NE Atlantic break-up: a re-examination of the Iceland mantle plume model and the Atlantic–Arctic linkage

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Abstract: Final break-up of Pangaea – opening of the NE Atlantic (NEA) and the Arctic Eurasia Basin – was associated with significant magmatism (in the NEA) and is commonly ascribed to thermal effects from a proto-Iceland plume. The plume is often assumed to be fixed with respect to the Earth's core and to have governed NEA break-up. It is argued here that the Iceland anomaly, past and present, cannot represent a fixed plume, nor be rooted at the core–mantle boundary and that the Greenland–Faroes Ridge is inconsistent with a classic time-transgressive hotspot track. It is shown that the Iceland anomaly has probably been located at the constructive plate boundary (Mid-Atlantic Ridge and antecedents) since its inception. While recent studies allow for some 'wandering' of hotspots relative to the core and mantle, it is considered unlikely that such drift of a mantle plume would precisely match lithospheric drift in order to achieve constant centering on the spreading ridge. The alternative view is, therefore, supported – that the anomaly is an upper mantle response to plate break-up. The two pulses of NEA magmatism are related to separate phases of North Atlantic break-up. Early Paleocene magmatism (*c*. 62–58 Ma) was governed by a short-lived attempt at seeking a new rift path, intermediate in time and space between the Labrador Sea–Baffin Bay and the NEA–Eurasia Basin rifts. The voluminous Early Eocene magmatism (*c*. 56–53 Ma) along the NEA margins was related to final break-up of Pangaea, exploiting the collapsed Caledonian fold belt. The interpretations here are at odds with Iceland representing a classic Morgan-type plume and it is suggested that the magmatism in the NEA and the Iceland anomaly represent a 'top-down' effect of plate tectonics.

Keywords: NE Atlantic, Arctic, Pangaea, Iceland, plume, hotspot, magmatism

The NE Atlantic margins (Fig. 1) were subject to several phases of episodic extension, between Devonian collapse of the Caledonian Orogen and Early Tertiary continental break-up, resulting in a wide rifted region. This *c*. 300 Ma long period of post-Caledonian extension has been described in detail by a number of workers (e.g. Ziegler 1988; Doré *et al*. 1999; Roberts *et al*. 1999) and is not repeated here. It appears that rifting, essentially exploiting the collapsed Caledonian fold belt, resulted in a relatively symmetrical necking of the lithosphere. Both conjugate margins show a broadly similar basinward-stepping rift pattern (e.g. Lundin & Doré 1997). However, both narrow and wide margin segments formed because the final rift phase cut obliquely across the previous rift grain. This is best exemplified by the Lofoten–Vøring margin segments and their conjugate Greenland margins (Tsikalas *et al*. 2005).

From the onset of North Atlantic seafloor spreading between Newfoundland and Iberia in Aptian time and until the Early Tertiary, the resultant passive margins were non-magmatic. In contrast, the Early Tertiary NE Atlantic margins were volcanic, with their characteristic seaward-dipping reflector sequence, abnormally thick oceanic crust, lower crustal high-velocity body, intrusives into and extrusives over the continental crust and sedimentary basins. Abnormally thick oceanic crust generation declined from a maximum to a steady state between break-up (*c*. 54 Ma) and Middle Eocene (*c*. 48 Ma) (Fig. 2), except for along the Greenland–Faroes Ridge, which is abnormally thick along its entire length (Holbrook *et al*. 2001). As much as $5–10 \times 10^6$ km^3 of melt is estimated to have been generated in only 2–3 Ma (White *et al*. 1987). This large melt volume has led to the NE Atlantic being characterized as a large igneous province (LIP) (e.g. Coffin & Eldholm 1992), commonly referred to as the North Atlantic Igneous Province (NAIP) (e.g. Saunders *et al*. 1997; Fig. 3).

The fifteen years since the publication of the key reference on the NAIP, *Early Tertiary Volcanism and the Opening of the North Atlantic* (Morton & Parson 1988) have seen a massive proliferation in available data and studies. High-resolution gravity and magnetic data are now available over much of the ocean basin and adjacent continental margins, while petroleum exploration (particularly west of Norway, the UK and Ireland) has hugely increased the seismic and well database. Despite this increase in knowledge, the time is now right to re-examine certain critical ideas that remain entrenched and largely unchallenged since the 1980s. Almost unanimously the NAIP magmatism has been associated with elevated temperatures from a mantle plume (e.g. Morgan 1971; White *et al*. 1987; White & McKenzie 1989; Skogseid *et al*. 2000), the so-called Iceland Plume. NE Atlantic break-up is also commonly perceived to have been triggered by this plume (e.g. White 1989; White & McKenzie 1989; Hill 1991).

By 'plume' this paper loosely refers to the general type suggested by Morgan (1971), Campbell & Griffiths (1990) or Sleep (1992), of a convective upwelling of lower mantle material, originating from a thermal instability near the core–mantle boundary. However, the authors recognize that different types or families of plumes are now proposed, including so-called primary plumes rooted at the core–mantle boundary, secondary plumes emanating from the upper–lower mantle transition, and tertiary 'hotspots' of shallow lithospheric origin (Courtillot *et al*. 2003). Courtillot *et al*. (2003) included Iceland in an exclusive group of seven deeply rooted plumes. Following Morgan (1971), other workers have refined the fixed hotspot framework, applied to plate reconstructions (e.g. Müller *et al*. 1993). This fixed nature of 'hotspots' was already contested in 1973 by Molnar & Atwater and more rigorous work has since demonstrated that a number of 'hotspots' are drifting significantly (e.g. Norton 2000;

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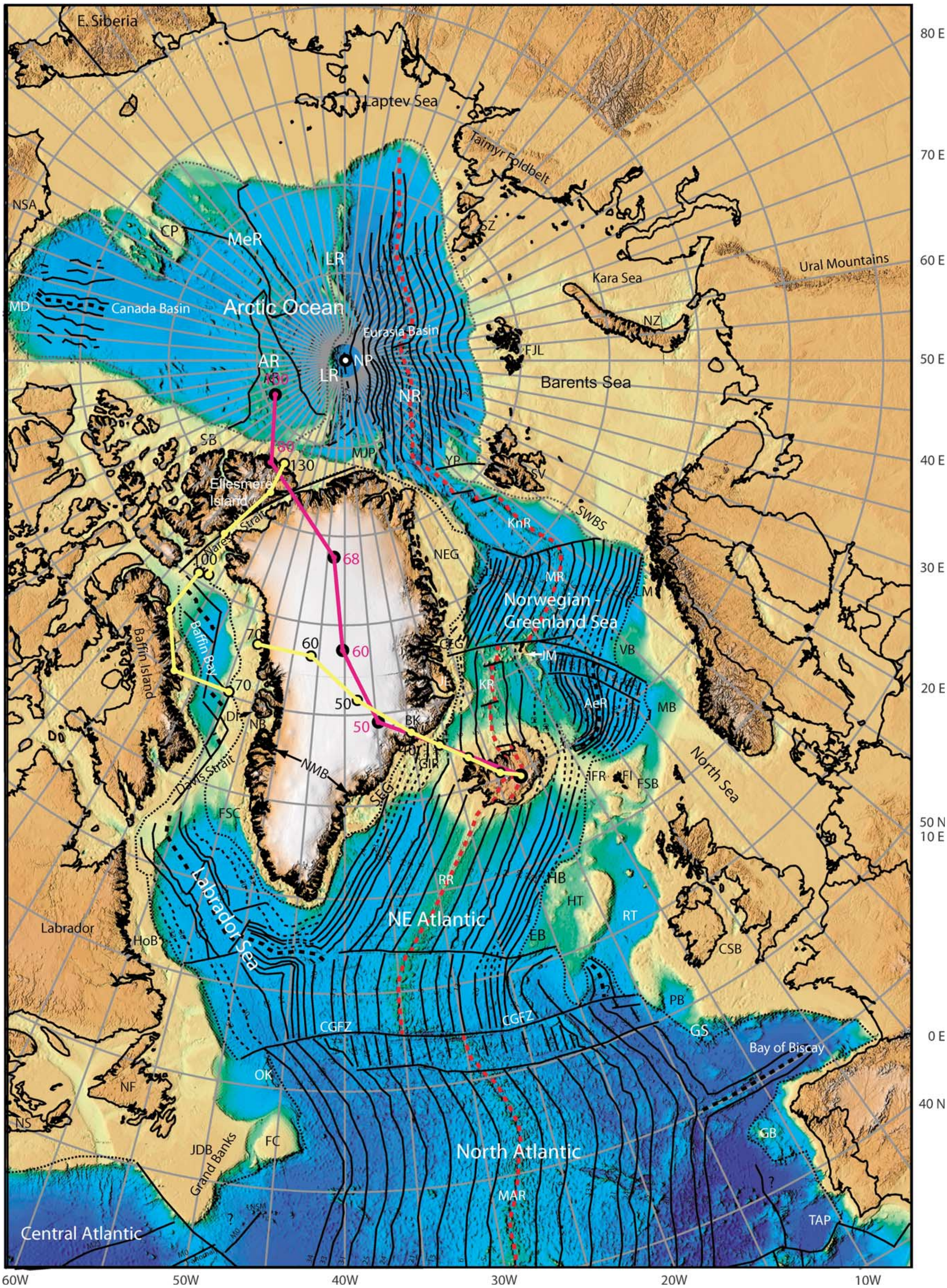


Fig. 1. Location map of the North Atlantic and Arctic (from Lundin 2002). Shaded relief bathymetry and topography image, based on data from Smith & Sandwell (1997) and Jakobsson *et al*. (2000), overlain by the authors' interpreted magnetic anomalies, fracture zones and spreading axes (black dashed = extinct axis, red dashed = active axis). Hotspot tracks proposed by Lawver & Müller (1994) (yellow dots/lines) and Forsyth *et al*. (1986) (magenta dots/lines) are included for reference. Abbreviations: AR, Alpha Ridge; AeR, Aegir Ridge; BK, Blosseville Kyst; CEG, Central East Greenland;

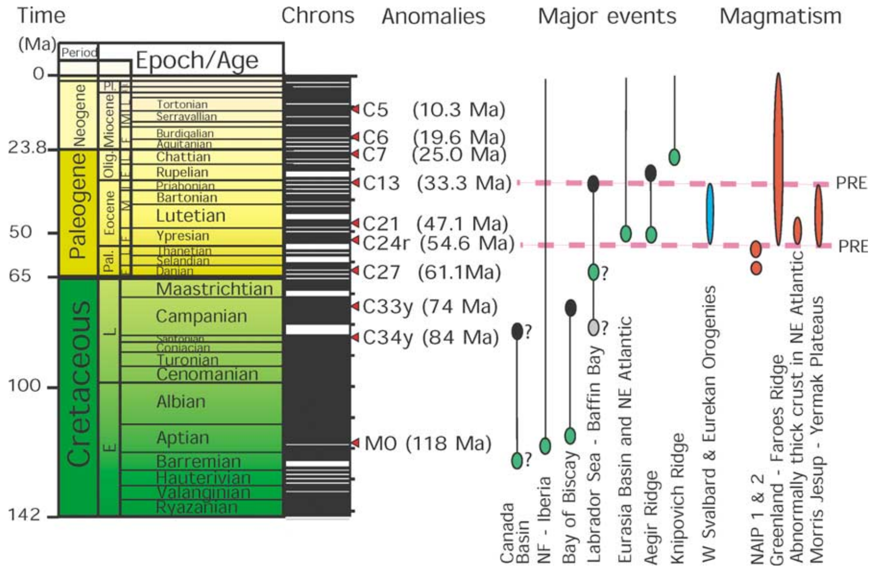


Fig. 2. Chronological diagram showing the relationship between major tectonic and magmatic events (after Eide 2002). PRE, Plate re-organization event.

Koppers 2001; Tarduno *et al.* 2003). Courtillot *et al.* (2003), however, argued that reported 'hotspot' drift is largely a function of erroneous grouping of different types of 'hotspots'. Thus, Courtillot *et al.* (2003) concluded that, although minor drift appears to occur (a magnitude lower velocity than plate motions according to their estimates), the fixed hotspot framework is generally valid for the last 80–100 Ma. Thereby, Courtillot *et al.* (2003) 'close the loop' back to the 30-year old original hypothesis of Morgan (1971); both agree that Iceland is underlain by a deeply rooted plume (core–mantle boundary origin) that has remained fixed with respect to the Earth's core. However, this does not necessarily mean that all workers adhere to such a model. For instance, White & McKenzie (1989) referred to a plume of undefined depth of origin that originated under East Greenland (i.e. quasi-fixed), while Sleep (1992) proposed a core–mantle origin for plumes under vigorous hotspots, including Iceland, but did not address plume fixity. This paper questions particularly the fixed nature of the Iceland anomaly, while it refers to independent work that challenges the depth of the Iceland anomaly.

The term 'hotspot' was initially applied to regions at the Earth's surface experiencing magmatic-volcanic activity that cannot be directly associated with plate tectonics, but the term now commonly also includes magmatism at plate boundaries. 'Hotspot' magmatism is commonly distributed in a time-transgressive pattern and thought to be located above a fixed plume or plume stem; Hawaii is probably the most widely cited intraplate example. Quotation marks are applied around the term 'hotspot' since it appears that many of them are not associated with abnormally high surface heat flows (Bonatti 1990; Stein & Stein 2003), questioning the presence of underlying anomalously hot mantle. The preference here is simply to refer to the Iceland 'anomaly' in order to avoid implying underlying processes typically associated with the terms 'plume' and 'hotspot'.

The interest lies in whether the longevity of the plume concept for the NAIP is due to the robustness of the hypothesis or due to an unwillingness to challenge it. A few challenges have already been made. Alternative views to the generally proposed plume influence for LIP generation have been suggested by, for example, Anderson (1996) and Sheth (1999). More recently, Foulger (2002) has argued against a plume origin for the NAIP magmatism and proposes melting of a normal temperature but heterogeneous (fertile) upper mantle. Geochemical anomalies in the Icelandic basalts, usually assumed to indicate a deep plume source (Schilling (1973) and many papers thereafter), have also been reinterpreted as indicative of shallower melt production in a heterogeneous mantle, while the fundamental concept of what geochemical signature a deep plume should have has also been challenged (Foulger *et al.* 2003*a*). A full discussion of the geochemical and petrological data on Iceland and the NAIP is beyond the scope of this paper, which emphasizes the tectonic and plate kinematic evidence. However, a few observations are made on the interpretation of geochemical and petrological data with respect to plumes, in general, and to the NAIP and Iceland, in particular.

Commonly (e.g. Schilling 1973; Campbell & Griffiths 1990), the underlying Earth model assumes a depleted upper mantle and an enriched lower mantle, where enrichment refers to the concentration of incompatible trace elements and Sr–Nd isotope signatures, relative to those of mid-ocean ridge basalts (MORB). Hot and enriched lower mantle is envisioned to rise via plumes into a depleted upper mantle and eventually to reach the lithosphere (Hofman & White 1982; Campbell & Griffiths 1990). Impingement of the hot plume head on the lithosphere and decompressional melting are, in this type of model, associated with the, development of continental flood basalt provinces, whereas the narrow and hotter tail is associated with long-lived supply of enriched and uncontaminated melt, which produces Ocean Island

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-Faroes Ridge; JL, Jameson Land; JM, Jan Mayen microcontinent; 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; NF, Newfoundland; NMB, Nagssugtogidion mobile belt; NP, North Pole; NR, Nansen Ridge; NS, Nova Scotia; NSA, North Slope of Alaska; NZ, Novaya Zemlya; OK, Orphan Knoll; PB, Porcupine Basin; RR, Reykjanes Ridge; RT, Rockall Trough; SB, Sverdrup Basin; SEG, Southeast Greenland; SV, Svalbard; SWBS, SW Barents Sea margin; SZ, Severnaya Zemlya; TAP, Tagus abyssal plain; VB, Vøring Basin; YP, Yermak Plateau.

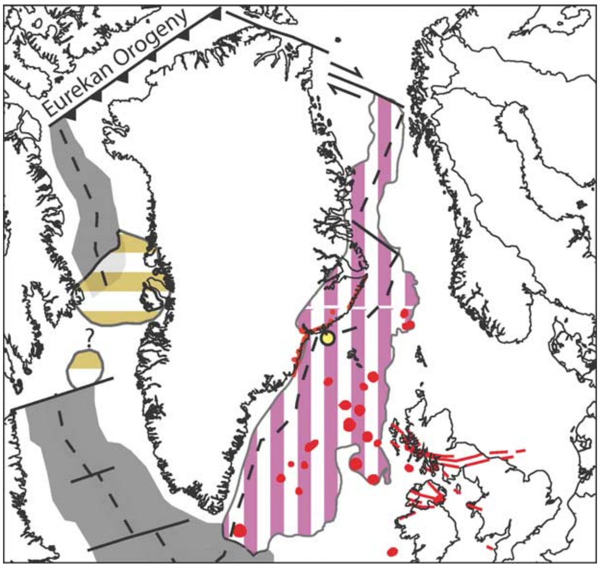


Fig. 3. North Atlantic plate reconstruction to Early Eocene (*c*. 54 Ma) (T. Torsvik, pers. comm. 2003) with distribution of basalt, flooded over the margins during break-up. The lava in West Greenland (brown striping) is older (*c*. 62–58 Ma) than the lava along the NE Atlantic margins (purple striping) (*c*. 56–53 Ma). Red blobs are seamounts, largely of Paleocene age. Red lines are simplified Early Paleocene dyke swarms. Grey represents oceanic or transitional crust. Note that shortening related to the Eurekan Orogeny in the Canadian Arctic Islands has not been palinspastically reconstructed.

Basalts including picrites. Minor variations to this model exist (e.g. Herzberg & O'Hara 2002), suggesting that picrites can form in the entire region above the plume head.

Petrologically, the best candidates for hot plume material are said to be komatiites and picrites (e.g. McKenzie & Bickle 1988; Campbell & Griffiths 1990; Herzberg & O'Hara 2002). In West Greenland and on Baffin Island a considerable proportion of the basalts formed during the early NAIP event (*c*. 62–58 Ma) are picritic, with MgO concentrations of *c*. 15–30% (Gill *et al*. 1992). At Skye and Mull, in the British Volcanic Province, MgO concentrations generally range between *c*. 5% and 14% (Kerr 1995; Scarrow & Cox 1995) but locally reach 18% (Bell & Williamson 1994). Basalts extruded during the later NAIP event (*c*. 56–53 Ma) in East Greenland and the Faroe Islands dominantly have MgO concentrations of *c*. 5–10%, except the so-called 'lava interval 2' that has a MgO content of *c*. 24% (Larsen *et al*. 1999a). Surprisingly, Iceland is dominated by normal MORB, i.e. tholeiites and **not** by picrites (Foulger *et al*. 2003*a*; Natland 2003; Presnall 2003). The most Mg-rich basalts on Iceland contain *c*. 10.5% Mg and are highly depleted with respect to major and trace element compositions and, thus, do not need to have formed at abnormally high temperature (Presnall 2003).

Presuming that the MgO content is a measure of eruption or potential temperature (e.g. Herzberg & O'Hara 2002), it is unclear why magmatism along the NE Atlantic margins should have been associated with a lower temperature plume head than in West Greenland. And, if Iceland today is situated directly above a hot plume tail (e.g. White *et al*. 1995), the basalts there should be highly picritic, which does not seem to be the case. High $^{3}He/^{4}He$ isotope ratios are often considered to be indicative of a lower mantle source and are observed above some 'hotspots', including Iceland. However, there appears to be no clear pattern between high $^{3}He/^{4}He$ ratios at 'hotspots' located above tomographically imaged low-velocity areas in the lower mantle (Montelli *et al*. 2003a). Alternative models exist that do not require a deep mantle source to explain high $^{3}He/^{4}He$ ratios (Foulger *et al*. 2003*a*; Meibom *et al*. 2003).

It is particularly important to recognize that more than one Earth model exists, e.g. 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 quite different models. This limited discussion is meant to emphasize that such interpretations are model-dependent. Claims of a distinctive geochemical or petrological 'plume signature' must be separated from evidence for a lower mantle origin or for plumes emanating from this level, because the precise rare element distribution in the mantle is unknown. Related to these arguments, recent publications (Anderson 1989, 2003; Sheth 1999; Foulger 2003; Hamilton 2003) have suggested that the plume concept as used by many adherents is fundamentally impossible to disprove using the scientific method. Since plumes are not seen 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. Given this reasoning, with which the authors agree, the intention is not, in this account, to disprove the plume hypothesis globally or to propose an all-encompassing alternative hypothesis. This paper's contribution to the debate is to address some inconsistencies – primarily geodynamic – relating to the interpretation of a plume origin for Iceland and the NAIP.

Three key topics are the focus.

(1) The mantle plume model for the NAIP and present-day Iceland. In particular, it is shown that the classical model of lithospheric drift over a fixed mantle plume is untenable for Iceland and the NAIP. Despite evidence that some 'hotspots' or 'hotspot' families move relative to one another (e.g. Molnar & Atwater 1973; Norton 2000; Koppers 2001; Tarduno *et al*. 2003), numerous recent publications, including by the current authors, assume the fixity of the Iceland 'hotspot' relative to lithospheric drift (e.g. Lawver & Müller 1994; Nadin *et al*. 1995; Clift 1996; Tegner *et al*. 1997; Larson & Saunders 1998; Saunders *et al*. 1997, 1998; Naylor *et al*. 1999; Ritchie *et al*. 1999; Skogseid *et al*. 2000; Müller *et al*. 2001; Lundin & Doré 2002; Mosar *et al*. 2002; Scott *et al*. 2004). This assumption is questioned. Most evidence reviewed herein indicates that the 'hotspot' (or plume centre) has remained stationary with respect to, and located upon, the plate boundary. Even given evidence for 'hotspot' drift, it seems unlikely that such migration of the Iceland 'plume' would precisely match lithospheric drift in order to achieve constant centering on the spreading ridge. In addition, the Iceland low-velocity anomaly, as defined by tomography, is restricted to the upper mantle. This evidence is incompatible with a source from a mantle plume rooted at the core–mantle boundary.

(2) Distribution of Early Paleocene magmatism in the British Volcanic Province and in West Greenland is here separated from the voluminous Early Eocene magmatism along the NE Atlantic margins. The two events trend almost perpendicular to each other. Rather than relating these magmatic events to a plume, alternative origins are investigated as consequences of plate tectonics.

(3) The linkage between Early–Middle Tertiary spreading in the Eurasian Basin and the NE Atlantic. The idea is challenged that onset of spreading was virtually synchronous across this area and facilitated by the arrival of the Iceland 'plume'. As an alternative, support is presented for a model involving ridges propagating from north and south and meeting in the approximate area of (palaeo-) Iceland.

Present-day indications of a hotspot under Iceland

The North Atlantic is characterized by a vast topographic/free air gravity anomaly starting near the Azores in the south, peaking over Iceland and extending to the gateway between the Norwegian–Greenland Sea and the Arctic Ocean in the north (e.g. Sandwell & Smith 1997; Andersen & Knudsen 1998). While a portion of the NE Atlantic uplift can be accounted for by the above-normal thickness of oceanic crust, a significant part (1.5–2 km centred on Iceland) is ascribed to dynamic uplift while the remainder is related to permanent uplift from overthickened crust (Jones *et al.* 2002a). According to Vogt (1983), the excess mass of this large topographic anomaly cannot be supported by the strength of the lithosphere and he proposed active mantle upwelling as the cause.

Iceland is situated over the northern part of a widespread positive geoid anomaly (*c.* 60 m) in the North Atlantic and NW Europe (King 2003; Köhler 2003). Marquart (1991) suggested that the North Atlantic geoid anomaly is a strong indication of upper mantle upwelling and that it may be the cause of the low mean ocean depths in the North Atlantic. According to Haxby & Turcotte (1978), there is 'considerable observational evidence that the topography of hotspot swells is directly associated with a geoid anomaly'. Malamud & Turcotte (1999) consider this as 'strong evidence that the excess topography and mass of the swell are compensated at depth by anomalously light (possibly hot) mantle material'. The current authors are, nevertheless, puzzled by the possible relationship between the vast N Atlantic topographic and geoid anomalies on the one hand and the upper mantle velocity anomaly beneath Iceland on the other hand. The core of the mantle velocity reduction beneath Iceland, as confined by teleseismic tomography, is a *c.* 200–250 km wide cylindrical shape (Foulger *et al.* 2000, 2001), while whole mantle tomography reveals an up to 2000 km wide upper mantle anomaly (Ritsema *et al.* 1999). However, the geoid anomaly is considerably larger, measuring 3000–4000 km and Iceland is far from centred on the anomaly (e.g. King 2003; Köhler 2003). Should the geoid anomaly represent the remnant thermal effect of a collapsed Iceland plume head, then it is now, after some 50 Ma of decay still much larger than the NAIP. Furthermore, there are few such vast positive geoid anomalies on the Earth and there is, thus, not a one-to-one correlation between them and other presumed plumes (compare, for example, Courtillot *et al.* (2003) with Köhler (2003)). Since the typical value for geoid anomalies associated with 'hotspots' is less than *c.* 8 m (e.g. Monnereau & Cazenave 1990), it is possible that the large N Atlantic geoid anomaly has no direct relationship to the Iceland 'hotspot' anomaly. Probably, a broader explanation must be sought.

The remarkable time-transgressive V-shaped ridges, extending up to 1000 km south from Iceland along the Reykjanes Ridge (Vogt 1971) and along the Kolbeinsey Ridge to the north (Jones *et al.* 2002b), are limited to oceanic crust dating back approximately to earliest Oligocene time. They are generally accepted to relate to crustal thickness changes of 1–2 km (e.g. Smallwood & White 1998). Views for the origin of the V-shaped ridges are that they relate to episodic excessive melt production caused by: (1) passage of hotter than normal asthenosphere travelling at high rates away from the Iceland plume (Vogt 1971; White *et al.* 1995; Smallwood & White 2002; Jones *et al.* 2002b), (2) plume pulses of constant temperature but varying flux (Ito 2001), or (3) compositional changes in the mantle (cf. Jones *et al.* 2002b). Alternatively, ridge migrations on Iceland, unrelated to a pulsing plume (Hardarson *et al.* 1997), have been suggested as a cause of the V-shaped ridges. In this model, it is the topographic troughs between the V-shaped ridges that represent anomalously low melt production. Regardless of origin, V-shaped ridges do not appear to be a general phenomenon associated with ridge-centred 'hotspots' world-wide. The only possible analogue that the authors are aware of is represented by the Miocene age seafloor south of the Azores. There, two elongated areas of anomalously shallow bathymetry form a V-shaped pattern, which is interpreted to relate to crustal thickness variations caused by a southward-propagating melt anomaly, active in the interval 10 Ma to 4 Ma (Cannat *et al.* 1999). However, the scale and expression is rather faint compared with the V-shaped ridges around Iceland.

Whole-mantle and teleseismic tomography reveal reduced P- and S-wave velocities beneath Iceland. Most studies constrain the low-velocity anomaly to the upper mantle (Tryggvason *et al.* 1983; Wolfe *et al.* 1997; Ritsema *et al.* 1999; Megnin & Romanowicz 2000; Foulger *et al.* 2000, 2001). The whole-mantle tomographic study by Bijwaard & Spakman (1999) stands out in that it indicated a velocity reduction extending from the surface to the core–mantle boundary. However, this work has been criticized for the manner in which the colour-scale of the tomographic images was saturated, producing an apparent continuous anomaly (Foulger & Pearson 2001). Finite frequence tomography (Montelli *et al.* 2003a) also indicates that the velocity anomaly beneath Iceland is constrained to the upper mantle.

Interestingly, the teleseismic study by Foulger *et al.* (2000, 2001) indicated that a vertical cylindrical anomaly with a diameter of *c.* 200–250 km in the upper 200 km of the mantle changes shape into a tabular anomaly at depth, elongated parallel to the NE Atlantic spreading system. This observation will be considered later.

Indications of the Iceland anomaly through geological history

The NAIP is generally considered to encompass a 2000–2500 km diameter area centred approximately between East Greenland and the Faroes Islands in a pre-break-up reconstruction (White & McKenzie 1989; Saunders *et al.* 1997; Smallwood & White 2002). Magmatism in the NAIP has been divided into two phases (e.g. Saunders *et al.* 1997): (1) 'Middle' Paleocene magmatism (*c.* 62–58 Ma) mainly confined to continent-based magmatism in the British Volcanic Province (BVP), eastern Baffin Island and West Greenland; and (2) latest Paleocene to earliest Eocene (*c.* 56–53 Ma) magmatism along the NE Atlantic margins. The latter of these phases featured considerably more voluminous magmatism than the former.

Following White (1988), most workers have sought to explain the Early Tertiary volcanism of the NAIP in terms of impingement of a mantle plume, an early manifestation of the anomaly beneath Iceland described in the preceding section. Attempts to explain the NAIP in terms of the plume model are hampered by a lack of consensus on how the plume appeared in time and space. This, in turn, has led to a wide variety of beliefs on the size and morphology of the plume; the plume has been characterized as a single point, the precise position of which can be located with a precision of *c.* 100 km based on geochemistry (Hardarson *et al.* 1997) and charted as a function of the drift of the crust over a fixed hotspot (e.g. Lawver & Müller 1994; Torsvik *et al.* 2001a) (Fig. 1), or at the other end of the scale as a continental-scale mantle anomaly acting simultaneously on areas separated by some 2000 km (Smallwood & White 2002).

To the authors' knowledge there is no geological evidence of a plume track crossing Greenland, as predicted by fixed hotspot plate reconstructions. Obviously, the Greenland ice cap prevents direct observation of most of the onshore geology along a presumed hotspot track. Indirect observations, however, provide far from convincing evidence. Magnetic data (Verhoef *et al.* 1996; Oakey *et al.* 1999) reveal an arched ENE-trending anomaly belt crossing from East to West Greenland but these data appear to mark the Nagssugtoqidian mobile belt, situated within the Archean terrains of Greenland (Gill *et al.* 1992; Escher & Pulvertaft 1995), rather than a continuation between the West Greenland igneous area and the Greenland–Faroes Ridge. A series of strong magnetic anomalies trending NNW from East Greenland and a belt of residual gravity anomalies extending towards North Greenland have been suggested to be a hotspot track (Brozena 1995), approximately similar to the track suggested by Forsyth *et al.* (1986) (Fig. 1). However, the gravity anomalies are located far east of the West Greenland volcanic area (Fig. 3), which led to the proposal that the plume head was first deflected to West Greenland and subsequently swung over to East Greenland (Brozena 1995). Receiver functions calculated for Greenland (Dahl-Jensen *et al.* 2003) do not reveal any significant changes in crustal thickness, indicative of a hotspot trail. Over-thickened crust along proposed ‘hotspot tracks’ has generally not been documented on continents, although such over-thickening is expected to occur (Farnetani *et al.* 1996); the Yellowstone–Snake River Plain region (Catchings & Mooney 1988) may represent an exception. In any event, the spatial density of the receiver function array on Greenland is arguably insufficient to determine the presence of a track of thickened crust.

A crucial problem with the ‘fixed hotspot’ and the ‘global hotspot reference frame’ (Müller *et al.* 1993) is that they indicate that the Iceland plume centre must have been situated beneath West Greenland at the onset of NAIP magmatism in the Early Paleocene (*c.* 62 Ma), in order that northwestwards drift of the lithosphere could place the hotspot under present-day Iceland. However, onset of basaltic lava extrusion appears to have been more or less simultaneous at both the northwestern and south-eastern extremities of the NAIP, for example in West Greenland and the Hebrides (e.g. Ritchie *et al.* 1999; Jolley & Bell 2002). This problem – the simultaneous inception of magmatism ‘all over’ the NAIP when the hotspot was supposedly at the most northwesterly outpost of the province – has created immense problems for plume models. Such a model must explain how ‘…abnormally hot mantle arrived simultaneously, or at least within the limits of resolution of our measurements of about one million years, across the entire region at points more than 2000 km apart in the pre-drift reconstruction’ (Smallwood & White 2002). An equally tricky problem is the lack of magmatism in areas that should have been within reach of the plume, such as the magmatically starved SW Greenland margin. This margin, bordering the Labrador Sea, was already an established passive margin when the plume is supposed to have been under West Greenland and should have been a prime area of magmatism (Gill *et al.* 1992).

Inconsistency between model and observations has variously been explained by (i) a separate and short-lived plume underneath West Greenland (e.g. Morgan 1983; Srivastava 1983); (i) a plume split into two arms arriving at different times (e.g. Holm *et al.* 1993); (ii) an ultrafast plume spreading out immense distances along the base of the lithosphere (presumably this spread must also have been unidirectional, between West Greenland and the British Isles) (Larsen *et al.* 1999b); (iii) channelling of plume material from beneath Greenland into the NE Atlantic spreading axis (Vink 1984) (note however that such channelling would not only have to reach the spreading axis – which in any case did not exist at 62 Ma – but significantly beyond it in order to cause the volcanism of the British province); (iv) blocking of plume material by a step at the base of the lithosphere (Nielsen *et al.* 2002); (v) a complete reworking of the plume concept, abandoning the popular image of a rising lava-lamp style blob in favour of one of ascending sheets thousands of kilometres long (Smallwood & White 2002). This proliferation of models may be ‘a sign of a hypothesis in trouble’ (Foulger 2003). What seems certain is that a Hawaii-style model for plate motion over a deeply rooted fixed plume is now untenable as an explanation for both the NAIP and Iceland.

Most studies of the NAIP that assume the plume hypothesis suffer from addressing the issue in microcosm rather than as a whole – i.e. they are geographically limited, or they address early magmatism but not break-up, or they address the NAIP but not subsequent ocean basin evolution. This has allowed a huge volume of ‘plume’ literature to accumulate, while sidestepping the inconsistencies described above. Smallwood & White’s (2002) concept of rising mantle sheets is notable in that it attempts to address the whole problem. In this model, early NAIP magmatism (about 62–58 Ma) derives from a narrow sheet-like plume extending NW–SE between West Greenland (possibly Baffin Island) and the Irish Sea. Immediately before and during NE Atlantic break-up, about 56–53 Ma and coincident with the most voluminous magmatism, this sheet refocuses into the NE Atlantic spreading axis, i.e. into a 2000 km rift orthogonal to the original sheet. Subsequently it refocuses again into a narrow stem (i.e. a conventional plume) beneath the constructional plate boundary as expressed by present-day Iceland. The requirement for such constant morphing of the plume seems to be a case of special pleading and certainly one that is not required by plumes elsewhere. Even setting this suspicion aside, there are still major problems with the hypothesis. First, the distribution of phenomena in the early NAIP is not easily satisfied by a single ‘mantle sheet’ – consequently up to three or four crossing sheets are invoked by Smallwood & White (2002). Secondly, unless the NW–SE mantle sheet ‘caused’ NE Atlantic break-up as implied by Smallwood & White (unlikely, since it cuts across the line of subsequent break-up and its extensional direction is at right angles to the one required), collapse of the sheet into a more NE–SW axially distributed phenomenon must have been in some way caused by the opening. This would, therefore, imply a thin-skinned plate tectonic control on the shape and distribution of the plume (‘top down’), in conflict with the generally held notion that plumes are generated at the core–mantle boundary or upper–lower mantle boundary and are more or less independent of plate tectonics (‘bottom up’). Lastly, if such a plume, with a deep-seated mantle origin, became focused beneath the plate boundary after opening, northwestwards drift of the plates (as shown by, for example, Torsvik *et al.* 2001a, Fig. 6) would place the plume centre at a location beneath northwestern Britain at present day (unless migration of the plume somehow contrived to mimic lithospheric drift). Clearly this is not the case. It is also noteworthy that palaeomagnetic data are at odds with a fixed hotspot model for Iceland (Torsvik *et al.* 2001a). Mismatches between palaeomagnetically determined palaeolatitudes and the hotspot latitudes are also reported for the Hawaii–Emperor Seamount Chain and are explained there by southerly drift of the Hawaii ‘hotspot’ (Tarduno *et al.* 2003).

As indicated elsewhere in this account, it may be necessary to examine the possibility that the melting anomaly associated with formation of the NE Atlantic volcanic passive margin and present-day Iceland represents a thin-skinned phenomenon that has been centred on the constructional plate boundary since its inception. This idea, however, leaves open the origin of the cross-cutting ‘early’ NAIP which extends in a NW–SE belt from Baffin Island to the northern and western British Isles. The linear nature of this province (Fig. 4) was understood by early workers, including Koch (1935) and Hall (1981) called it the ‘Thulean Volcanic Line’. It is characterized, at least in its Eurasian portion, by intense NW–SE dyke swarms, mainly mafic in character (e.g. Dewey & Windley 1988; England 1988). These swarms are not confined to the Hebridean province, but extend in a SE direction across northern England to the Central North Sea (Kirton & Donato 1985) and south to Lundy Island in the Bristol Channel, where numerous NW–SE dykes occur in association with a granite pluton (e.g. Blundell 1957). The BVP trend of magmatism may extend as far south as the Massif Central in France where Ziegler (1992) described Paleocene magmatism. As remarked by England (1988), the frequency and consistent trend of the dykes indicate a NE–SW extensional stress field across Britain during part of the Paleocene. The early NAIP may, therefore, represent a transient failed attempt by NW Europe and Greenland to break-up along a NW–SE axis. This idea has been suggested previously by Dewey & Windley (1988), who proposed the existence of a ‘Gallic subplate’ in the Palaeogene, bounded to the NW by the opening Atlantic, to the SE

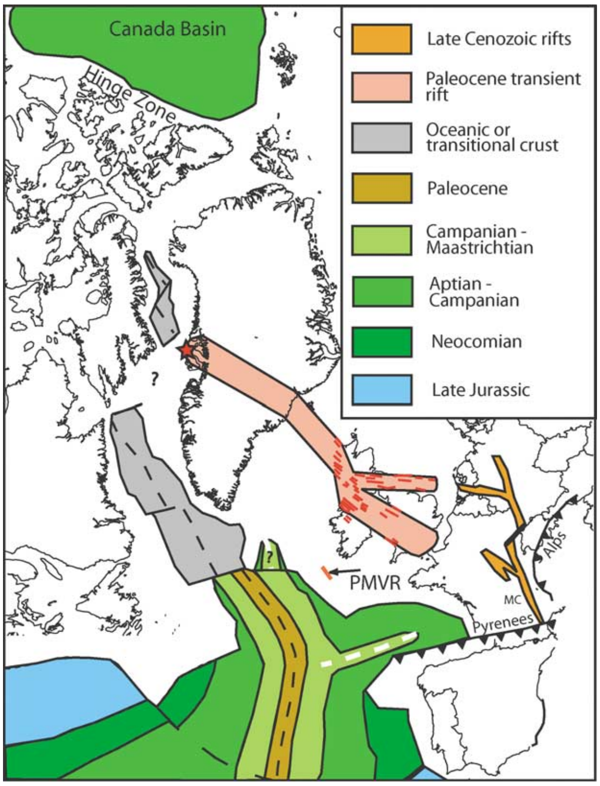


Fig. 4. North Atlantic plate reconstruction to 60 Ma (T. Torsvik, pers. comm. 2003) with simplified seafloor ages. The main dyke trend in the British Volcanic Province (shown by red lines), a zone of weak extension, is indicated with its suggested link to the West Greenland magmatic area (shown by red star) and early spreading centres in Baffin Bay. Note the consistency of this NW-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 in order 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.

by the Alpine convergent boundary and to the NE by 'a fracture-dyke boundary, which almost succeeded in splitting the subplate from its Eurasian parent to the east'. Such an extensional direction would logically have been a continuation of mid-late Cretaceous stress fields; during this interval Atlantic seafloor spreading propagated northwestwards between a triple junction west of Iberia and the Charlie Gibbs Fracture Zone, a phase probably associated with near-separation in the Porcupine Basin and the emplacement of the NW–SE Porcupine Median Volcanic Ridge, and with further extensional propagation northwestwards into the Labrador Sea (see, for example, Johnston *et al.* 2001, fig. 6). Elements of the frequently documented NW–SE 'transfer' trend of the NE Atlantic margin (Rumph *et al.* 1993; Doré *et al.* 1997; Naylor *et al.* 1999) may be a further expression of this extension, as may be the dominant fjord and dyke grain of the Faroes and the fjord grain of East Greenland. Recently reported NW-trending half-graben structures containing Upper Cretaceous and Palaeogene shallow-marine sediments in the Christian IV Gletcher area (just east of Kangerlussuaq) also follow this trend (Larsen & Whitham 2005). In the volcanic area of West Greenland both the fjord grain and a set of Paleocene extensional faults trend NW–SE (Nøhr-Hansen *et al.* 2002). Offshore in Baffin Bay, Paleocene opening was probably manifested as a series of NW-trending spreading cells, possibly offset from the Labrador Sea. Taken together, these observations provide good support for a transient arm of extension linking the BVP across Greenland into Baffin Bay (Fig. 4). This stress field was replaced as stretching and subsequent separation refocused on the NE Atlantic margin in the later Paleocene–Early Eocene. Both the early NAIP and the subsequent, orthogonal volcanic passive margin development can be explained in terms of plate tectonic processes – i.e. break-up of a crust already stretched by numerous preceding extensional episodes, above a heterogeneous (and locally fertile) melt-prone mantle. Eclogites from subducted Iapetus oceanic crust are one suggested alternative (Foulger *et al.* 2003*a*). Another possibility may be eclogites from a residual non-exhumed Caledonian orogenic root (cf. Ryan & Dewey 1997).

Implications of the Greenland–Faroes Ridge symmetry

An important characteristic of the Iceland anomaly is that it is located along the aseismic Greenland–Faroes Ridge (GFR) (bridging Greenland and NW Europe), which has been proposed to be all or part of a 'hotspot track' (e.g. Morgan 1971, 1981; Holbrook & Keleman 1993; Lawver & Müller 1994). In contrast to typical 'hotspot' tracks, such as the Hawaii–Emperor Seamount Chain, the GFR is not time-transgressive in one direction but appears to have formed symmetrically about Iceland. Symmetrical construction of the GFR was also proposed by Sleep (1992) who, at the same time, advocated a plume rooted at the core–mantle boundary.

The major argument presented here for the Iceland 'anomaly' to have formed *in situ*, approximately between Kangerlussuaq and the Faroes Islands, and to have been captured in the spreading system following break-up, is the existence and shape of the GFR. Seismic refraction data demonstrate that the ridge segments on either side of Iceland, the Greenland–Iceland Ridge and the Iceland–Faroes Ridge, consist of anomalously thick (*c.* 30 km) oceanic crust (Bott 1983; Richardson *et al.* 1998; Smallwood *et al.* 1999; Holbrook *et al.* 2001; Foulger *et al.* 2003*b*). Abnormally thick oceanic crust, such as beneath the GFR is often referred to as Icelandic type crust (Bott 1974) and development of oceanic crust thicker than *c.* 7 km is generally thought to require anomalously high asthenosphere temperatures, typically associated with a mantle plume (e.g. White & McKenzie 1989; Smallwood *et al.* 1999). However, alternative views exist for generating the abnormally thick Greenland–Faroes Ridge oceanic crust, such as melting of a fertile upper mantle (e.g. Anderson 1996; Foulger *et al.* 2003*a*).

A corollary of plate reconstructions assuming a fixed hotspot framework, estimating the Paleocene position of the Iceland plume (centre) beneath South Central Greenland (e.g. Lawver & Müller 1994; Torsvik *et al.* 2001*a*), is that the Iceland hotspot can never have been positioned beneath the Iceland–Faroes side of the GFR since its present-day location would represent its easternmost position relative to the overriding plates. This paradox was recognized by Vink (1984) who provided a model whereby asthenosphere from the Iceland plume was channelled the shortest distance from the plume centre under Greenland to the nearby Reykjanes Ridge. Vink's model thereby provided a mechanism for forming the GFR in a fixed hotspot framework. However, with such a model a pronounced V-shaped hotspot track should have formed, since palaeomagnetic data reveal that North America, Greenland and Eurasia have moved significantly northwards since break-up (as well as before) (e.g. Torsvik *et al.* 2001*b*). To a first order, the GFR is linear, not V-shaped (Fig. 1), contradicting Vink's model.

Magnetic data over the GFR show a patchy pattern (Fig. 5a), distinctly different from the typical magnetic seafloor striping. It is suspected that the patchy magnetic pattern along the GFR reflects the more complicated distribution of lava formed during subaerial extrusion (e.g. Bott 1983), i.e. long flow paths interacting with the topography of pre-existing flows, complicated further by erosion until the ridge subsided below wave base (cf. Hardarson *et al.* 1997). In addition, the pattern may relate to extinct volcanic

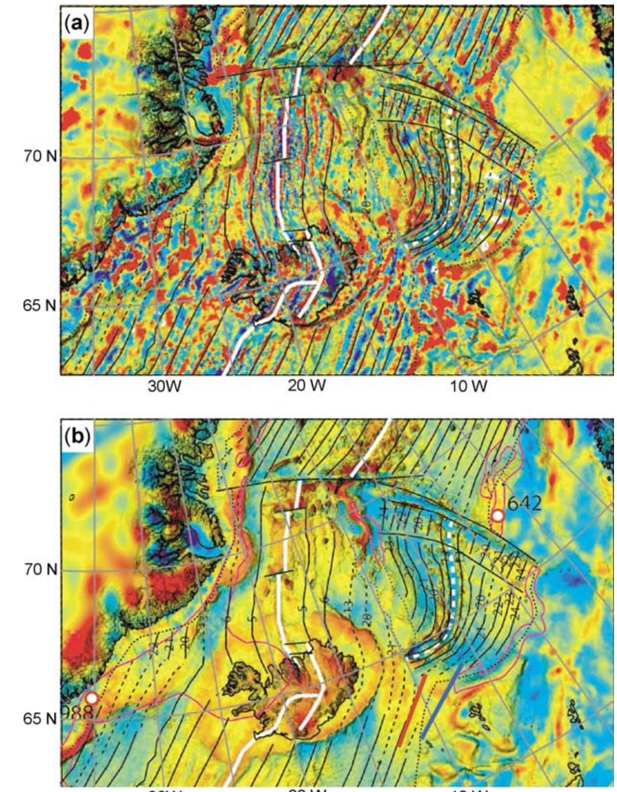


Fig. 5. Shaded relief image of: (**a**) magnetic data in the Norwegian–Greenland Sea (Verhoef *et al.* 1996) draped on bathymetry (Smith & Sandwell 1997) (**b**) free air gravity data in the Norwegian–Greenland Sea (Andersen & Knudsen 1998) draped over bathymetry (Smith & Sandwell 1997). Solid white lines are active spreading axes, dashed white line is abandoned Aegir Ridge, thin solid black lines are interpreted magnetic anomalies; thick solid black lines are fracture zones; dotted black lines are Continent–ocean boundaries; purple lines are distribution of seaward-dipping reflectors (from Planke & Alvestad 1999); red and blue lines are refraction profiles by Bott (1983) and Makris *et al.* (1995), respectively. Red indicates positive values and blue, negative values.

centres, analogous to such centres on Iceland (Vogt *et al.* 1981), and to small-scale shifts of the spreading axis, as seen on Iceland today (e.g. Smallwood & White 2002). Regardless of the precise nature of the magnetic anomalies observed along the GFR, this characteristic pattern is present along the entire ridge, suggesting that the same process of crustal accretion operated during construction of both sides of the ridge.

In summary, the presence of the Iceland–Faroes side of the GFR, and the compelling evidence for symmetrical construction of the ridge as a whole, are at odds with the GFR being a classic time-transgressive hotspot track. It is argued that the GFR developed *in situ* above an upper mantle upwelling that has maintained its position at the plate boundary since break-up. A key question following this assertion is whether the Iceland 'anomaly' was triggered by the break-up (rather than causing it by weakening of the lithosphere, as is often assumed). This question is addressed by investigating the evolution of the Labrador Sea–Baffin Bay, the NE Atlantic and the Arctic Eurasia Basin.

Final break-up of Pangea – linking the North Atlantic and Arctic

Labrador Sea and Baffin Bay versus the Arctic

Rifting along the Labrador Sea margins occurred in Early Cretaceous time (*c.* Barremian) (Balkwill 1987; Chalmers & Pulvertaft 2001). 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. This is consistent with the apparent continuity of geological features across the Nares Strait (e.g. Dawes & Kerr 1982; Okulitch *et al.* 1990). Minor lateral motion along the Wegner Transform in the Nares Strait is plausible, however. An older magnetic anomaly X was identified in the Eurasia Basin by Vogt *et al.* (1979) and has more recently been proposed to represent Chron 25, implying that the earliest seafloor spreading in the Eurasia Basin may have been linked with spreading in the Labrador Sea–Baffin Bay (Brozena *et al.* 2003).

Chron 33 (*c.* 81 Ma) (Fig. 2) is the oldest recognized magnetic anomaly in the Labrador Sea (Roest & Srivastava 1989; Srivastava & Roest 1999). These workers interpret the anomalies as relating to seafloor, implying that the northward-propagating North Atlantic reached into the Labrador Sea by Late Cretaceous time. However, the nature of the anomalies has been contested. Chalmers & Laursen (1995) and Chalmers & Pulvertaft (2001) recognize the same anomalies, but argue that the inner anomalies relate to highly intruded continental crust and that seafloor spreading did not start until Early Paleocene (Chron 27). Chian *et al.* (1995) mapped transitional crust along the margins of the Labrador Sea, between Chrons 33 and 31, and interpreted this as serpentinized upper mantle beneath a thin (2 km) crustal layer of unknown affinity (continental or oceanic). Similar transitional crust is reported from the non-volcanic Iberian margin (Pickup *et al.* 1996). In any event, it appears clear that seafloor was never able to propagate beyond the northern tip of Baffin Bay (e.g. Reid & Jackson 1997). There is no dispute about the Chron 27–13 anomalies in the Labrador Sea, however, nor about the orientation of fracture zones associated with the two phases of opening (pre-Chron 24 and post-Chron 24).

Magnetic data acquired in Baffin Bay (Jackson *et al.* 1979) permitted interpretation of NNW-trending linear anomalies assumed to represent seafloor spreading. However, at that time the Chron 24–13 northward motion of Greenland versus North America was not fully appreciated. The subsequent definition of NNW-trending fracture zones in Baffin Bay (Roest & Srivastava 1989; Srivastava & Roest 1999) permits reinterpretation of the Baffin Bay magnetic data (Jackson *et al.* 1979), resulting in a 'swap' of a previously interpreted spreading axis (Jackson *et al.* 1979) with a fracture zone. This, in turn, forms the basis for reinterpreting the magnetic anomalies. By doing so, magnetic anomalies correlating to Chron 26n or Chron 25n (middle Paleocene) may be defined in Baffin Bay (Oakey *et al.* 2003). Because the magnetic survey (Jackson *et al.* 1979) did not span the entire width of Baffin Bay, Chron 25/26n does not necessarily mark the oldest possible anomaly present.

When 'seafloor spreading' reached the northern tip of Baffin Bay in latest Cretaceous or Early Paleocene time, it approached the passive margin hinge zone to the Canada Basin. Although of poorly defined age, the Canada Basin is estimated to have formed between Hauterivian (Grantz *et al.* 1990) and Campanian time (Weber & Sweeney 1990), or Hauterivian and Turonian time (Lawver & Baggeroer 1983) (Fig. 2). Hence, the Canadian Basin passive margin was *c.* 65 Ma old when approached by the propagating rift/seafloor in Baffin Bay. This hinge zone probably acted as a barrier to further propagation and triggered plate reorganization, analogous to the way the Neo-Tethyan hinge zone hindered further propagation of the Red Sea–Gulf of Suez rift (Steckler & ten Brink 1986). As described earlier, a transient Early Paleocene attempt at developing a new rift path is proposed to have taken place through the BVP–W Greenland and into Baffin Bay. Ultimately, a new rift path formed in Early Eocene time in the NE Atlantic utilizing the collapsed Caledonian fold belt and the associated Mesozoic rift system. Break-up in the Arctic followed the Canada Basin shear margin (Grantz *et al.* 1990) and split off the Lomonosov Ridge (a microcontinent) in the process. This is another example of how the lithospheric strength control provided by the Canada Basin influenced NE Atlantic–Arctic break-up.

During the following *c*. 20 Ma, simultaneous spreading occurred along two arms of the North Atlantic: the Labrador Sea/Baffin Bay arm and the NE Atlantic arm. This simultaneous spreading was linked at a triple junction south of Greenland, and the northward motion of Greenland induced the Eurekan Orogeny (Oakey 1994). The end of the Eurekan Orogeny coincided with the termination of seafloor spreading in the Labrador Sea and Baffin Bay at Chron 13 (*c*. 35 Ma) (Fig. 2). Oakey's (1994) study of west-central Ellesmere Island and East Axel Heiberg Island revealed a dominant structural transport direction of *c*. N60°W, corresponding almost perfectly with the calculated N67°W convergence direction between Greenland and North America (Roest & Srivastava 1989; Srivastava & Roest 1999). The angle of convergence was, thus, very high, with limited lateral motion along the Wegner Transform (located in the Nares Strait – trending *c*. N40°E), explaining why the Labrador Sea/Baffin Bay arm of spreading was unable to become (or possibly remain) a successful link with the Arctic Eurasia Basin.

The essential point from the foregoing discussion, therefore, is that the abandonment of the Labrador Sea/Baffin Bay arm of spreading and diversion of seafloor spreading through the Caldeonian fold belt (NE Atlantic spreading arm) was a natural outcome of plate tectonic reorganization, partly dictated by the strength distribution of the lithosphere (particularly the influence of the strong Canada Basin lithosphere) and partly by the orthogonal convergence across the Nares Strait preventing lateral motion along the Wegner Transform. Lithospheric weakening in the proto-NE Atlantic due to the arrival of a plume need not be invoked.

Linkage between the NE Atlantic and the Arctic

In large parts of the North Atlantic the magnetic seafloor anomalies are well defined and of little or no controversy. Previous interpretations have been largely followed in the following regions – North Atlantic: Srivastava & Tapscott (1986), Vogt (1986); Arctic: Oakey *et al*. (1999), Brozena *et al*. (2003); Labrador Sea: Roest & Srivastava (1989), Srivastava & Roest (1999); Norwegian–Greenland Sea: Talwani & Eldholm (1977), Vogt *et al*. (1980), Escher & Pulvertaft (1995), Jung & Vogt (1997), Skogseid *et al*. (2000). In the more complicated area surrounding the Aegir and Kolbeinsey ridges (e.g. Talwani & Eldholm 1977; Vogt *et al*. 1980; Nunns 1982, 1983; Jung & Vogt 1997), some of the boundaries and magnetic anomalies have been reinterpreted (Figs 5a and b). It is suggested here that both the Aegir and Kolbeinsey ridges show classic signs of propagation (e.g. Vink 1982) of opposed orientation. The model presented here for the Aegir and Kolbeinsey ridges is relatively similar to that of Nunns (1982, 1983), implying simultaneous spreading on two opposed and overlapping spreading axes, but contrasts with the model implying a ridge jump from the Aegir to the Kolbeinsey Ridge (e.g. Talwani & Eldholm 1977; Vink 1984). The interpretations in this paper of magnetic anomalies, fracture zones and continent–ocean boundaries (COB) in the NE Atlantic and Norwegian–Greenland Sea have been used as the basis for a reconstruction of magnetic grids, applying the method of Verhoef *et al*. (1990) (Fig. 6; Table 1).

Critical observations to a propagation model

Of importance to the interpretation presented here is the eastward termination of the West Jan Mayen Fracture Zone (WJMFZ).

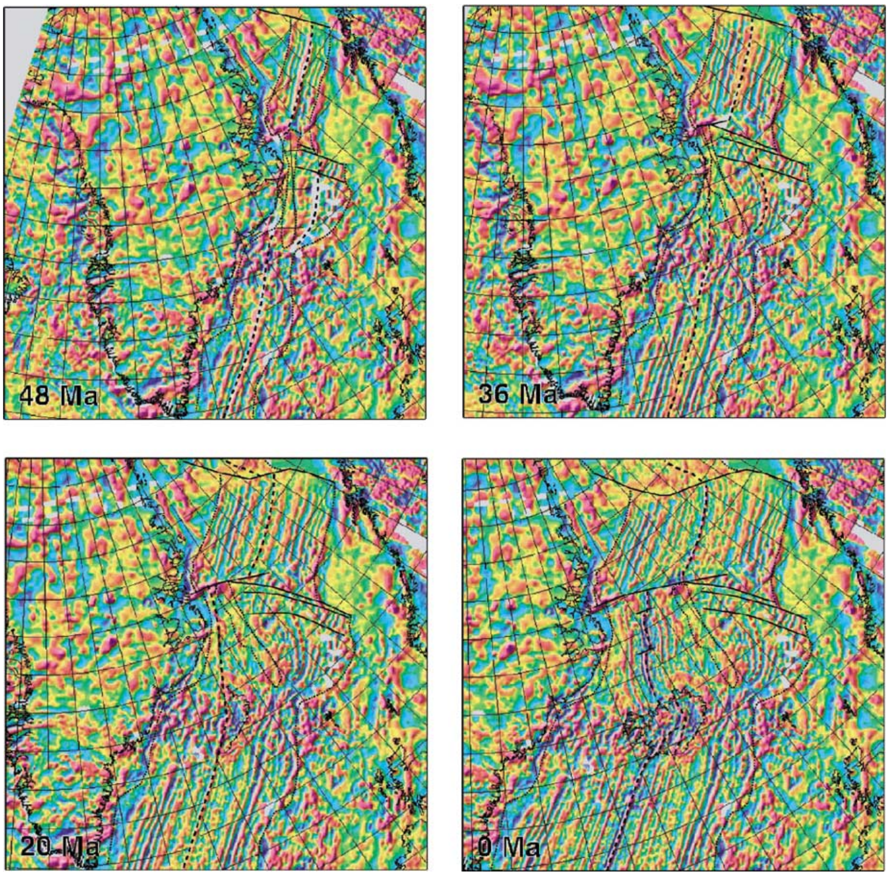


Fig. 6. NE Atlantic and Norwegian–Greenland Sea reconstruction of gridded magnetic data (Verhoef *et al*. 1996), applying the method of Verhoef *et al*. (1990) Reconstructed grid node positions were achieved by rotating the grids according to plate reconstruction parameters (Müller *et al*. 1997). Dotted lines mark continent–ocean boundaries, while heavier dashed lines mark spreading axes. The Euler poles are listed in Table 1. These images are extracted from an animation by Lundin *et al*. (2002). Red indicates positive values and blue, negative values.

Table 1. Euler poles (interpolated from Müller *et al*. 1997) at the shown reconstruction steps in Figure 6

Ma	Greenland versus Eurasia			Jan Mayen versus Eurasia		
	Lat	Long	Cum. Rotation	Lat	Long	Cum. Rotation
0	90	0	0	90	0	0
20	67.261	135.480	4.708	90	0	0
36	66.926	135.426	8.134	−64.619	168.090	10.397
48	57.236	131.360	9.372	−64.617	167.496	34.085

Note that Eurasia is held fixed.

Combining magnetic and bathymetric data reveals that the fracture zone extends to Chron 13 on the east side of the Mohns Ridge (Figs 7a and b). Indeed, seafloor maps often reveal that the fracture zone ends near Chron 13 (e.g. Skogseid *et al*. 2000), but the tectonic implication of this is generally not emphasized. Since the WJMFZ indisputably links the Kolbeinsey and Mohns ridges, its eastward termination should mark the time of kinematic linkage between the two spreading axes. The authors recognize that such an early linkage contrasts with the common interpretation of the oldest seafloor along the northern Kolbeinsey Ridge, proposed to have formed during Chron 6C (*c*. 24 Ma) (Vogt *et al*. 1980). Based on the previously mentioned eastern termination of WJMFZ it is argued that the linkage ought to date back to earliest Oligocene time (Chron 13), in turn, implying that both the Aegir and Kolbeinsey ridges were active between Chron 13 and 12; Jung & Vogt (1997) are followed in their interpretation that spreading along the Aegir Ridge ended at Chron 12. Below, it will be argued that the period of overlapping activity may have spanned between break-up and Chron 12.

Magnetic seafloor anomalies along the East Greenland margin are ‘truncated’ northwards against the continent–ocean boundary, approximately between Kangerlussuaq and Traill Ø (Fig. 1). A simple comparison of the magnetic data on either side of the Kolbeinsey Ridge (Figs 8a and b) suggests symmetrical northward propagation. Larsen (1988) and Rowley & Lottes (1988) also interpreted diachronous northward development of the margins bordering East Greenland and the west side of Jan Mayen. If one accepts that the Reykjanes and Kolbeinsey ridges were previously aligned (Fig. 6, reconstruction 48 Ma, 36 Ma, and 20 Ma), then it is possible to argue that seafloor spreading started propagating north from the Kangerlussuaq area toward Traill Ø near the time of break-up.

With respect to the extinct Aegir Ridge, one critical part of the interpretation in this paper is the location of the continent–ocean boundary to the southeast, against the Faroe Islands. The COB has been placed somewhat further NW than interpreted by other workers (e.g. Skogseid *et al*. 2000), but this position is constrained by refraction profiles published by Bott (1983) and Makris *et al*. (1995), located on oceanic and continental crust, respectively (Fig. 5b). This COB interpretation is also permissible based on the FIRE refraction profile along the Iceland–Faroes Ridge (Richardson *et al*. 1998). Elsewhere along the Aegir Ridge margins, this interpretation of the COB coincides with published positions of the seaward-dipping reflector series (SDRS) (e.g. Planke & Alvestad 1999). The position of the COB on the west side of the Aegir Ridge is placed slightly east of the continental blocks of the Jan Mayen microcontinent (Kuvaas & Kodaira 1997). Also, here, the COB is constrained by published positions of the SDRS. The interpretation in this paper suggests that the Aegir Ridge is relatively symmetrical about its axis, although curving along its length. The magnetic anomaly pattern reveals a southward-propagating pattern, with a gradual lengthening of the younger anomalies.

In summary, the Reykjanes and Kolbeinsey ridges may have been a single northward-propagating spreading system, overlapping with the southward-propagating Aegir Ridge. The opposed ridge system was active between break-up (Chron 24, 54 Ma) and Chron 12 (32 Ma) when the Aegir Ridge was abandoned (Fig. 2). The overlapping ridge systems worked in concert, one compensating for the other such that the sum of generated seafloor was approximately equal along the length of the rift, short of differences related to the distance from the pole of rotation. This is a general requirement if one accepts rigid plate behaviour of Eurasia and Greenland.

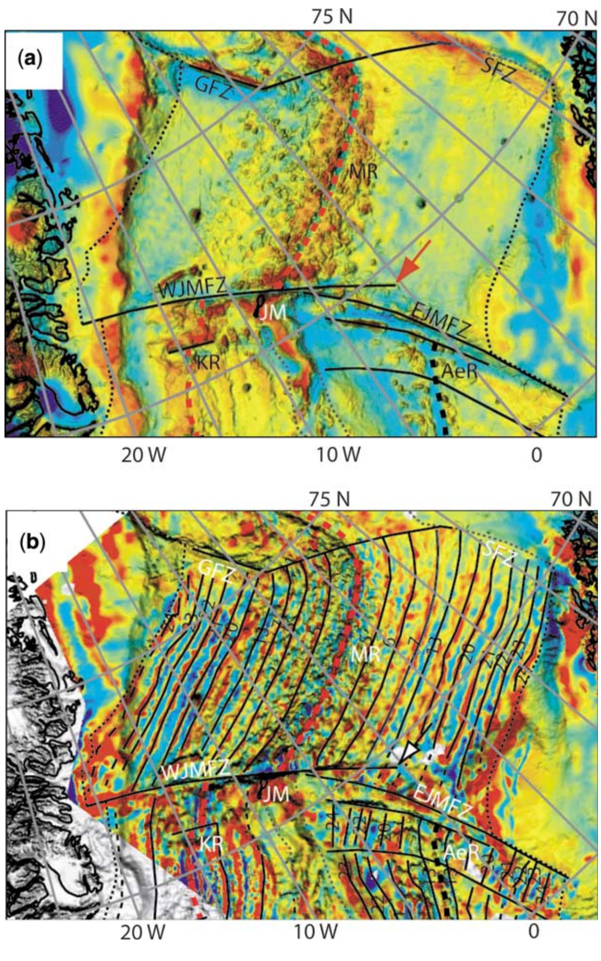
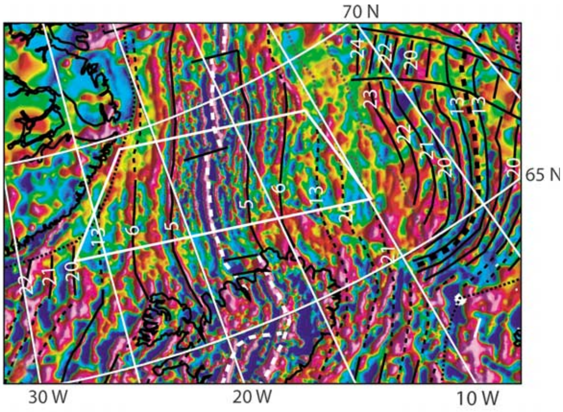


Fig. 7. Shaded relief image of (**a**) free air gravity (Andersen & Knudsen 1998) draped over bathymetry of Norwegian–Greenland Sea (Smith & Sandwell 1997) – the red arrow marks the eastern termination of the clear bathymetric expression of the West Jan Mayen Fracture Zone; (**b**) magnetics in the Norwegian – Greenland Sea (Verhoef *et al*. 1996) draped over bathymetry (Smith & Sandwell 1997). The West Jan Mayen Fracture Zone (WJMF2) can be traced readily by its expression in (a) and the eastern termination (arrow) can, thus, be correlated with the magnetic anomalies of the east side of the Mohns Ridge. Collectively, this demonstrates that the Kolbeinsey Ridge was kinematically linked with the Mohns Ridge at least by earliest Oligocene time (Chron 13). Red indicates positive values and blue, negative values. Abbreviations: AeR, Aegir Ridge; GFZ, Greenland Fracture Zone; JM, Jan Mayen; KR, Kolbeinsey Ridge; MR, Mohns Ridge; SFZ, Senja Fracture Zone.



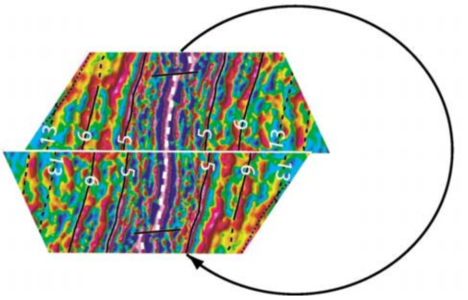


Fig. 8. (**a**) Shaded relief image of magnetic data (Verhoef *et al.* 1996) draped over bathymetry (Smith & Sandwell 1997) in the Kolbeinsey Ridge area. The interpreted magnetic anomalies are shown as lines. The marked polygon indicates the area used in. Red indicates positive values and blue, negative values. (**b**) Comparison of magnetic grid across the southern part of the Kolbeinsey Ridge. The polygon is copied, rotated 180° and matched at the present-day ridge. Despite probable minor differences in spreading rates between the two sides of the axis, the comparison suggests symmetry across the ridge. Since the SW side of the ridge is generally accepted to be oceanic crust, the SE side ought to be oceanic as well.

Conceivably therefore, opening of the NE Atlantic may be viewed as the result of opposed ridge propagation, southwards from the Arctic and northwards from the southern North Atlantic (Lundin *et al.* 2002). Recent seismic refraction investigations from the SE part of the Yermak Plateau area indicate that at least this part of the plateau is underlain by continental crust (Ritzmann & Jokat 2003). It is still unknown what type of crust underlies the northern part of the Yermak Plateau, or underlies the Morris Jesup Plateau, but the pronounced magnetic and bathymetric anomalies of these areas could indicate a magmatic construction. However, if these areas are also continental it is difficult to invoke the concept that early opening of the Eurasia Basin was linked with the Mohns Ridge. Hence, the idea of southward propagation from the Arctic is speculative. Regardless of whether the early Gakkel Ridge in the Eurasia Basin was linked with the Mohns Ridge or not, it seems plausible that the Iceland anomaly may be related to convergence between the proto-Mohns/Aegir Ridge and the proto-Reykjanes Ridge (Fig. 6). An analogue may be the Afar area in NE Africa–Arabia, where inwards propagation toward a hotspot has been proposed (Courtillot 1980, 1982; Courtillot *et al.* 1987). In both cases the situation is opposite to the model proposed by Burke & Dewey (1973), whereby plumes were proposed to induce outward-propagating triple junction rifting.

The reported vertical shape change of the core of the upper mantle velocity anomaly beneath Iceland (Foulger *et al.* 2000, 2001), from a cylindrical shape near the surface to a tabular shape aligned with the plate boundary at depth, resembles geometries observed in analogue experiments of plastic materials below extending brittle material (e.g. Guglielmo *et al.* 1997). In natural geological systems this type of plastic reactive response is a well-known characteristic of salt tectonics (e.g. Vendeville & Jackson 1992), but also occurs in the lower crust if it is heated sufficiently (e.g. Gans 1987; Block & Royden 1990; McKenzie *et al.* 2000). Passive upwelling of asthenosphere beneath extending lithosphere has long been accepted as the general ocean-forming process (e.g. Morgan 1971; Turcotte & Schubert 1982). While it has been suggested that deeply rooted plumes can cause plate break-up (e.g. Morgan 1971; Campbell & Griffiths 1990) and even be the main plate driving force (Morgan 1971) (in addition to generating ‘hotspot’ magmatism) it is speculated here that the opposite may be more plausible for the Iceland anomaly.

At least for salt and plastic lower crust it can be argued that the rise of plastic material beneath an extending brittle overburden occurs in response to pressure reductions induced from above, rather than being effects of density differences. If it is correct that some ‘hotspots’ need not be anomalously hot (Bonatti 1990; Stein & Stein 2003), it appears plausible that mantle upwelling under ‘hotspots’ also may be a passive response to changes in the overburden (i.e. lithosphere). Regardless of triggering mechanism, it is suspected that some ‘hotspot’ upwellings, at least at plate boundaries, are triggered and maintained by the plate tectonics, as opposed to the other way around. Other Atlantic examples of ‘hotspots’ apparently captured at the plate boundary are the Jan Mayen, Azores, Ascension and Tristan da Cunha. A possible Arctic example is provided by the Morris Jesup–Yermak Plateaus (so-called Yermak hotspot, Feden *et al.* 1979). All of these features have remained at or near the constructive boundary since their inception.

Comparatively little is written about the Jan Mayen ‘hotspot’ (Morgan 1981), but it must be young, as it lies on the junction between the Mohns Ridge and the West Jan Mayen Fracture Zone and has no hotspot track. The Azores ‘hotspot’ first became active at *c.* 20 Ma (Gentle *et al.* 2003) and the Ascension ‘hotspot’ is less than 7 Ma old (Harris *et al.* 1983). These three ‘hotspots’ are young features that lack hotspot tracks to the bordering margins and, thus, it is unlikely that they had any role in the creation of the mid-Atlantic ridge (i.e. break-up). Notably, these features are located near intersections between major fracture zones and the spreading ridge, which suggests a plate tectonic control on their locations. The Azores ‘hotspot’ has been claimed to have resulted from compression along the Africa–Europe plate boundary and was removed from the Indo-Atlantic hotspot list (Norton 2000). Unlike the other S Atlantic ridge-centered ‘hotspots’, Tristan da Cunha does have a continuous track along the Walvis Ridge, which is oblique to the S Atlantic fracture zone trend. On the conjugate South American side, a significant gap is present between the spreading ridge and the Rio Grande Rise. These characteristics could indicate that the mid-Atlantic ridge passed over an underlying plume, placing the ‘hotspot’ on the African plate (e.g. O’Connor & Duncan 1990).

It is not clear if the mentioned S Atlantic ‘hotspots’ relate to deeply rooted plumes. A recent finite frequency tomographic study (Montelli *et al.* 2003b) reveals that neither the Ascension nor Tristan da Cunha ‘hotspots’ are connected to deep low-velocity mantle anomalies. In another report of the same study, Montelli *et al.* (2003a) interpreted that the mantle anomaly underneath Ascension reaches the core–mantle boundary while nothing was mentioned about Tristan da Cunha. Montelli *et al.* (2003a) claimed the Azores ‘hotspot’ is deeply rooted, but that it lacks a visible anomaly in the middle mantle. If the Morris Jesup and northern Yermak Plateaus signify a magmatic construction, this magmatism appears to have started when the Eurasia Basin opened and to have ceased when the SW Barents Sea shear margin opened obliquely at Chron 13 (*c.* 35 Ma). Chron 13 marks the initiation of a continuous spreading axis between the Arctic and the NE Atlantic. It is proposed here that the Morris Jesup–Yermak Plateaus, like Iceland, are top-down phenomena related to plate tectonics. With respect to the young ridge-centered (or nearly so) ‘hotspots’, that lack time-transgressive tracks, it is difficult to envision a relationship with deep mantle plumes postulated to have been associated with break-up. Whether or not the ridge-centered 'hotspots' relate to velocity reductions in the mantle, it is difficult to avoid concluding that the surface manifestations must be dictated by plate tectonics.

With respect to the cause of the voluminous NAIP magmatism it is recognized that more than one possibility exists. The traditional view of elevated mantle temperature remains attractive, although if the mantle anomaly beneath Iceland today is indicative of the past, then the NAIP probably originated from a temperature anomaly no deeper than the 660 km discontinuity (cf. Malamud & Turcotte 1999; Hamilton 2003). Petrological support for high temperature magmatism stems from picrites, particularly prominent in West Greenland, but it now appears uncertain at what temperatures picrites form (e.g. Gudfinnsson *et al*. 2003). The possibility of a heterogeneous and locally melt-prone upper mantle (e.g. Anderson 1996; Foulger *et al*. 2003*a*) is an attractive alternative for the NAIP magmatism.

Conclusions

The formation of the British Volcanic Province, the NE Atlantic volcanic passive margins, and present-day Iceland are all widely assumed to relate to the influence of a major mantle plume, commonly perceived to be rooted at the core–mantle boundary and to be fixed with respect to the Earth's core. A number of inconsistencies have been pointed out between this model and observed phenomena. These inconsistencies are little acknowledged in the literature, or argued around using implausibly elaborate models.

(1) The Iceland anomaly lacks a time-transgressive hotspot track as predicted by the 'hotspot reference frame'. To the contrary, the Greenland–Faroes Ridge appears to be symmetrical in age about Iceland. All evidence suggests that the Iceland anomaly developed at the plate boundary during break-up and has remained there throughout its history.

(2) This, in turn, strongly suggests that there is a lithospheric control on the Iceland anomaly. Independent published evidence suggests that the low-velocity anomaly beneath Iceland is confined to the upper mantle only.

(3) The early NAIP, characterized by the British Volcanic Province and potentially extending to the West Greenland volcanic area, represents weak NE–SW extension of the plate. It can be viewed as a continuation of Late Cretaceous plate-wide events and as complementary extension to the contemporaneous Paleocene motion in the southern North Atlantic (Bay of Biscay–Charlie Gibbs Fracture Zone), Labrador Sea and Baffin Bay. Break-up of the plate along such lines was probably enhanced by the Paleocene (Pyrenean) phase of the Alpine collision. This magmatism over a linear domain 2000 km long need not appeal to a mantle plume of extraordinary shape and flexibility, but can instead be viewed as a by-product of plate break-up.

(4) The Iceland 'plume' is frequently cited as the causal factor in the NE Atlantic break-up, via lithospheric weakening. However, it is shown from plate tectonic considerations that seafloor propagation from the southern North Atlantic to the Arctic via the Labrador Sea and Baffin Bay was probably impeded by the Canada Basin hinge zone, in the Canadian Arctic Islands region. Plate break-up was, therefore, accomplished by exploitation of the Caldeonian suture zone to form the NE Atlantic. This arm of the N Atlantic can be viewed as the natural consequence of Pangaean break-up and need not appeal to lithospheric weakening by a plume.

(5) Linkage between the Arctic and the N Atlantic can be viewed as accomplished by southward- and northward-propagating ridges. These ridges overlapped in the region of Iceland. Conceivably, the Iceland mantle upwelling anomaly is related to the convergence of these ridge tips.

(6) The phenomenon of melt production and regional uplift around Iceland and in the earlier NAIP, requiring extraction of melt from upwelling mantle, is readily acknowledged. However, if these effects indeed relate to existence of a deep-seated plume, an explanation is required as to why the 'hotspot' has been fixed to the plate boundary throughout its history. This observation is strongly discordant with Courtillot *et al*.'s (2003) assertion that Iceland ranks as one of the world's most certain 'hotspots' related to a plume rooted at the core–mantle boundary. At the very least, the time-transgressive hotspot from Western Greenland to present-day Iceland, often quoted as an inevitable outcome of the 'hotspot reference frame' and used as an *a priori* assumption, must be questioned.

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