: Washington, D.C., American Geophysical Union Geophysical Monograph 136, p. 91–127.

Den Hartog Jager, D., Giles, M.R., and Griffiths, G.R., 1993, Evolution of Paleogene submarine fans of the North Sea in space and time, *in* Parker, J.R., ed., Petroleum geology of northwest Europe: Proceedings of the 4th conference: London, Geological Society of London, p. 59–71.

Dewey, J.F., and Windley, B.F., 1988, Palaeocene-Oligocene tectonics of NW Europe, *in* Morton, A.C., and Parson, L.M., eds., Early Tertiary volcanism and the opening of the NE Atlantic: London, Geological Society of London Special Publications 39, p. 25–31.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P.E., and Fichler, C., 1999, Principal tectonic events in the evolution of the northwest European Atlantic margin, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum geology of northwest Europe: Proceedings of the 5th conference: London, Geological Society of London, p. 41–61.

Driscoll, N., and Karner, G., 1998, Lower crustal extension across the northern Carnarvon basin, Australia: Evidence for an eastward dipping detachment: Journal of Geophysical Research, v. 103, p. 4975–4991.

Eldholm, O., Thiede, J., Taylor, E., 1989, Evolution of the Voring volcanic margin, *in* Eldholm, O., et al., eds, Proceedings of the Ocean Drilling Program, Norwegian Sea; covering Leg 104 of the cruises of the Drilling Vessel JOIDES Resolution, Bremerhaven, Germany, to St. John's, Newfoundland, Sites 642-644, 19 June 1985–23 August 1985: College Station, Texas A & M University, Ocean Drilling Program, p. 1033–1065.

Eldholm, O., Skogseid, J., Planke, S., and Gladczenko, T.P., 1995, Volcanic margin concepts, *in* Banda, E., et al., eds., Rifted ocean-continent boundaries: Amsterdam, Kluwer Academic Press, p. 1–16.

Eldholm, O., Gladczenko, T.P., Skogseid, J., and Planke, S., 2000, Atlantic volcanic margins: A comparative study, *in* Nøttvedt, A., et al., eds., Dymanics of the Norwegian margin: London, Geological Society of London Special Publications 167, p. 411–428.

England, R.W., 1988, The early Tertiary stress regime in NW Britain: Evidence from the patterns of volcanic activity, *in* Morton, A.C., and Parson, L.M., eds., Early Tertiary volcanism and the opening of the NE Atlantic: London, Geological Society of London Special Publications 39, p. 381–389.

Ernst, R.E., and Buchanan, K.L., 1997, Giant radiating dike swarms: Their use in identifying pre-Mesozoic large igneous provinces and mantle plumes, *in* Mahoney, J.J., and Coffin, M.F., eds., Large igneous provinces: Continental, oceanic, and planetary flood volcanism: Washington, D.C., American Geophysical Union Monograph 100, p. 297–333.

Faleide, J.I., Vågnes, E., and Gudlaugsson, S.T., 1993, Late Mesozoic-Cenozoic evolution of the south-western Barents Sea in a regional rift-shear tectonic setting: Marine and Petroleum Geology, v. 10, p. 186–214, doi: 10.1016/0264-8172(93)90104-Z.

Farnetani, C.G., and Richards, M.A., 1994, Numerical investigation of mantle plume initiation model for continental flood basalt events: Journal of Geophysical Research, v. 99, p. 13,813–13,833, doi: 10.1029/94JB00649.

Fitton, J.G., Saunders, A.D., Norry, M.J., Hardarson, B.S., and Taylor, R.N., 1997, Thermal and chemical structure of the Iceland plume: Earth and Planetary Science Letters, v. 153, p. 197–208, doi: 10.1016/S0012-821X(97)00170-2.

Forsyth, D.A., Morel, A.L., Huissier, P., Asudeh, I., and Green, A.G., 1986, Alpha ridge and Iceland; products of the same plume?: Journal of Geodynamics, v. 6, p. 197–214, doi: 10.1016/0264-3707(86)90039-6.

Foulger, G.R., 2002, Plumes, or plate tectonic processes?: Astronomy and Geophysics, v. 43, p. 6.19–6.23.

Foulger, G.R., 2003a, Plumes, plates and popper: Geoscientist, v. 13, no. 5, p. 16–17.

Foulger, G.R., 2003b. On the apparent eastward migration of the spreading ridge in Iceland: Proceedings of the Penrose Conference Plume IV: Beyond the plume hypothesis, 25–29 August, Hveragerdi, Iceland, Abstracts.

Foulger, G.R., Pritchard, M.J., Julian, B.R., Evans, J.R., Allen, R.M., Nolet, G., Morgan, W.J., Bergsson, B.H., Erlendsson, P., Jakobsdottir, S., Ragnarsson, S., Stefansson, R., and Vogfjörd. K., 2001, Seismic tomography shows that upwelling beneath Iceland is confined to the upper mantle: Geophysical Journal International, v. 146, p. 504–530, doi: 10.1046/j.0956-540x.2001.01470.x.

Foulger, G.R., Du, Z., and Julian, B.R., 2003, An alternative model for Iceland, and the North Atlantic Igneous Province: Proceedings of the Penrose Conference Plume IV: Beyond the plume hypothesis, 25–29 August, Hveragerdi, Iceland, Abstracts.

Gee, D.G., 2004, The Barentsian Caledonides: Death of the high Arctic Barents craton: Arctic Geology, Hydrocarbon Resources and Environmental Challenges, Abstracts and Proceedings of the Geological Society of Norway: Tromsø, Geological Society of Norway, p. 48–49.

Gee, D.G., and Tebenkov, A.M., 2004. Svalbard: A fragment of the Laurentian Caledonian margin, *in* Gee, D.G., and Pease, V., eds., The Neoproterozoic Timanide orogen of eastern Baltica: London, Geological Society of London Memoir, p. 191–206.

Gernigon, L., Ringenbach, J.C., Planke, S., Le Gall, B., and Jonquet-Kolstø, H., 2003, Extension, crustal structure and magmatism at the outer Vøring Basin, Norwegian margin: Journal of the Geological Society of London, v. 160, p. 197–208.

Gibbs, P., Brush, E., and Fiduk, J., 2003, The evolution of the syn-rift and transition phases of central/southern Brazilian and West African conjugate margins: The implications for source rock distribution in time and space, and their recognition on seismic data, *in* 8th International Congress of the Brazilian Geophysical Society, September 14–18, Rio de Janeiro, Abstracts.

Gill, R.C.O., Pedersen, A.K., and Larsen, J.G., 1992, Tertiary picrites in west Greenland: Melting at the periphery of a plume? *in* Storey, B.C., Alabaster, T., and Pankhurst, R.J., eds., Magmatism and the causes of continental break-up: London, Geological Society of London Special Publication 68, p. 335–348.

Goes, S., Govers, R., and Vacher, P., 2000, Shallow mantle temperatures under Europe from P and S wave tomography: Journal of Geophysical Research, v. 105, p. 11,153–11,169, doi: 10.1029/1999JB900300.

Goff, E., Guerrot, C., Maurin, G., Johan, V., Tegyey, M., and Ben-Zerga, M., 2001, Discovery of Hercynian eclogites in the northern Mauritanides, West Africa: Comptes Rendus de l'Academie des Sciences, Serie II, Sciences de la Terre et des Planetes, v. 333, p. 711–718.

Gomes, P.O., Gomes, B.S., Palma, J.J.C., Jinno, K., and de Souza, J.M., 2000, Ocean-continent transition and tectonic framework of the oceanic crust at the continental margin off NE Brazil: Results of the LEPLAC Project, *in* Mohriak, W., and Ralwani, M., eds., Atlantic rifts and continental margins: Washington, D.C., American Geophysical Union Geophysical Monograph 115, p. 261–289.

Grantz, A., May, S.D., Taylor, P.T., and Lawver, L.A., 1990, Canada Basin, *in* Grantz, A., Johnson, L., and Sweeney, J.F., eds., The Arctic Ocean region, The Geology of North America, v. L: Boulder, Colorado, Geological Society of America, p. 379–402.

Green, P.F., Duddy, I.R., Hegarty, K.A., and Bray, R.J., 1999, Early Tertiary heat flow along the UK Atlantic margin and adjacent areas, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum geology of northwest Europe: Proceedings of the 5th conference: London, Geological Society of London, p. 349–357.

Hall, B.D., and White, N.J., 1994, Origin of anomalous Tertiary subsidence adjacent to North Atlantic continental margins: Marine and Petroleum Geology, v. 11, p. 702–714.

Hall, J.M., 1981. The Thulean volcanic line, *in* Kerr, J.W., Fergusson, A.J., and Machan, L.C., eds., Geology of the north Atlantic borderlands: Canadian Society of Petroleum Geologists, Memoir 7, p. 231–244.

Hames, W.E., Renne, P.R., and Ruppel, C., 2000, New evidence for geologically instantaneous emplacement of earliest Jurassic central Atlantic magmatic province basalts on the North American margin: Geology, v. 28, p. 859–862, doi: 10.1130/0091-7613(2000)028<859:NEFGIE>2.3.CO;2.

Hamilton, W.B., 2003, An alternative Earth: GSA Today, v. 13, p. 4–12.

Hansen, K., 1996, Thermotectonic evolution of a rifted continental margin: Fission track evidence from the Kangerlussuaq area, SE Greenland: Terra Nova, v. 8, p. 458–469.

Hansen, K., 2000, Tracking thermal history in East Greenland: An overview: Global and Planetary Change, v. 24, p. 303–309.

Hansen, K., and Brooks, C.K., 2002, The evolution of the east Greenland margin as revealed from fission-track studies: Tectonophysics, v. 349, p. 93–111.

Hardarson, B.S., Fitton, J.G., Ellam, R.M., and Pringle, M.S., 1997, Rift relocation—A geochemical and geochronological investigation of a palaeo-rift in northwest Iceland: Earth and Planetary Science Letters, v. 153, p. 181–196, doi: 10.1016/S0012-821X(97)00145-3.

Helgason, J., 1984, Frequent shifts of the volcanic zone in Iceland: Geology, v. 12, p. 212–216, doi: 10.1130/0091-7613(1984)12<212:FSOTVZ>2.0.CO;2.

Henriksen, S., Fichler, C., Grønlie, A., Henningsen, T., Laursen, I., Løseth, H., Ottesen, D., and Prince, I., 2004, The Norwegian Sea during the Cenozoic, *in* Wandås, B., ed., Onshore-offshore relationships on the Nordic Atlantic margin: Oslo, Norwegian Petroleum Society Special Publication 12, p. 111–134.

Herzberg, C., and O'Hara, M.J., 2002, Plume-associated ultramafic magmas of Phanerozoic age: Journal of Petrology, v. 43, p. 1857–1883, doi: 10.1093/petrology/43.10.1857.

Hill, R.I., 1991, Starting plumes and continental break-up: Earth and Planetary Science Letters, v. 104, p. 398–416, doi: 10.1016/0012-821X(91)90218-7.

Hofmann, A.W., and White, W.M., 1982, Mantle plumes from ancient oceanic crust: Earth and Planetary Science Letters, v. 57, p. 421–436, doi: 10.1016/0012-821X(82)90161-3.

Holbrook, W.S., and Keleman, P.B., 1993, Large igneous province on the U.S. Atlantic margin and implications for magmatism during continental breakup: Nature, v. 364, p. 433–436, doi: 10.1038/364433a0.

Holbrook, S.W., Larsen, H.C., Korenaga, J., Dahl-Jensen, T., Reid, I.D., Kelemen, P.B., Hopper, J.R., Kent, G.M., Lizzarralde, D., Berstein, S., and Detrick, R.S., 2001, Mantle structure and active upwelling during continental breakup in the North Atlantic: Earth and Planetary Science Letters, v. 190, p. 251–266, doi: 10.1016/S0012-821X(01)00392-2.

Ito, G., 2001, Reykjanes "V"-shaped ridges originating from a pulsing and dehydrating mantle plume: Nature, v. 411, p. 681–684, doi: 10.1038/35079561.

Jackson, M.P.A., Cramez, C., and Fonck, J.-M., 2000, Role of subaerial volcanic rocks and mantle plumes in creation of south Atlantic margins: Implications for salt tectonics and source rocks: Marine and Petroleum Geology, v. 17, p. 477–498, doi: 10.1016/S0264-8172(00)00006-4.

Jahn, B.M., Caby, R., and Monie, P., 2001, The oldest UHP eclogites of the World: Age of UHP metamorphism, nature of protoliths and tectonic implications: Chemical Geology, v. 178, p. 143–158, doi: 10.1016/S0009-2541(01)00264-9.

Jakobsson, M., Cherkis, N., Woodward, J., Macnab, R., and Oakley, B., 2000, New grid of Arctic bathymetry aids scientists and mapmakers: Eos (Transactions, American Geophysical Union), v. 81, p. 89, 93, 96.

Japsen, P., Green, P.F., and Chalmers, J.A., 2005, Separation of Palaeogene and Neogene uplift on Nussuaq, west Greenland: Journal of the Geological Society of London, v. 162, p. 299–314.

Johnston, S., Doré, A.G., and Spencer, A.M., 2001, The Mesozoic evolution of the southern north Atlantic region and its relationship to basin development in the south Porcupine Basin, offshore Ireland, *in* Shannon, P.M., et al., eds., The petroleum exploration of Ireland's offshore basins: London, Geological Society of London Special Publication 188, p. 237–263.

Jolley, D.W., and Bell, B.R., 2002, The evolution of the North Atlantic Igneous Province and the opening of the NE Atlantic rift, *in* Jolley, D.W., and Bell, B.R., eds., The North Atlantic Igneous Province, tectonic, volcanic and magmatic processes: London, Geological Society of London Special Publication 197, p. 1–13.

Jones, S.M., White, N., and Lovell, B., 2001, Cenozoic and Cretaceous transient uplift in the Porcupine Basin and its relationship to a mantle plume, *in* Shannon, P.M., et al., eds., The petroleum exploration of Ireland's offshore basins: London, Geological Society of London Special Publication 188, p. 345–360.

Jones, S.M., White, N., and Maclennan, J., 2002a, V-shaped ridges around Iceland: Implications for spatial and temporal patterns of mantle convection: Geochemistry, Geophysics, Geosystems, v. 3, p. 1–23, doi: 10.1029/2002GC000361.

Jones, S.M., White, N., Clarke, B.J., Rowley, E., and Gallagher, K., 2002b, Present and past influence of the Iceland plume on sedimentation, *in* Doré, A.G., et al., eds., Exhumation of the North Atlantic margin: Timing, mechanisms and implications for petroleum exploration: London, Geological Society of London Special Publication 196, p. 13–25.

Joy, A.M., 1992, Right place, wrong time: Anomalous post-rift subsidence in the sedimentary basins around the north Atlantic Ocean, *in* Storey, B.C., et al., eds., Magmatism and the causes of continental break-up: London, Geological Society of London Special Publication 68, p. 387–393.

Karner, G.D., Driscoll, N.W., and Barker, D.H.N., 2003, Syn-rift regional subsidence across the West African continental margin: The role of lower plate ductile extension, *in* Arthur, T.J., et al., eds., Petroleum geology of Africa: New themes and developing technologies: London, Geological Society of London Special Publication 207, p. 105–129.

Keen, C.E., Stockmal, G.S., Welsink, H., Quinlan, G., and Mudford, B., 1987, Deep crustal structure and evolution of the rifted margin northeast of Newfoundland: Results from LITHOPROBE East: Canadian Journal of Earth Sciences, v. 24, p. 1537–1549.

Kelemen, P.B., and Holbrook, W.S., 1995, Origin of thick, high-velocity igneous crust along the U.S. east coast margin: Journal of Geophysical Research, v. 100, p. 10,077–10,094.

Kempton, P.D., Fitton, J.G., Saundersm, A.D., Nowell, G.M., Taylor, R.N., Hardarson, B.S., and Pearson, G., 2000, The Iceland plume in space and time: A Sr-Nd-Pb-Hf study of the north Atlantic rifted margin: Earth and Planetary Science Letters, v. 177, p. 255–271, doi: 10.1016/S0012-821X(00)00047-9.

Kerr, A.C., 1995, The geochemistry of the Mull-Morven Tertiary lava succession, NW Scotland: An assessment of mantle sources during plume-related volcanism: Chemical Geology, v. 122, p. 43–58, doi: 10.1016/0009-2541(95)00009-B.

Klitgord, K.D., and Schouten, H., 1986, Plate kinematics of the central Atlantic, *in* Vogt, P.R., and Tucholke, B.E., eds., The geology of North America, v. M, The western Atlantic region: Boulder, Colorado, Geological Society of America, p. 351–377.

Köhler, W., 2004, Section 1.3: Gravity field and Earth models, gravitational geopotential in terms of geoid heights, http://www.gfz-potsdam.de.

Koppers, A.A.P., Phipps Morgan, J., Morgan, J.W., and Staudigel, H., 2001, Testing the fixed hotspot hypothesis using ^{40}Ar/^{39}Ar age progressions along seamount trails: Earth and Planetary Science Letters, v. 185, p. 237–252, doi: 10.1016/S0012-821X(00)00387-3.

Kristoffersen, Y., and Talwani, M., 1977, Extinct triple junction south of Greenland and the Tertiary motion of Greenland relative to North America: Geological Society of America Bulletin, v. 88, p. 1037–1049.

Kusznir, N.J., Hunsdale, R., Roberts, A.M., and iSIMM Team, 2005, Timing and magnitude of depth-dependent lithosphere stretching on the southern Lofoten and northern Vøring continental margins offshore mid-Norway: Implications for subsidence and hydrocarbon maturation at volcanic rifted margins, *in* Doré, A.G., and Vining, B.A., eds., Northwest European petroleum geology and global perspectives: Proceedings of the 6th Conference: London, Geological Society of London, p. 767–784.

Lamers, E., and Carmichael, S.M.M., 1999, The Paleocene deepwater sandstone play West of Shetland, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum geology of northwest Europe: Proceedings of the 5th Conference: London, Geological Society of London, p. 645–660.

Larsen, H.C., and Marcussen, C., 1992, Sill-intrusion, flood basalt emplacement and deep crustal structure of the Scoresby Sund region, east Greenland, *in* Storey, B.C., et al., eds., Magmatism and the causes of continental break-up: London, Geological Society of London Special Publication 68, p. 365–386.

Larsen, H.C., and Saunders, A.D., 1998, Tectonism and volcanism at the southeast Greenland rifted margin: A record of plume impact and later continental rupture, *in* Saunders, A.D., et al., eds., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 152: College Station, Texas, Ocean Drilling Program, p. 503–533.

Larsen, M., and Whitham, A.G., 2005, Evidence for a major sediment input point into the Faroe-Shetland Basin from southern east Greenland, *in* Doré, A.G., and Vining, B.A., eds., Northwest European petroleum geology and global perspectives: Proceedings of the 6th Conference: London, Geological Society of London, p. 913–922.

Lawver, L.A., and Müller, D.R., 1994, Iceland "hotspot" track: Geology, v. 22, p. 311–314, doi: 10.1130/0091-7613(1994)022<0311:IHT>2.3.CO;2.

Lawver, L.A., Grantz, A., and Gahagan, L.M., 2002, Plate kinematic evolution of the present Arctic region since the Ordovician, *in* Miller, E.L., et al., eds., Tectonic evolution of the Bering Shelf–Chukchi Sea–Arctic margin and adjacent landmasses: Boulder, Colorado, Geological Society of America Special Paper 360, p. 333–358.

Lundin, E.R., and Doré, A.G., 2002, Mid-Cenozoic post-breakup deformation in the "passive" margins bordering the Norwegian–Greenland Sea: Marine and Petroleum Geology, v. 19, p. 79–93, doi: 10.1016/S0264-8172(01)00046-0.

Lundin, E.R., and Doré, A.G., 2005, NE-Atlantic break-up: A re-examination of the Iceland mantle plume model and the Atlantic-Arctic linkage, *in* Doré, A.G., and Vining, B.A., eds., Northwest European petroleum geology and global perspectives: Proceedings of the 6th Conference: London, Geological Society of London, p. 739–754.

Maher, H.D., Jr., 2001, Manifestations of the Cretaceous high Arctic large igneous province in Svalbard: Journal of Geology, v. 109, p. 91–104, doi: 10.1086/317960.

Malamud, B.D., and Turcotte, D.L., 1999, How many plumes are there?: Earth and Planetary Science Letters, v. 174, p. 113–124, doi: 10.1016/S0012-821X(99)00257-5.

Marquart, G., 1991, Interpretations of geoid anomalies around the Iceland "hotspot": Geophyical Journal International, v. 106, p. 149–160.

Maruyama, S., and Liou, J.G., 1998, Initiation of ultra-high pressure metamorphism and its significance on the Proterozoic-Phanerozoic boundary: Island Arc, v. 7, p. 6–35, doi: 10.1046/j.1440-1738.1998.00181.x.

Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesteo, M., Bellieni, G., and De Min, A., 1999, Extensive 200-million-year-old continental flood basalts of the central Atlantic Magmatic Province: Science, v. 284, p. 616–618, doi: 10.1126/science.284.5414.616.

May, P.R., 1971, Pattern of Triassic-Jurassic diabase dykes around the north Atlantic in context of predrift position of the continents: Geological Society of America Bulletin, v. 82, p. 1285–1292.

McDonnel, A., and Shannon, P.M., 2001, Comparative Tertiary stratigraphic evolution of the Porcupine and Rockall basins, *in* Shannon, P.M., et al., eds., The petroleum exploration of Ireland's offshore basins: London, Geological Society of London Special Publication 188, p. 323–344.

McHone, J.G., 1996, Broad-terrane Jurassic flood basalts across northeastern North America: Geology, v. 24, p. 319–322, doi: 10.1130/0091-7613(1996)024<0319:BTJFBA>2.3.CO;2.

McHone, J.G., 2000, Non-plume magmatism and rifting during the opening of the central Atlantic Ocean: Tectonophysics, v. 316, p. 287–296, doi: 10.1016/S0040-1951(99)00260-7.

McKerrow, W.S., Mac Niocaill, C., and Dewey, J.F., 2000, The Caledonian orogeny redefined: Journal of the Geological Society of London, v. 157, p. 1149–1154.

Megnin, C., and Romanowicz, B., 2000, The three-dimensional velocity structure of the mantle from the inversion of body, surface and higher-wave-mode waveforms: Geophysical Journal International, v. 143, p. 709–728, doi: 10.1046/j.1365-246X.2000.00298.x.

Mitchell, S.M., Beamish, G.W.J., Wood, M.V., Malacek, S.J., Armentrout, J.A., Damuth, J.E., and Olson, H.C., 1993, Paleogene sequence stratigraphic framework of the Faroe Basin, *in* Parker, J.R., ed., Petroleum geology of northwest Europe: Proceedings of the 4th conference: London, Geological Society of London, p. 1011–1023.

Mjelde, R., Raum, T., Breivik, A., Shimamura, H., Murai, Y., Takanami, T., and Faleide, J.I., 2005, Crustal structure of the Vøring margin, NE Atlantic: A review of geological implications based on recent OBS-data, *in* Doré, A.G., and Vining, B.A., eds., Northwest European petroleum geology and global perspectives: Proceedings of the 6th conference: London, Geological Society of London, p. 803–814.

Molnar, P., and Atwater, T., 1973, Relative motion of hot spots in the mantle: Nature, v. 246, p. 288–291.

Monnereau, M., and Cazenave, A., 1990, Depth and geoid anomalies over oceanic hotspot swells: A global survey: Journal of Geophysical Research, v. 95, B10, p. 15,429–15,438.

Montelli, R., Nolet, G., Dahlen, F.A., and Hung, S.-H., 2003, Finite frequency tomography reveals a variety of plumes in the mantle: Proceedings of the Penrose Conference Plume IV: Beyond the plume hypothesis, 25–29 August, Hveragerdi, Iceland, Abstracts.

Morgan, W.J., 1971, Convection plumes in the lower mantle: Nature, v. 230, p. 42–43.

Morgan, W.J., 1981, Hotspot tracks and the opening of the Atlantic and Indian oceans, *in* Emiliani, C., ed., The oceanic lithosphere: New York, John Wiley and Sons, p. 443–487.

Morton, A.C., Hallsworth, C.R., and Wilkinson, G.C., 1993, Stratigraphic evolution of sand provenance during Paleocene deposition in the northern North Sea area, *in* Parker, J.R., ed., Petroleum geology of northwest Europe: Proceedings of the 4th Conference: London, Geological Society of London, p. 73–84.

Mosar, J., Lewis, G., and Torsvik, T.H., 2002, North Atlantic seafloor spreading rates: Implications for the Tertiary inversion structures of the Norwegian-Greenland Sea: Journal of the Geological Society of London, v. 159, p. 503–515.

Müller, R.D., Royer, J.-Y., and Lawver, L.A., 1993, Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks: Geology, v. 21, p. 275–278, doi: 10.1130/0091-7613(1993)021<0275:RPMRTT>2.3.CO;2.

Müller, R.D., Gaina, C., Roest, W.R., and Lundbek Hansen, D., 2001, A recipe for microcontinent formation: Geology, v. 29, p. 203–206, doi: 10.1130/0091-7613(2001)0292.0.CO;2.

Mutter, J.C., Talwani, M., and Stoffa, P., 1982, Origin of seaward-dipping reflectors in oceanic crust off the Norwegian margin by "subaerial seafloor spreading": Geology, v. 10, p. 353–357, doi: 10.1130/0091-7613(1982)10<353:OOSRIO>2.0.CO;2.

Nadin, P.A., and Kusznir, N.J., 1995, Palaeocene uplift and Eocene subsidence in the northern North Sea Basin from 2D forward and reverse stratigraphic modelling: Journal of the Geological Society of London, v. 152, p. 833–848.

Nadin, P.A., Kusznir, N.J., and Toth, J., 1995, Transient regional uplift in the Early Tertiary of the northern North Sea and the development of the Iceland plume: Journal of the Geological Society of London, v. 152, p. 953–958.

Nadin, P.A., Kusznir, N.J., and Cheadle, M.J., 1997, Early Tertiary plume uplift of the North Sea and Faroe-Shetland Basin: Earth and Planetary Science Letters, v. 148, p. 109–129, doi: 10.1016/S0012-821X(97)00035-6.

Natland, J.H., 2003, What's going on at Iceland?: Proceedings of the Penrose Conference Plume IV: Beyond the plume hypothesis, 25–29 August, Hveragerdi, Iceland, Abstracts.

Naylor, P.H., Bell, B.R., Jolley, D.W., Durnall, P., and Fredsted, R., 1999, Palaeogene magmatism in the Faroe-Shetland Basin: Influences on uplift history and sedimentation, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum geology of northwest Europe: Proceedings of the 5th conference: London, Geological Society of London, p. 545–558.

Nielsen, S.B., Paulsen, G.E., Hansen, D.L., Gemmer, L., Clausen, O.R., Jacobsen, B.H., Balling, N., Huuse, M., and Gallagher, K., 2002, Paleocene initiation of Cenozoic uplift in Norway, *in* Doré, A.G., et al., eds., Exhumation of the north Atlantic margin: Timing, mechanisms and implications for petroleum exploration: London, Geological Society of London Special Publication 196, p. 45–65.

Nøhr-Hansen, H., Sheldon, E., and Dam, G.A., 2002, A new biostratigraphic scheme for the Paleocene onshore west Greenland and its implications for the timing of the prevolcanic evolution, *in* Jolley, D.W., and Bell, B.R., eds., The North Atlantic Igneous Province, tectonic, volcanic and magmatic processes: London, Geological Society of London Special Publication 197, p. 111–156.

Norton, I.O., 2000, Global hotspot reference frames and plate motion, *in* Richards, M.A., et al., eds., The history and dynamics of global plate motions: Washington, D.C., American Geophysical Union Geophysical Monograph 121, p. 339–357.

Oakey, G.N., 1994, A structural fabric defined by topographic lineaments: Correlation with Tertiary deformation of Ellesmere and Axel Heiberg Islands, Canadian Arctic: Journal of Geophysical Research, v. 99, B10, p. 20,311–20,321.

Oakey, G.N., Roest, W.R., and Lundin, E.R., 2003, The structure and evolution of Baffin Bay and its implication on the development of the continental margins of northwest Greenland, the Nares Strait, and Baffin Island, Canada, *in* American Geophysical Union Fall Meeting, December 8–12, San Francisco, Abstracts.

O'Connor, J.M., and Duncan, R.A., 1990, Evolution of the Walvis ridge–Rio Grande Rise hot spot system: Implications for African and South American plate motions over plumes: Journal of Geophysical Research, v. 95, p. 17,475–17,502.

Oh, J., Austin, J.A., Jr., Phillips, J.D., Coffin, M.F., and Stoffa, P.L., 1995, Seaward-dipping reflectors offshore the southeastern United States: Seismic evidence for extensive volcanism accompanying sequential formation of the Carolina trough and Blake Plateau basin: Geology, v. 23, p. 9–12, doi: 10.1130/0091-7613(1995)023<0009:SDROTS>2.3.CO;2.

Okulitch, A.V., Dawes, P.R., Higgins, A.K., Soper, N.J., and Christie, R.L., 1990, Towards a Nares Strait solution: Structural studies on southeastern Ellesmere Island and northwestern Greenland: Marine Geology, v. 93, p. 369–384, doi: 10.1016/0025-3227(90)90093-Y.

Olafsson, I., Sundvor, E., Eldholm, O., and Grue, K., 1992, Møre margin: Crustal structures from analysis of expanded spread profiles: Marine Geophysical Research, v. 14, p. 137–162.

Olesen, O., Lundin, E., Nordgulen, Ø., Osmundsen, P.T., Skilbrei, J.R., Smethurst, M.A., Solli, A., Bugge, T., and Fichler, C., 2002, Bridging the gap between the onshore and offshore geology in Nordland, northern Norway: Norwegian Journal of Geology, v. 82, p. 243–262.

Olesen, O., Skilbrei, J.R., Osmundsen, P.T., and Hartz, E.H., 2004, Is the segmentation of the rifting in the Norwegian-Greenland Sea controlled by Late Caledonian detachment structures? *in* The 26th Nordic Geological Winter Meeting, 6–9 January, Uppsala, Abstracts, p. 82–83.

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

Presnall, D.C., 2003, Petrological constraints on potential temperature: Proceedings of the Penrose Conference Plume IV: Beyond the plume hypothesis, 25–29 August, Hveragerdi, Iceland, Abstracts.

Reid, I., and Jackson, H.R., 1997, Crustal structure of northern Baffin Bay: Seismic refraction results and tectonic implications: Journal of Geophysical Research, v. 102, B1, p. 523–542.

Richardson, K.R., Smallwood, J.R., White, R.S., Snyder, D.B., and Maguire, P.K.H., 1998, Crustal structure beneath the Faroe Islands and the Faroe-Iceland ridge: Tectonophysics, v. 300, p. 159–180, doi: 10.1016/S0040-1951(98)00239-X.

Riis, F., 1996, Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data: Global and Planetary Change, v. 12, p. 331–357, doi: 10.1016/0921-8181(95)00027-5.

Ritchie, J.D., Gatliff, R.W., and Richards, P.C., 1999, Early Tertiary magmatism in the offshore NW UK margin and surrounds, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum geology of northwest Europe: Proceedings of the 5th conference: London, Geological Society of London, p. 573–584.

Ritsema, J., van Heijst, H.J., and Woodhouse, J.H., 1999, Complex shear wave velocity structure imaged beneath Africa and Iceland: Science, v. 286, p. 1925–1928, doi: 10.1126/science.286.5446.1925.

Roberts, A., Lundin, E.R., and Kusznir, N.J, 1997, Subsidence of the Vøring Basin and the influence of the Atlantic continental margin: Journal of the Geological Society of London, v. 154, p. 551–557.

Roberts, D.G., Thompson, M., Mitchener, B., Hossack, J., Carmichael, S., and Bjørnseth, H.-M., 1999, Palaeozoic to Tertiary rift and basin dynamics: Mid-Norway to the Bay of Bicsay—A new context for hydrocarbon prospectivity in the deep water frontier, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum geology of northwest Europe: Proceedings of the 5th conference: London, Geological Society of London, p. 7–40.

Robinson, P., 1991, The eye of the petrographer, the mind of the petrologist: American Mineralogist, v. 76, p. 1781–1810.

Roeser, H.A., 1982, Magnetic anomalies in the magnetic quiet zone off Morocco, *in* von Rad, U., et al., eds., Geology of the northwest African continental margin: New York, Springer-Verlag, p. 61–68.

Roest, W.R., and Srivastava, S.P., 1989, Sea-floor spreading in the Labrador Sea: A new reconstruction: Geology, v. 17, p. 1000–1003, doi: 10.1130/0091-7613(1989)017<1000:SFSITL>2.3.CO;2.

Rohrman, M., and van der Beek, P., 1996, Cenozoic postrift domal uplift of the North Atlantic margins: An asthenospheric diapir model: Geology, v. 24, p. 901–904, doi: 10.1130/0091-7613(1996)024<0901:CPDUON>2.3.CO;2.

Roussel, J., Lecorche. J.-P., Ponsard, J.F., Sougy, J., and Villeneuve, M., 1984, Panafrican to Hercynian deformations in the Mauritanides and tectonic significance of gravity anomalies: Tectonophysics, v. 109, p. 41–59.

Rumph, B., Reaves, C.M., Orange, V.G., and Robinson, D.L., 1993, Structuring and transfer zones in the Faroe Basin in a regional context, *in* Parker, J.R., ed., Petroleum geology of northwest Europe: Proceedings of the 4th conference: London, Geological Society of London, p. 999–1010.

Ryan, P.D., 2001, The role of deep basement during continent-continent collision: A review, *in* Miller, J.A., et al., eds., Continental reactivation and reworking: London, Geological Society of London Special Publication 184, p. 39–55.

Ryan, P.D., and Dewey, J.F., 1997, Continental eclogites and the Wilson Cycle: Journal of the Geological Society of London, v. 154, p. 437–442.

Saemundsson, K., 1979, Outline of the geology of Iceland: Jokull, v. 29, p. 7–28.

Sage, F., Basile, C., Mascle, J., Pontoise, B., and Whitmarsh, R.B., 2000, Crustal structure of the continent-ocean transition off the Côte d'Ivoire–Ghana transform margin: Implications for thermal exchanges across the palaeotransform boundary: Geophysical Journal International, v. 143, p. 662–678, doi: 10.1046/j.1365-246X.2000.00276.x.

Sandwell, D.T., and Smith, W.H.F., 1997, Marine gravity anomaly from GEOSAT and ERS 1 satellite altimetry: Journal of Geophysical Research, v. 102, B5, p. 10,039–10,054.

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J., and Kent, R.W., 1997, The North Atlantic Igneous Province, *in* Mahoney, J.J., and Coffin, M.L., Large igneous provinces: Washington, D.C., American Geophysical Union Geophysical Monograph 100, p. 45–93.

Saunders, A.D., Larsen, H.C., and Fitton, J.G., 1998, Magmatic development of the southeast Greenland margin and evolution of the Iceland plume: Geochemical constraints from leg 152, *in* Saunders, A.D., et al., eds., Proceedings of the Ocean Drilling Program, scientific results, Volume 152: College Station, Texas, Ocean Drilling Program, p. 479–501.

Schilling, J.G., 1973, Iceland mantle plume: Geochemical study of the Reykjanes ridge: Nature, v. 242, p. 565–571.

Schlische, R.W., 1993, Anatomy and evolution of the Triassic-Jurassic continental rift system, eastern North America: Tectonics, v. 12, p. 1026–1042.

Scott, R.A., Ramsey, L.A., Jones, S.M., Sinclair, S., and Pickles, C.S., 2005, Development of the Jan Mayen microcontinent by linked propagation and retreat of spreading ridges, *in* Wandås, B., ed., Onshore–offshore relationships on the Nordic Atlantic margin: Oslo, Norwegian Petroleum Society, Special Publication 12, p. 69–82.

Sebai, A., Feraud, G., Bertrand, H., and Hanes, J., 1991, ^{40}Ar/^{39}Ar dating and geochemistry of tholeiitic magmatism related to the early opening of the central Atlantic rift: Earth and Planetary Science Letters, v. 104, p. 455–472, doi: 10.1016/0012-821X(91)90222-4.

Sheth, H.C., 1999, Flood basalts and large igneous provinces from deep mantle plumes: Fact, fiction, or fallacy?: Tectonophysics, v. 311, p. 1–29, doi: 10.1016/S0040-1951(99)00150-X.

Skogseid, J., Planke, S., Faleide, J.I., Pedersen, T., Eldholm, O., and Neverdal, F., 2000, NE Atlantic rifting and volcanic margin formation, *in* Nøttvedt, A., et al., eds., Dymanics of the Norwegian margin: London, Geological Society of London Special Publication 167, p. 295–326.

Sleep, N.H., 1992, Hotspot volcanism and mantle plumes: Annual Review of Earth and Planetary Science, v. 20, p. 19–43, doi: 10.1146/annurev.ea.20.050192.000315.

Smallwood, J.R., and White, R.S., 2002, Ridge-plume interaction in the North Atlantic and its influence on continental breakup and seafloor spreading, *in* Jolley, D.W., and Bell, B.R., eds., The North Atlantic Igneous Province, Stratigraphy, tectonic, volcanic and magmatic processes: London, Geological Society of London Special Publication 197, p. 15–37.

Smallwood, J.R., Staples, R.K., Richardson, R.K., and White, R.S., 1999, Crust generated above the Iceland mantle plume: From continental rift to oceanic spreading center: Journal of Geophysical Research, v. 104, B10, 22,885–22,902.

Smith, W.H.F., and Sandwell, D.T., 1997, Global sea floor topography from satellite altimetry and ship depth soundings: Science, v. 277, p. 1956–1962.

Srivastava, S.P., and Roest, W.R., 1999, Extent of oceanic crust in the Labrador Sea: Marine and Petroleum Geology, v. 16, p. 65–84, doi: 10.1016/S0264-8172(98)00041-5.

Steckler, M.S., and ten Brink, U., 1986, Lithospheric strength variations as a control on new plate boundaries: Examples from the northern Red Sea region: Earth and Planetary Letters, v. 79, p. 120–132, doi: 10.1016/0012-821X(86)90045-2.

Steckler, M., and Watts, A.B., 1978, Subsidence of the Atlantic-type continental margin off New York: Earth and Planetary Science Letters, v. 41, p. 1–13, doi: 10.1016/0012-821X(78)90036-5.

Steinberger, B., and O'Connell, R.J., 1998, Advection of plumes in mantle flow: Implications for hotspot motion, mantle viscosity and plume distribution: Journal of Geophysics International, v. 132, p. 412–434, doi: 10.1046/j.1365-246x.1998.00447.x.

Steltenpohl, M., Hames, W., Andresen, A., and Marki, G., 2003, New Caledonian eclogite province in Norway and potential Laurentian (Taconic) and Baltic links: Geology, v. 31, p. 985–988, doi: 10.1130/G19744.1.

Stoker, M.S., Hitchen, K., and Graham, C.C., 1993, The geology of the Hebrides and west Shetland shelves, and adjacent deep-water areas: London, British Geological Survey, Her Majesty's Stationery Office, 149 p.

Stoker, M.S., Preag, D., Shannon, P.M., Hjelstuen, B.O., Laberg, J.S., Nielsen, T., van Weering, T.C.E., Sejrup, H.P., and Evans, D., 2005, Neogene evolution of the Atlantic continental margin of NW Europe (Lofoten Islands to SW Ireland): Anything but passive, *in* Doré, A.G., and Vining, B.A., eds., Northwest European petroleum geology and global perspectives: Proceedings of the 6th conference: London, Geological Society of London, p. 1057–1074.

Talwani, M., and Abreau, V., 2000, Inferences regarding initiation of oceanic crust formation from the U.S. east and conjugate south Atlantic margins, *in* Mohriak, W., and Ralwani, M., eds., Atlantic rifts and continental margins: Washington, D.C., American Geophysical Union Geophysical Monograph 115, p. 211–233.

Talwani, M., and Eldholm, O., 1977, Evolution of the Norwegian-Greenland Sea: Geological Society of America Bulletin, v. 88, p. 969–999.

Tarduno, J.A., Duncan, R.A., Scholl, D.W., Cottrell, R.D., Steinberger, B., Thordarson, T., Kerr, B.C., Neal, C.R., Frey, F.A., Torii, M., and Carvallo, C., 2003, The Emperor Seamounts: Southward motion of the Hawaiian hotspot plume in Earth's mantle: Science, v. 301, p. 1064–1068, doi: 10.1126/science.1086442.

Tate, M.P, 1993, Structural framework and tectonostratigraphic evolution of the Porcupine Seabight Basin, offshore western Ireland: Marine and Petroleum Geology, v. 10, p. 95–123.

Tegner, C., Duncan, R.A., Bernstein, S., Brooks, C.K., Bird, D.K., and Storey, M., 1998, A^{40}-A^{39} geochronology of Tertiary mafic intrusions along the east Greenland rifted margin: Relation to flood basalts and the Iceland hotspot track: Earth and Planetary Science Letters, v. 156, p. 75–88, doi: 10.1016/S0012-821X(97)00206-9.

Torsvik, T.H., Mosar, J., and Eide, E.A., 2001a, Cretaceous-Tertiary geodynamics: A north Atlantic exercise: Geophysical Journal International, v. 146, p. 850–866, doi: 10.1046/j.0956-540x.2001.01511.x.

Torsvik, T.H., Van der Voo, R., Meert, J.G., Mosar, J., and Walderhaug, H.J., 2001b, Reconstructions of continents around the north Atlantic at about the 60th parallel: Earth and Planetary Science Letters, v. 187, p. 55–69, doi: 10.1016/S0012-821X(01)00284-9.

Trettin, H.P., 1991, Late Silurian–Early Devonian deformation, metamorphism and granitic plutonism, northern Ellesmere and Axel Heiberg Islands, *in* Trettin, H.P., ed., Geology of the Innuitian orogen and Arctic platform of Canada and Greenland, Boulder, Colorado, Geological Society of America, The geology of North America, v. E, p. 295–301.

Trompette, R., 1997, Neoproterozoic (~600 Ma) aggregation of western Gondwana: A tentative scenario: Precambrian Research, v. 82, p. 101–112, doi: 10.1016/S0301-9268(96)00045-9.

Turner, J. D., and Scrutton, R.A., 1993, Subsidence patterns in western marginal basins: Evidence from the Faeroe-Shetland Basin, *in* Parker, J.R., ed., Petroleum geology of northwest Europe: Proceedings of the 4th conference: London, Geological Society of London, p. 975–984.

Vink, G.E., 1984a, A hotspot model for Iceland and the Vøring Plateau: Journal of Geophysical Research, v. 89, B12, p. 9949–9959.

Vink, G.E., 1984b, Preferential rifting of continents; a source of displaced terranes: Journal of Geophysical Research, v. 89, p. 10,072–10,076.
Vogt, P.R., 1971, Asthenosphere motion recorded by the ocean floor south of Iceland: Earth and Planetary Science Letters, v. 13, p. 153–160, doi: 10.1016/0012-821X(71)90118-X.
Vogt, P.R., 1973, Early events in the opening of the north Atlantic, *in* Tarling, D.H., and Runcorn, S.K., eds., Implications of continental drift to the earth sciences: New York, Academic Press, p. 693–712.
Vogt, P.R., 1983, The Iceland mantle plume: Status of the hypothesis after a decade of new work, *in* Bott, M.H.P., et al., eds., Structure and development of the Greenland-Scotland ridge: New methods and concepts: New York, Plenum Press, p. 191–213.
Vogt, P.R., Kovacs, L.C., Johnson, G.L., and Feden, R.H., 1979. The Eurasia Basin, *in* Proceedings of the Norwegian Sea Symposium: Oslo, Norwegian Petroleum Society, paper NSS-3.
Waagstein, R., 1988, Structure, composition and age of the Faroes basalt plateau, *in* Morton, A.C., and Parson, L.M., eds., Early Tertiary volcanism and the opening of the NE Atlantic: London, Geological Society of London Special Publication 39, p. 225–238.
Weber, J.R., 1990, The structures of the Alpha ridge, Arctic Ocean and Iceland-Faroes ridge, north Atlantic: Comparisons and implications for the evolution of the Canada Basin: Marine Geology, v. 93, p. 43–68, doi: 10.1016/0025-3227(90)90077-W.
Weber, J.R., and Sweeney, J.F., 1990, Ridges and basins in the central Arctic Ocean, *in* Grantz, A., et al., eds., The Arctic Ocean region, Boulder, Colorado, Geological Society of America, Geology of North America, v. L: p. 305–336.
White, N., and Latin, D., 1993, Subsidence analyses from the North Sea "triple-junction": Journal of the Geological Society of London, v. 150, p. 473–488.
White, N., and Lovell, B., 1997, Measuring the pulse of a plume with the sedimentary record: Nature, v. 387, p. 888–891, doi: 10.1038/43151.
White, R.S., 1988, A hot-spot model for Early Tertiary volcanism in the N. Atlantic, *in* Morton, A.C., and Parson, L.M., eds., Early Tertiary volcanism and the opening of the NE Atlantic: London, Geological Society of London Special Publication 39, p. 3–13.
White, R.S., and McKenzie, D., 1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, p. 7685–7729.
White, R.S., Spence, G.D., Fowler, S.R., McKenzie, D.P., Westbrook, G.K., and Bowen, N., 1987, Magmatism at rifted continental margins: Nature, v. 330, p. 439–444, doi: 10.1038/330439a0.
White, R.S., Bown, J.W., and Smallwood, J.R., 1995, The temperature of the Iceland plume and origin of outward-propagating V-shaped ridges: Journal of the Geological Society of London, v. 152, p. 1039–1045.
Wilson, J.T., 1965, Convection currents and continental drift. Evidence from ocean islands suggesting movement in the Earth: Philosophical Transactions of the Royal Society, v. 258, p. 145–167.
Wilson, M., 1997, Thermal evolution of the central Atlantic passive margins: Continental break-up above a Mesozoic super-plume: Journal of the Geological Society of London, v. 154, p. 491–495.
Wortel, M.J.R., and Spakman, W., 2000, Subduction and slab detachment in the Mediterranean-Carpathian region: Science, v. 290, p. 1910–1917, doi: 10.1126/science.290.5498.1910.
Wright, J.D., and Miller, K.G., 1996, Control of north Atlantic deep water circulation by the Greenland-Scotland ridge: Paleoceanography, v. 11, p. 157–170, doi: 10.1029/95PA03696.
Yaxley, G.M., 2000, Experimental study of the phase and melting relations of homogeneous basalt + peridotite mixtures and implications for the petrogenesis of flood basalts: Contributions to Mineralogy and Petrology, v. 139, p. 326–338, doi: 10.1007/s004100000134.
Ziegler, P.A., 1988, Evolution of the Arctic–north Atlantic and the western Tethys: American Association of Petroleum Geologists Memoir 43, 198 p.
Ziegler, P.A., 1992, European rift system: Tectonophysics, v. 208, p. 91–111.

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