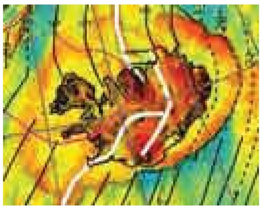

The Iceland "Anomaly" – An Outcome of Plate Tectonics

[1]Erik Lundin & [2]Tony Doré

[1]*StatoilHydro ASA, Research Centre, 7005 Trondheim, NORWAY*
ERLUN@StatoilHydro.com

[2]*Statoil UK Ltd., Statoil House, 11a Regent Street, London SW1Y 4ST, U.K.*
agdo@statoil.com

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Abstract

Iceland is commonly considered to be the surface expression of a plume originating at the core-mantle boundary. Likewise, Paleocene magmatism in the NE Atlantic (NEA) is typically ascribed to thermal effects from the proto-Iceland plume, which furthermore is often invoked as a decisive factor in NEA breakup. We argue that neither the present-day Iceland anomaly, nor its supposed ancient manifestation, is related to a deeply-rooted plume. We also propose that NEA breakup can be explained as a natural outcome of plate tectonics, not requiring any plume weakening of the lithosphere. In contrast to the common perception that the Greenland-Faroes Ridge is a hot spot track related to the Iceland plume, we consider it a symmetric construction that formed above an upper-mantle upwelling maintained at the plate boundary. We relate the two pulses of NEA magmatism to separate tectonic phases of North Atlantic breakup:

1. *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,*

2. *The voluminous Early Eocene magmatism (c. 56-53 Ma) along the NEA margins was related to final breakup of Pangea and exploitation of the collapsed Caledonian fold belt.*

We consider both the NEA magmatism and the current Iceland anomaly to represent "top down" effects of plate tectonics.

Implications of Greenland-Faroes Ridge symmetry

In a recent review, Iceland was placed in an exclusive group of seven hot spots, supposedly related to plumes originating from the core-mantle boundary (*Courtillot et al.*, 2003). Others argue that, while there is good evidence from seismic tomography for an upper mantle velocity reduction beneath Iceland, the anomaly cannot be proven to reach the Earth's core (*e.g., Foulger et al.*, 2000, 2001).

The Iceland anomaly is located on the aseismic Greenland-Faroes Ridge (GFR), proposed to be all or part of a "hot spot track" (*e.g., Morgan*, 1971, 1981; *Holbrook & Keleman*, 1993; *Lawver & Müller*, 1994) above a deeply rooted, fixed plume. This view has encouraged workers to estimate the position of the Iceland "hot spot " through time (*e.g., Forsyth et al.*, 1986; *Lawver & Müller*, 1994; *Torsvik et al.*, 2001a) (Figure 1). Such estimates assume a fixed point-like "plume" located under South Central or West Greenland during Early Paleocene. As Greenland moved northwestward the proposed plume supposedly emerged beneath the East Greenland margin and gradually entered the NE Atlantic (Figure 1). There is, however, to our knowledge no *a priori* evidence for a time-transgressive path of the "hot spot" eastwards towards present-day Iceland. Furthermore, a corollary to such estimates is that the "hot spot" or plume centre cannot have been located east of its current position, which presents a problem since physiography (Figure 1), crustal structure/thickness (*Bott*, 1983; *Smallwood et al.*, 1999; *Holbrook et al.*, 2001; *Foulger et al.*, 2002, 2003b) and magnetic data (Figure 2) suggest symmetry of the GFR about Iceland.

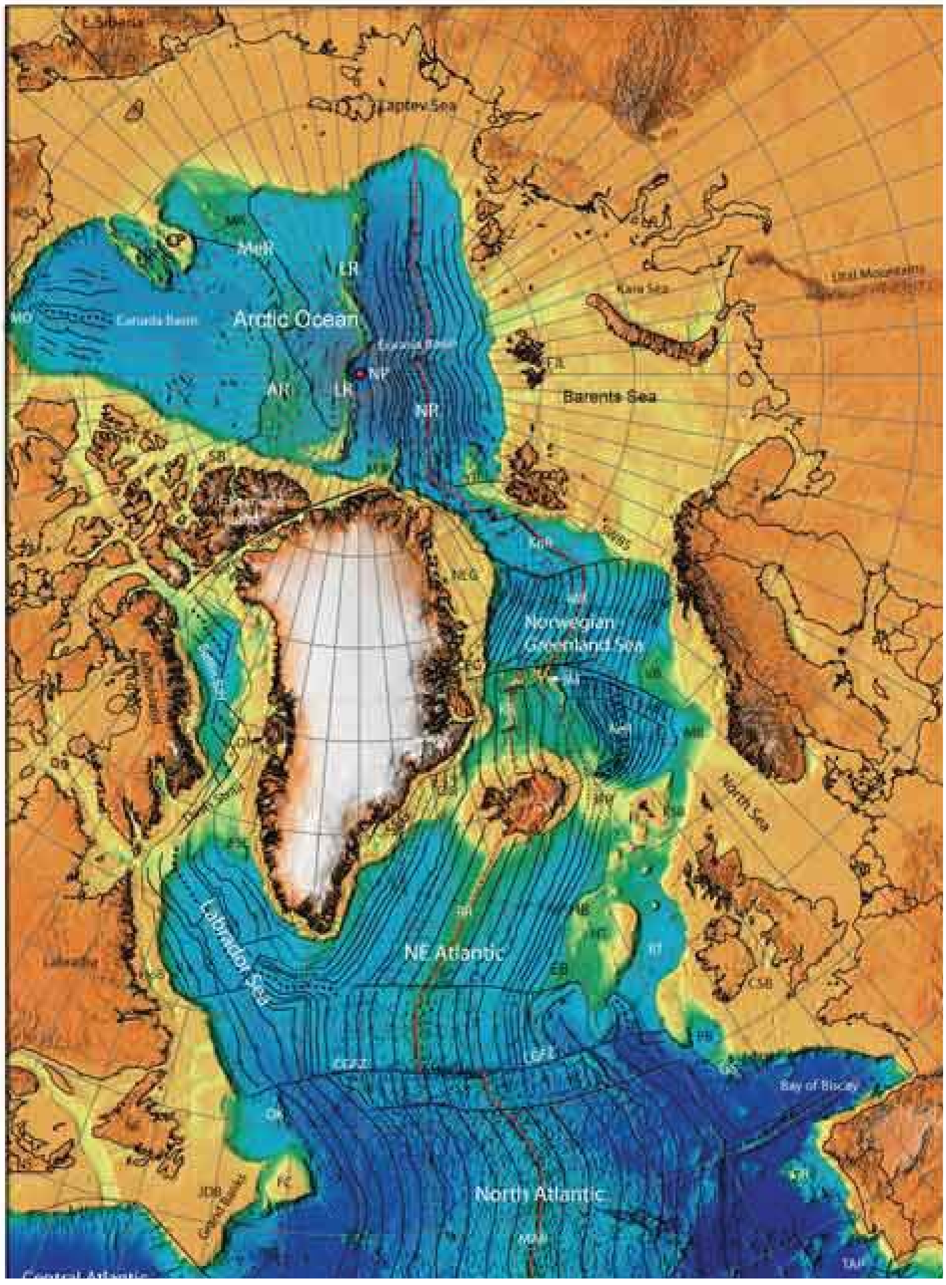

Figure 1 (Previous Page). Location map. Bathymetry and topography from Lundin (2002). Based on data from Smith & Sandwell (1997) and Jakobsson et al. (2000), overlain by our interpreted magnetic anomalies, fracture zones and spreading axes (black dashed = extinct, red dashed = active). MJP: Morris Jesup Plateau, YP: Yermal Plateau. MJP is off N Greenland, and YP is just west of Svalbard. KnR: Knipovich Ridge.

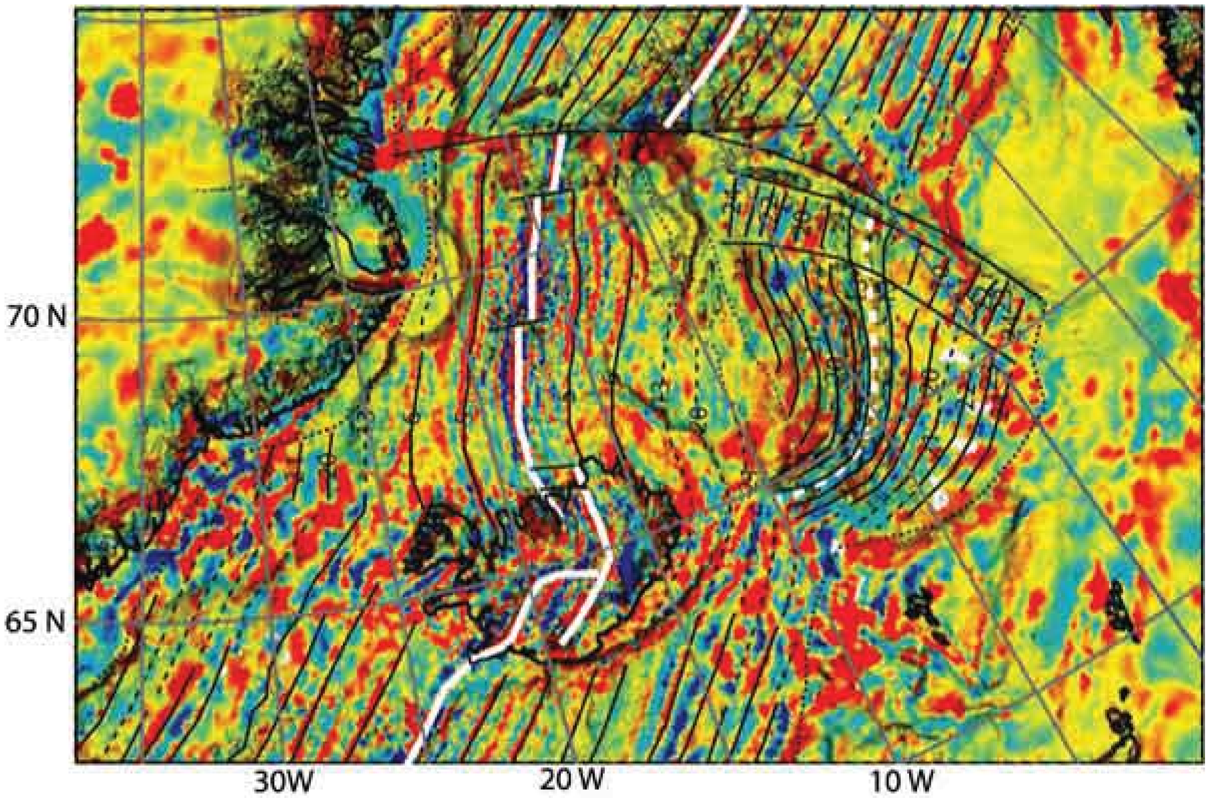

Figure 2a. Shaded relief image of magnetic data (Verhoef et al., 1996) draped on bathymetry (Smith & Sandwell, 1997). Solid white lines = active spreading axes, dashed white line = abandoned Aegir Ridge, thin solid black lines = interpreted magnetic anomalies, thick solid black lines = fracture zones; dotted black lines = Continent-Ocean Boundary (COB). We attribute the patchy magnetic pattern to subaerial lava extrusion (e.g., Bott, 1983), interacting with the topography of pre-existing flows, and being further complicated by erosion until the ridge subsided below the wave base.

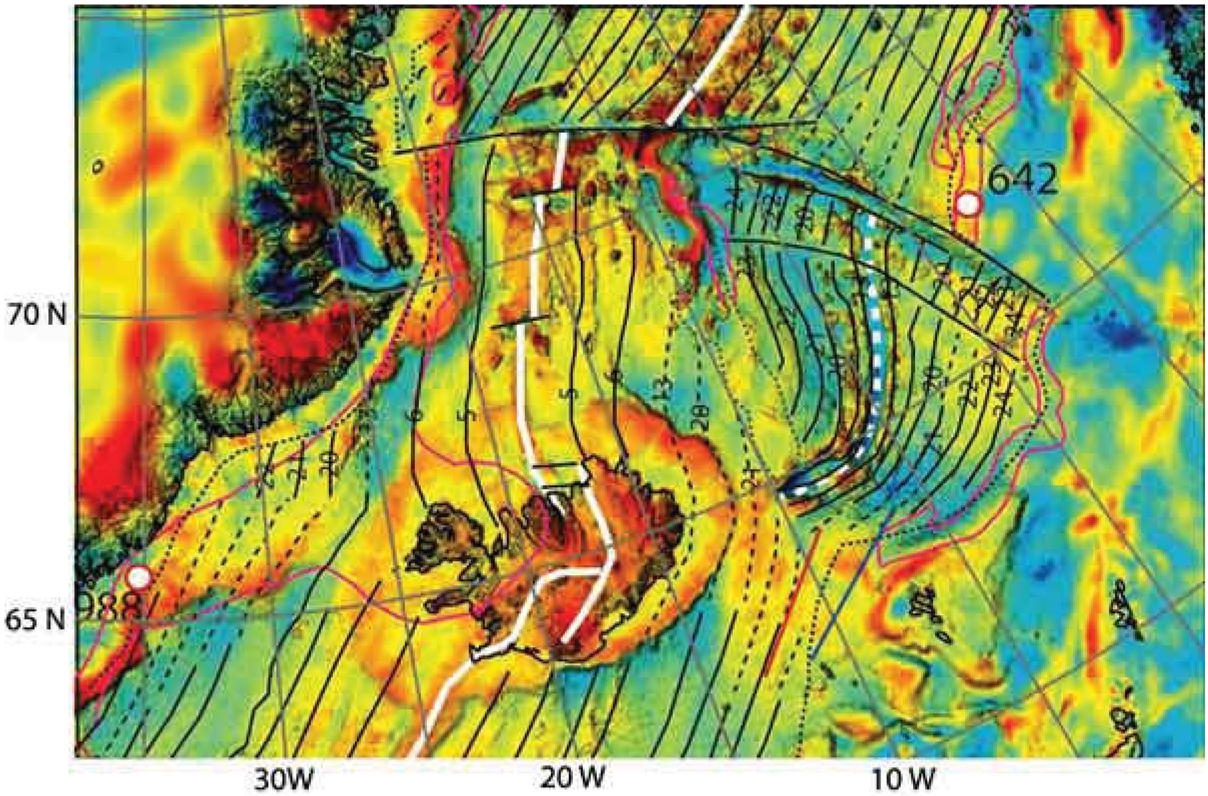

Figure 2b. Shaded relief image of free air gravity (Andersen & Knudsen, 1998) draped over bathymetry (Smith & Sandwell, 1997). Symbols as in Figure 2a. Purple lines = distribution of seaward dipping reflectors (from Planke & Alvestad, 1999).

Vink (1984) recognized the paradox of explaining the development of the GFR in a fixed hot spot framework, and proposed a model whereby asthenosphere was channelled the shortest distance from a presumed plume centre under Greenland to the nearby Reykjanes Ridge. However, with such a model a pronounced V-shaped hot spot-fed plateau should have formed, since palaeomagnetic data reveal that North America, Greenland, and Eurasia have moved significantly northward since break-up (*e.g., Torsvik et al.*, 2001b). To a first order, the GFR is linear (Figure 1), contradicting Vink's model.

The Iceland anomaly through geological history

Following *White et al.* (1987) and *White* (1988) most workers explain the Early Tertiary volcanism of the North Atlantic Igneous Province (NAIP) in terms of lithospheric impingement of the proto-Iceland mantle plume. A wide variety of beliefs on the size and morphology of the plume exist, from a single point (*e.g., Forsyth*, 1986; *Lawver & Müller,* 1994; *Torsvik et al.,* 2001a) (Figure 1) to a continental-scale mantle anomaly acting simultaneously on areas separated by some 2000 km (*Smallwood & White*, 2002).

NAIP magmatism can be divided into two phases (*e.g., Saunders et al.*, 1997):

1. "Middle" Paleocene (c. 62-58 Ma) continent-based magmatism in Britain and West Greenland, and

2. the voluminous latest Paleocene to earliest Eocene (c. 56-53 Ma) magmatism along the NEA margins.

A crucial problem with the "fixed hot spot" and the "global hot spot reference frame" is the supposed position of the Iceland plume centre beneath West Greenland at the onset of NAIP magmatism in the Early Paleocene (c. 62 Ma). Such a position is not consistent with the more or less simultaneous onset of basaltic magmatism between this area and southeastern NAIP, for example in the Hebrides (*e.g., Jolley & Bell,* 2002; *Ritchie et al.*, 1999). An equally tricky problem to explain is the lack of magmatism in areas that should have been in close proximity to the plume, such as the already-established passive margin of SW Greenland.

Inconsistency between model and observations in the NAIP has led to various adjustments of the *Morgan* (1971) plume hypothesis, such as

- invoking separate plumes (*Morgan*, 1983; *Srivastava*, 1983),
- a plume split into two arms arriving at different times (*e.g., Holm et al.*, 1993),
- an ultrafast plume spreading out immense distances along the base of the lithosphere (*Larsen et al.*, 1999),
- channelling of plume material from beneath Greenland into the NE Atlantic spreading axis (*Vink*, 1984),
- blocking of plume material by a step at the base of the lithosphere (*Nielsen et al.*, 2002),
- 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 can be viewed as “a sign of a hypothesis in trouble” (*Foulger*, 2003a). What seems certain is that a Hawaii-style model for plate motion over a deeply-rooted and fixed plume is now untenable as an explanation for both the NAIP and Iceland.

It appears possible to interpret the melting anomaly associated with formation of the NEA volcanic passive margin and present-day Iceland as 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 early phase of NAIP magmatism, extending between the BVP and W Greenland. Early workers (*e.g., Hall*, 1981) called this 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), extending from the Hebridean province in an ESE direction to the Central North Sea (*Kirton & Donato*, 1985) and SE to the Bristol Channel (*e.g., Blundell*, 1957). The frequency and consistent trend of the dykes indicate a NE-SW extensional stress field across Britain during that part of the Paleocene (*England*, 1988). The early NAIP may therefore, represent a transient failed attempt by NW Europe and Greenland to break up along a NW-SE axis, an idea previously suggested by *Dewey & Windley* (1988). Such extension would logically have been a continuation of mid-late Cretaceous stress fields associated with N Atlantic opening (*e.g., Johnston et al.*, 2001). Further expressions may include the fjord and dyke grain of the Faroes, the fjord grain of East Greenland, and recently reported NW-trending half-graben structures containing Upper Cretaceous and Palaogene shallow marine sediments in the Christian IV Gletcher area (just east of Kangerlussuaq) (*Larsen & Whitham*, 2003). In the volcanic area of West Greenland both the fjord grain and a set of Paleocene extensional faults trend northwest (*Nøhr-Hansen et al.*, 2002).

The NE-SW extensional stress field was replaced as stretching and subsequent separation refocused on the NEA margin in the later Paleocene - Early Eocene. Both the early NAIP and the subsequent, NEA volcanic passive margin development can be explained in terms of plate tectonic processes – i.e. breakup of a crust already stretched by numerous preceding extensional episodes, above a labile and melt-prone mantle.

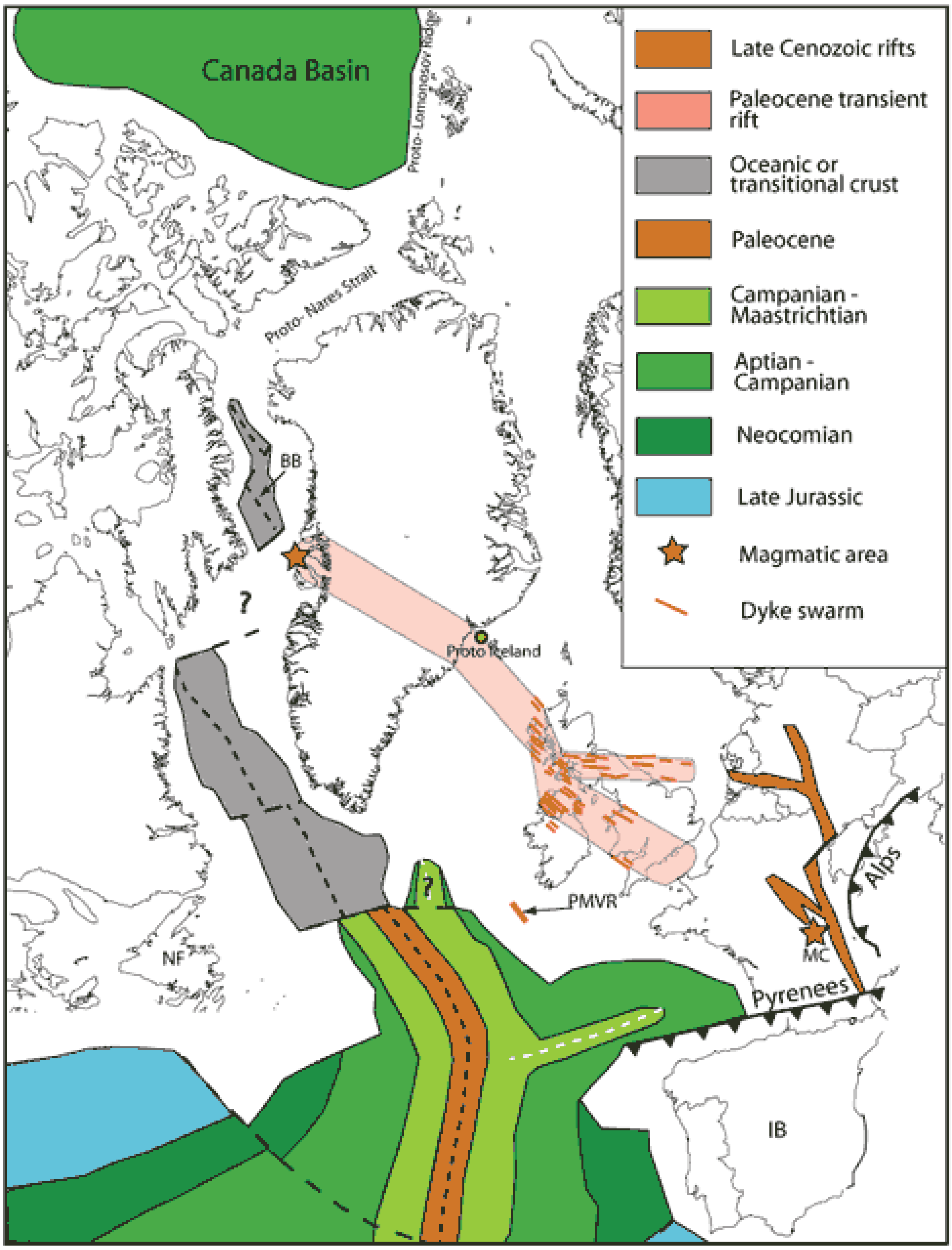

Figure 3. Plate reconstruction to 60 Ma (Trond Torsvik, pers. com. 2003) with simplified seafloor. The main dike trend in the British Volcanic Province schematically shown to extend to the West Greenland magmatic area, is invoked to utilize a zone of weak extension. The Late Cenozoic European rift system (from Ziegler, 1992) is included in order to illustrate a more evolved stage extension, also related to compression in the Pyrenees and the Alps. NF: Newfoundland, BB: Baffin Bay, IB: Iberia

Final breakup of Pangea – linking the North Atlantic and Arctic

Labrador Sea and Baffin Bay versus the Arctic

Opening of the Labrador Sea was a continuation of the general northward propagation of the N Atlantic that started between Newfoundland and Iberia in Hauterivian time. Two schools of thought exist on the timing of onset of spreading in the Labrador Sea; *Roest*

& Srivastava (1989) and *Srivastava & Roest* (1999) interpret onset of spreading at Chron 33 (c. 81 Ma) while *Chalmers & Laursen* (1995) propose that seafloor spreading started in Early Paleocene (Chron 27). Further north, in Baffin Bay, magnetic data have recently been re-interpreted to reveal the presence of magnetic Chron 26n or Chron 25n (middle Paleocene) (*Oakey et al.*, 2003). Regardless of the dispute about onset of spreading in the Labrador Sea, it appears clear from the crustal structure that seafloor never propagated beyond the northern tip of Baffin Bay (*e.g., Reid & Jackson*, 1997).

We argue that when "seafloor spreading" reached the northern tip of Baffin Bay in latest Cretaceous or Early Paleocene time, it approached the by-then c. 65 to 80 Ma old passive margin hinge zone to the Canada Basin (approximately Hauterivian; *Grantz et al.*, 1990, *Lawver & Baggeroer*, 1983). The hinge zone probably acted as a barrier to further propagation and triggered plate reorganization, analogous to the manner the Neo-Tethyan hinge zone hindered further propagation of the Red Sea – Gulf of Suez rift (*Steckler & ten Brink*, 1986).

The Labrador Sea – Baffin Bay rift system preceeded or overlapped in time with the transient Early Paleocene rift through the BVP – W Greenland. Ultimately, a new rift path in the NEA formed in Early Eocene time, utilizing the collapsed Caledonian fold belt and the associated Mesozoic rift system. Breakup in the Arctic followed the Canada Basin shear margin (*Grantz et al.*, 1990), splitting off the Lomonosov Ridge (a microcontinent), which is another example of lithospheric strength control by the Canada Basin on NEA-Arctic breakup.

During the following c. 20 Ma, simultaneous spreading occurred along two arms of the North Atlantic – the Labrador Sea/Baffin Bay and the NEA arms – linked at a triple junction south of Greenland. The resultant northward motion of Greenland induced the Eurekan Orogeny (*Oakey*, 1994). The angle of convergence between Greenland and the Candian Arctic Islands was very high (*Oakey*, 1994), preventing significant lateral motion along the Wegner Transform (in Nares Strait) (*e.g., Dawes & Kerr*, 1982; *Okulitch et al.*, 1990), in turn explaining why the Labrador Sea/Baffin Bay arm of spreading was unable to link with the Arctic Eurasia Basin. 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).

The essential point from the foregoing discussion, is that the abandonment of the Labrador Sea/Baffin Bay arm of spreading, the transient Paleocene BVP-W Greenland rift, and the final diversion of seafloor spreading through the Caldeonian fold belt (the NEA spreading arm) was a natural outcome of plate tectonic reorganization, strongly influenced by lithospheric strength distribution. Lithospheric weakening in the NEA 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. We follow prexisting interpretations here. However, in the more complicated area surrounding the Aegir and Kolbeinsey Ridges (*e.g., Talwani & Eldholm*, 1977; *Vogt et al.*, 1980; *Nunns*, 1983; *Jung & Vogt*, 1997), we have reinterpreted some of the continent-ocean boundaries and magnetic anomalies (Figures 2a and 2b). We suggest that both the Aegir and Kolbeinsey Ridges show classic signs of propagation (*e.g., Vink*, 1982), but in opposite directions. This model for the Aegir and Kolbeinsey Ridges is rather similar to the one by *Nunns* (1983), implying simultaneous spreading on two complimentary and overlapping spreading axes, and contrasts with the model implying a ridge jump from the Aegir to the Kolbeinsey Ridge (*e.g., Talwani & Eldholm*, 1977; *Vink*, 1984). Our interpretations of magnetic anomalies, fracture zones, and COBs in the NEA and Norwegian-Greenland Sea, have been used as the basis for a reconstruction of magnetic grids (*Lundin et al.*, 2002), applying the method of *Verhoef et* *al.* (1990) (Figure 4).

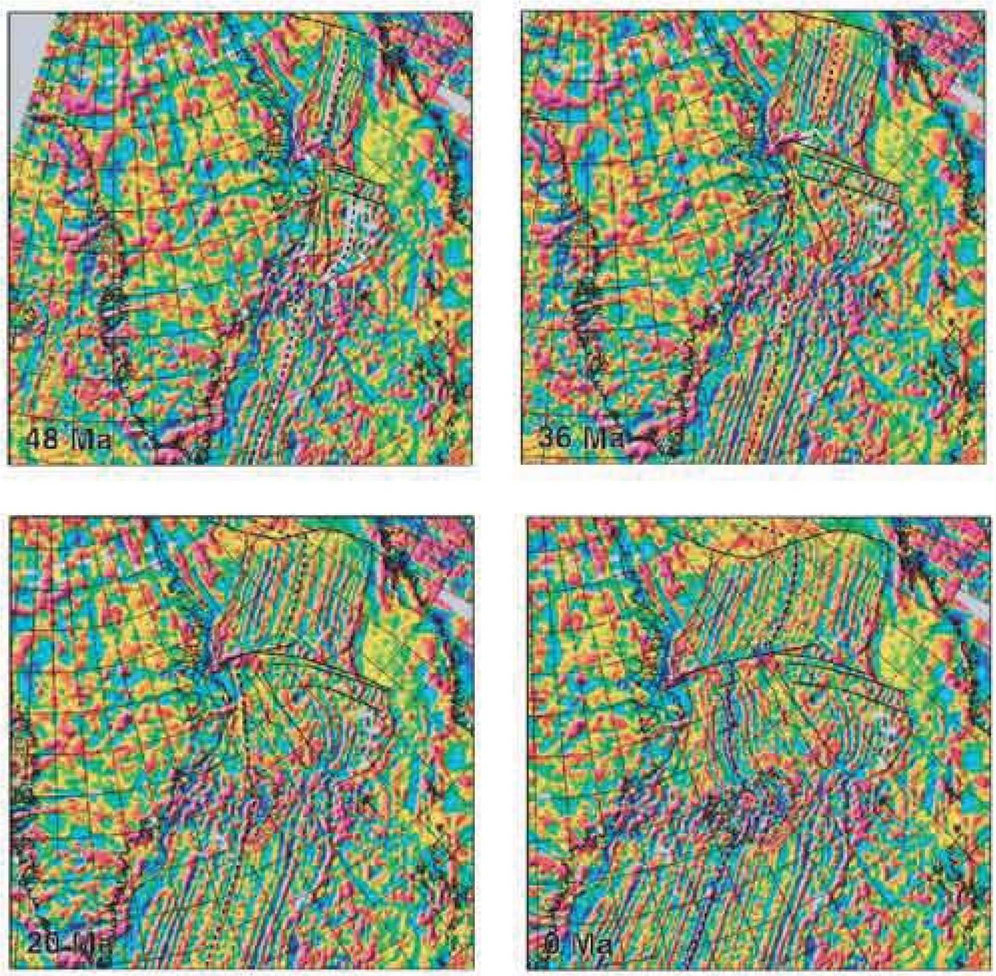

Figure 4. NE Atlantic and Norwegian-Greenland Sea reconstruction of gridded magnetic data (Verhoef et al., 1996), applying the method of Verhoef et al. (1990). Reconstructed grid node positions were achieved by rotating the grids according to plate reconstruction parameters (Müller et al., 1997). The Euler poles are listed in Table 1. These images were extracted from an animation by Lundin et al. (2002). Click on image to enlarge.

Greenland versus Eurasia				Jan Mayen versus Eurasia		
Ma	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

Table 1. Euler poles (interpolated from Müller et al., 1997) at the reconstruction steps shown in Figure 4. Eurasia is held fixed.

Opening of the NEA and Arctic can be viewed as the result of southward ridge propagation from the Arctic and northward ridge propagation from the southern North Atlantic, meeting in the area of proto-Iceland. Hence, it is tempting to speculate on whether the mantle upwelling at Iceland in some way relates to the ridge convergence.

We suspect that “hot spot” upwellings, at least at plate boundaries, are triggered and maintained by the separating plates, as opposed to the other way around. Other examples of Atlantic-Arctic “hot spots” apparently forming at the plate boundary are the

Azores, Jan Mayen, Yermak, and possibly Tristan da Cunha. All these "hot spots" have remained at or near the constructive boundary since their inception, possibly with the exception of Tristan da Cunha, which has a gap in the "hot spot track" on the west side of the S Atlantic, arguably marking a jump from one side of the plate boundary to the other. The Azores "hot spot" became active first at c. 20 Ma (*Gentle et al.*, 2003) and therefore, clearly had no role in the creation of the Central and North Atlantic spreading ridges (opening at c. 180 Ma and c.123 Ma respectively). According to our interpretations, magmatism at the Morris Jesup and Yermak Plateaus (*Feden et al.*, 1979) can be bracketed in time between opening of the Eurasia Basin (c. 54 Ma) and Chron 13 (c. 35 Ma), when the SW Barents Sea shear margin opened obliquely and inititated a through-going spreading axis between the Arctic and the NE Atlantic (the Knipovich Ridge). Little is written about the Jan Mayen "hot spot" (*Morgan*, 1981), but it must be young and lies on the junction between the Mohns Ridge and the West Jan Mayen Fracture Zone.

With respect to the cause of the voluminous NAIP magmatism we recognize that more than one possibility exists. The traditional view of elevated mantle temperature remains attractive, although recent data on surface heat flow suggests that Iceland is not anomalously hot (*Stein & Stein*, 2003). Even if mantle temperatures are elevated we would argue that the hot mantle material does not stem from the core-mantle boundary, but probably stems from a shallower level in the Earth, such as the 660 km discontinuity (*Hamilton*, 2003). The possibility of a heterogeneous and locally melt-prone upper mantle (*e.g., Anderson*, 1996, *Foulger et al.*, 2004a, 2004b), in particular related to the Caledonian fold belt, is an attractive alternative process.

Conclusions

1. All evidence suggests that the Iceland anomaly developed at the plate boundary during breakup and has remained there throughout its history.

2. The GFR is a symmetric subaerial magmatic construction, formed above passively upwelling upper mantle (cf. *Foulger et al.*, 2000, 2001), apparently of normal temperature (*Stein & Stein*, 2003). The GFR is not part of a classic time-transgressive hot spot track, nor does such a track exist for the Iceland "hot spot".

3. We argue that the separating plates have controlled the upwelling forming the Iceland anomaly.

4. The early NAIP, characterized by the BVP and conceivably extending to the West Greenland volcanic area, is explained as a result of weak NE-SW extension. This magmatism over a linear domain 2,000 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 breakup.

5. The Iceland "plume" is frequently cited as the causal factor in NE Atlantic breakup, via lithospheric weakening. However, we show from plate tectonic considerations that opening of the NE Atlantic and Arctic Eurasia can be explained as a natural consequence lithospheric strength control on final breakup of Pangea, and need not appeal to lithospheric weaking by a plume.

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

7. We readily acknowledge that the phenomena of melt production and regional uplift around Iceland, and in the earlier NAIP, require mantle upwelling. However, if these effects indeed relate to existence of a deep-seated plume, an explanation

is required as to why the "hot spot" has been fixed to the plate boundary throughout its history. This observation is strongly discordant with the assertion of *Courtillot et al.* (2003) that Iceland ranks as one of the world's most certain hot spots related to a plume rooted at the core-mantle boundary. At the very least, the time-transgressive "hot spot" from Western Greenland to present-day Iceland, often quoted as an inevitable outcome of the "hot spot reference frame", and used as an *a priori* assumption in the literature, must be seriously questioned.

News & Discussion

No Plume Under Iceland
Iceland plume: four articles, pro and con

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