

The North Atlantic Igneous Province: A review of models for its formation

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ABSTRACT

The mantle plume concept is currently being challenged as an explanation for North Atlantic Igneous Province formation. Alternative models have been suggested, including delamination, meteorite impact, small-scale rift-related convection, and chemical mantle heterogeneities. We review available data sets on uplift, strain localization, age and chemistry of igneous material, and tomography for the North Atlantic Igneous Province and compare them with predictions from the mantle plume and alternative models. The mantle plume concept is quite successful in explaining the formation of the North Atlantic Igneous Province, but unexplained aspects remain. Delamination and impact models are currently not supported. Rift-related small-scale convection models appear to be able to explain volcanic rifted margin volcanism well. However, the most important problem that nonplume models need to overcome is the continuing, long-lived melt anomaly extending via the Greenland and Faeroe ridges to Iceland. Mantle heterogeneities resulting from an ancient subducted slab are included in plate tectonic models to explain the continuing melt production as an alternative to the mantle plume model, but there are still uncertainties related to this idea that need to be solved.

Keywords: North Atlantic Igneous Province, volcanic rifted margins, LIP formation, mantle plume versus alternatives, continent breakup

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INTRODUCTION: CHALLENGING THE MANTLE PLUME CONCEPT

Continental breakup at the Paleocene–Eocene transition marked the culmination of an ~350 m.y. period of predominately extensional deformation in the northern North Atlantic subsequent to the Caledonian orogeny (e.g., Ziegler, 1988; Doré et al., 1999). During this period, numerous sedimentary basins developed that can now be found on the North Atlantic continental margins. Basin formation was not accompanied by significant magmatism, except around Eurasia–Greenland breakup time. The magmatic events prior to and during continental separation, and the postbreakup continuous activity of the Iceland melting anomaly, have resulted in one of the largest large igneous provinces (LIPs) in the world: the North Atlantic Igneous Province. The North Atlantic Igneous Province was long ago recognized by the significant regional on-shore distribution of volcanic features, including flood basalt traps and mafic and ultramafic complexes (Hutton, 1788). For the past forty years, numerous seismic studies and commercial and scientific drilling have shown that this magmatic province also extends off-shore. It is well developed along the Kolbeinsey and Reykjanes spreading ridges, which are still anomalously productive, and the breakup axis of the Northeast Atlantic, which is highly volcanic. Over the last decade or so, tomographic studies have provided information on the mantle seismic velocity structure beneath the area, and a 3-D picture of the mantle below the North Atlantic Igneous Province has emerged. The low-seismic-velocity anomaly beneath parts of the province is now generally thought to be linked to its formation.

As a result of intense scientific and economic interest, the North Atlantic Igneous Province is the most thoroughly documented LIPs on Earth. From current observations, a regional picture emerges of widespread early Paleogene magmatism extending from the Charlie Gibbs fracture zone in the south to the Senja Fracture Zone in the north on the eastern side of the North Atlantic. On the western side of the North Atlantic, the North Atlantic Igneous Province extends from south of East Greenland northward to the Greenland Fracture Zone and includes parts of West Greenland and Baffin Island, bordering Baffin Bay. It includes the Greenland, Iceland, and Faeroes ridges; the Kolbeinsey and Reykjanes spreading systems; and Iceland itself (e.g., Upton, 1988; White and McKenzie, 1989; Coffin and Eldholm, 1994; Saunders et al., 1997) (Fig. 1). The area covered by flood basalts, both on-shore and off-shore, may represent $\sim 1.3 \times 10^6$ km², with a volume of $\sim 1.8 \times 10^6$ km³. Including magmatic underplating and other intrusions, it could reach 5×10^6 to 1×10^7 km³ (Eldholm and Grue, 1994).

The scientific progress made in the last few decades has led to an exciting development in the context of the present volume: The plume concept as an explanation for North Atlantic Igneous Province formation is now being challenged. The reason is that not all plume model predictions have yet been supported by observations. The lack of a clear plume trail and the absence of a

distinct lower-mantle continuation of the upper-mantle seismic wavespeed anomaly are arguments against the plume model as an explanation for North Atlantic Igneous Province formation (e.g., Foulger, 2005). Not only is a mantle plume source for LIP formation challenged; the “plume concept” itself is a topic of debate as well. For discussion of this aspect, we refer the reader to Anderson and Natland (2005) and Foulger (2005).

Following Morgan (1971), most workers have explained the Early Paleogene volcanism of the North Atlantic Igneous Province in terms of lithospheric impingement of the proto-Iceland mantle plume, and a wide variety of ideas on plume size, plume origin and path, and the possibility of multiple plume heads or pulsating plumes have been discussed in the literature in this context (e.g., Lawver and Müller, 1994; White et al., 1995; Nadin et al., 1997; Saunders et al., 1997; Torsvik et al., 2001). This evolution of the mantle plume concept has been addressed by several authors (e.g., Anderson and Natland, 2005; Foulger, 2005), and alternative hypotheses on North Atlantic Igneous Province formation have been formulated over the past ten years or so. These include moderately elevated mantle temperatures, fertile patches in the upper mantle, and small-scale convection (e.g., King and Anderson, 1995, 1998; Boutilier and Keen, 1999; van Wijk et al., 2001; Korenaga, 2004; Anderson and Natland, 2005; Foulger and Anderson, 2005; Foulger et al., 2005; Lundin and Doré, 2005; <http://www.mantleplumes.org>).

The objective of this review article is to test existing geodynamic models for North Atlantic Igneous Province and LIP formation against available geochemical, structural, and geophysical data. Predicted features of the various geodynamic models include uplift history, timing, duration, location and chemical signature of magma that is produced, and strain localization (rift formation). There is a wealth of data available that allow us to test these model predictions. We summarize the data sets in the next sections. We then discuss the characteristic predictions of the main models for North Atlantic Igneous Province formation and compare model predictions with observations. We conclude our study by exploring an alternative, non-mantle-plume model to explain the formation of this province.

GEOLOGICAL, GEOCHEMICAL, AND GEOPHYSICAL OBSERVATIONS

Rifting Episodes

The Northeast Atlantic domain has undergone multiphase evolution, from rifting to continental rupture (e.g., Ziegler, 1988; Doré et al., 1999). Extensional deformation began with post-orogenic collapse in East Greenland, the northern United Kingdom, and Norway (Séranne and Séguret, 1987; Strachan, 1994) as early as Devonian times. It continued with widespread Permian–Triassic rifting in Greenland, Norway, off-shore United Kingdom, off-shore Ireland, the North Sea, and East Greenland (Ziegler, 1988; Coward, 1995; Doré et al., 1999) (Fig. 2). Magmatism has been associated with this rift phase. There is evidence from East

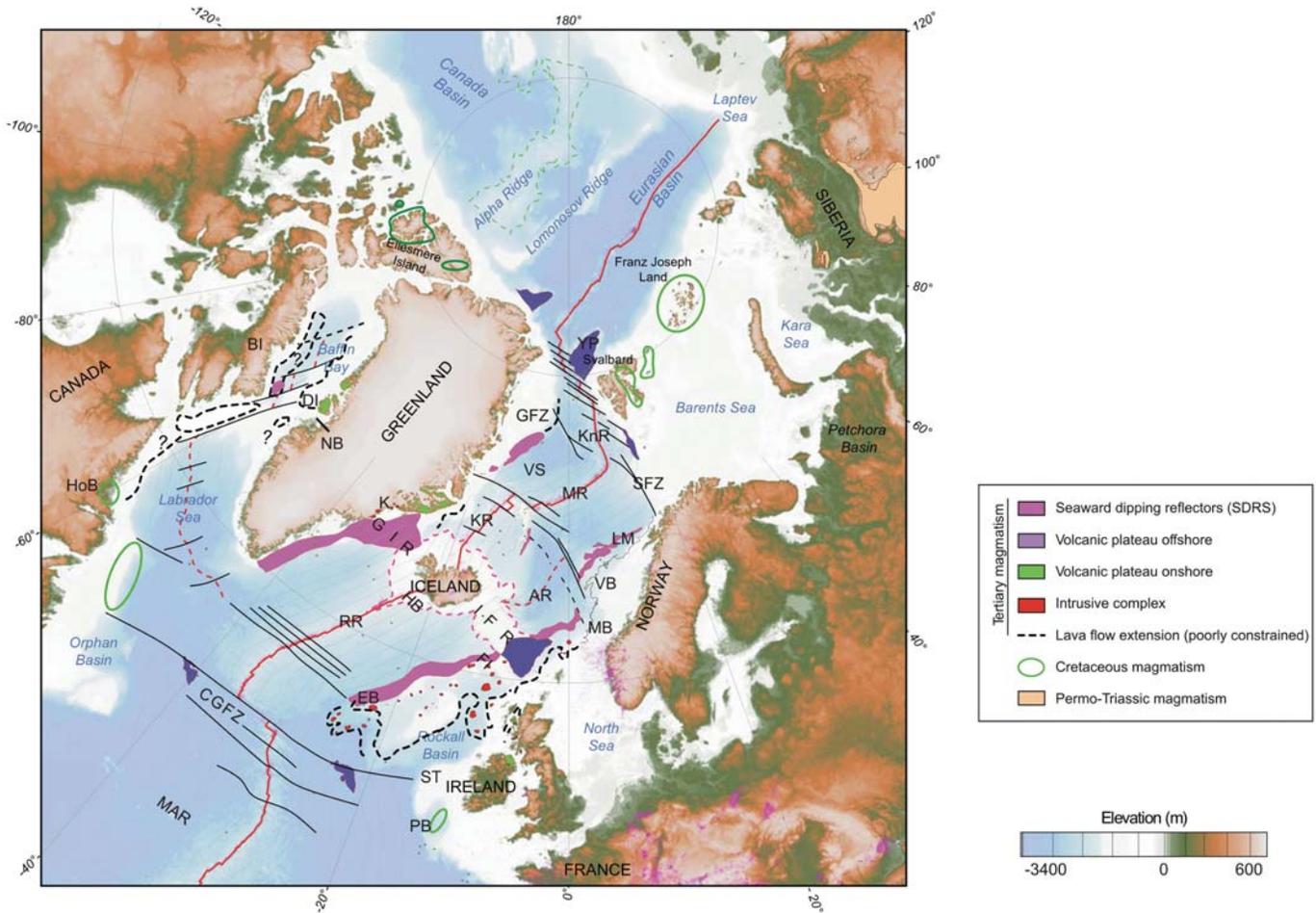


Figure 1. The North Atlantic Igneous Province. Tertiary on-shore and off-shore magmatism is indicated, as well as older Cretaceous and Permo-Triassic magmatism, interpreted magnetic anomalies, (extinct) spreading ridges, and fracture zones. AR—Aegir Ridge; BI—Baffin Island; CGFZ—Charlie Gibbs Fracture Zone; DI—Disko Island; EB—Edoras Bank; FI—Faeroe Islands; GFZ—Greenland Fracture Zone; GIR—Greenland-Iceland Ridge; HB—Hatton Bank; HoB—Hopedale Basin; IFR—Iceland-Faeroe Ridge; K—Kangerlussuaq; KnR—Knipovich Ridge; KR—Kolbeinsey Ridge; LM—Lofoten margin; MAR—Mid-Atlantic Ridge; MB—Møre Basin; MR—Mohs Ridge; NB—Nuussuaq Basin; PB—Porcupine Basin; RR—Reykjanes Ridge; SFZ—Senja Fracture Zone; ST—Slyne Trough and Erris Basin; VB—Vøring Basin; VS—Vesteris Seamount; YP—Yermak Plateau.

Greenland, the southwestern Oslo Rift and the North Sea area (Fig. 2; Surlyk, 1990; Heeremans and Faleide, 2004). Following the Permian rift phase, several more rifting episodes occurred in the Jurassic. Limited early Middle Jurassic rifting is documented north to off-shore mid-Norway (Blystad et al., 1995; Koch and Heum, 1995; Dancer et al., 1999; Erratt et al., 1999). Rifting along the Porcupine and Slyne basins first occurred in the Permo-Triassic and then again in the Late Jurassic (e.g., Tate, 1993; Chapman et al., 1999; Dancer et al., 1999).

A Middle Jurassic uplift event occurred in the central part of the North Atlantic (Doré et al., 1999) (Fig. 2). This was a non-breakup-related magmatic event in a period of broad uplift (Fig. 2). The Late Jurassic period is usually defined as a major rifting episode that affected the entire North Atlantic (Doré et al., 1999). It is recognized in the Central Graben, Viking Graben,

and Moray Firth Basin (Erratt et al., 1999) of the North Sea rift system. The effects of this event possibly extended north to the Møre Basin and the Haltenbanken, as well as off-shore Norway (Koch and Heum, 1995), and it may also have influenced the East Greenland basins (Surlyk, 1990). The northernmost expression of this rift system is documented in the Norwegian part of the Barents Sea (Faleide et al., 1993).

Early Cretaceous extension (Fig. 2) is often interpreted as a separate extensional event and represents a significant geodynamic change in the evolution of the North Atlantic rifted basins (Doré et al., 1999). This event marks the end of the rift activity in the North Sea and the development of a new northeast-southwest-oriented rift axis stretching from South Rockall to Lofoten in Norway and to the Barents Sea. At the same time, a northwest-southeast-oriented rift developed from the Iberia-

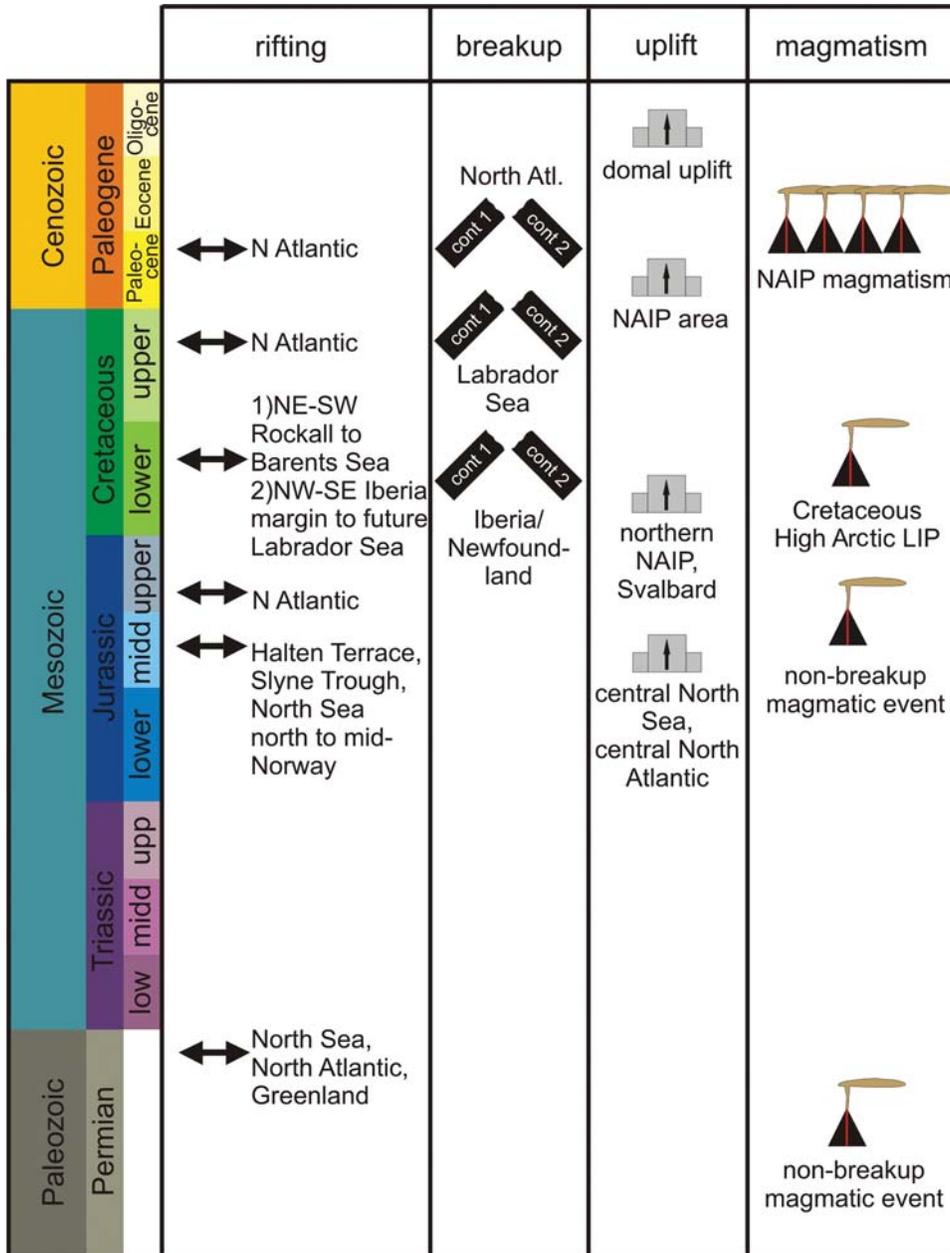


Figure 2. Schematic overview of the tectonic history of the North Atlantic Igneous Province (NAIP) region since Permian times. Several separate rifting episodes have affected the area since the Devonian extensional deformation that followed orogenic collapse: a widespread Permian-Triassic rift event is documented in the North Sea, North Atlantic, and Greenland. Limited early Middle Jurassic rifting is documented north to off-shore of mid-Norway. A major rifting episode affected the North Atlantic region (including the North Sea area) in the Late Jurassic. Prior to the breakup-related uplift event, a Jurassic period of uplift affected the central North Atlantic. This uplift was related to a period of magmatism; several magmatic episodes (relatively minor in volume) preceded the formation of the North Atlantic Igneous Province. Continental breakup in the Northeast Atlantic followed the Paleocene rift event. See text for references.

Newfoundland margins to the future Labrador Sea. West Iberia broke away from the Grand Banks of Newfoundland in the Early Cretaceous (e.g., Driscoll et al., 1995). A nonbreakup magmatic event of Lower to Upper Cretaceous age related to a period of uplift is documented in the Hopedale Basin and Svalbard areas. This magmatic event is defined as having formed an independent LIP (the so-called Cretaceous High Arctic Large Igneous Province) (Maher, 2001) (Fig. 2).

The Late Cretaceous phase of extension leading to seafloor spreading in Late Paleocene– Early Eocene time is well recognized in the North Atlantic (Doré et al., 1999). In Norway, this episode started around early Campanian time but was not necessarily

synchronously all along the margin segments (Gernigon et al., 2003). The onset of formation of oceanic crust in the Labrador Sea following the trend of the South Rockall-Hatton margin is still controversial. While older models propose that seafloor spreading in the Labrador Sea had already started at chron 33 in the Late Cretaceous (Roest and Srivastava, 1989), recent studies suggest opening in the Paleocene (Chalmers and Laursen, 1995).

Continental separation between Scandinavia and Greenland (Fig. 2) commenced in Early Eocene time (C24, ca. 53 Ma). After breakup, early seafloor spreading immediately northeast of Iceland first occurred along the now extinct Aegir Ridge un-

till anomaly C13 (Mosar et al., 2002), or maybe longer, till C10 (Breivik et al., 2006). Subsequently, seafloor spreading along the incipient Kolbeinsey Ridge began (Vogt et al., 1980; Nunns, 1983).

Extensional deformation in the northern Atlantic domain thus occurred long before commencement of the final Late Cretaceous–Paleocene rift phase, which resulted in continental separation.

Magmatism: Pre-Breakup- and Breakup-Related

Norwegian Margins. Ocean Drilling Program (ODP) efforts on the mid-Norway margin at the Vøring plateau (leg 104) recovered volcanic rock successions that record the magmatic activity from the early continental breakup phase. The volcanic sequence is divided into an upper and lower series (US and LS). The US includes the seaward-dipping reflector sequences (SDRSs), interpreted as tilted subaerial and transitional-type tholeiitic mid-ocean ridge basalt (MORB) lava flows with interbedded volcanoclastic sediments (Eldholm et al., 1987). The LS comprises a sequence of intermediate extrusive flow units and volcanoclastic sediments erupted prior to the onset of MORB-type magmatism and derived, at least partially, from continental source material. A similar lithology, of a US basaltic SDRS and an underlying LS of strongly crustally contaminated units has been sampled at the southeast Greenland margin (ODP leg 152, 1993, and leg 163, 1995) (Larsen et al., 1999; Saunders et al., 1999).

Available geochemical data for southeast Greenland and the Vøring Plateau show that the plateau US and the south Greenland US are chemically and isotopically rather similar. The LS from both areas are fundamentally different from each other in many respects (e.g., LS southeast Greenland $^{87}\text{Sr}/^{86}\text{Sr} < 0.702$ and LS Vøring Plateau $^{87}\text{Sr}/^{86}\text{Sr} > 0.710$) (Meyer et al., 2005). The marked difference in the geochemical signatures of the southeast Greenland and Vøring plateau samples points to a substantial difference in either the prebreakup crustal composition at the two localities or to different styles of mantle-crust interaction.

West Greenland and Baffin Island. Igneous rocks are recorded from Disko to Svartenhuk on-shore West Greenland (Larsen and Pedersen, 1988), as well as on Baffin Island and in the Labrador and Baffin Sea areas (e.g., Skaarup et al., 2006). The Nuussuaq Basin extends from Disko to Svartenhuk. Volcanism started here in Middle Paleocene time in a subsiding marine environment, so the earliest volcanic rocks are hyaloclastite breccias. After a significant Early Paleocene uplift, later volcanism was almost entirely subaerial (Dam et al., 1998). The volcanic rocks are divided into three formations (Gill et al., 1992). The lower formation consists mainly of picritic and other olivine-rich tholeiitic basalts, with local evidence of crustal contamination. The other two formations are composed of olivine and plagioclase phyric olivine tholeiitic basalts, basaltic tuffs, transitional basalts, and acidic ignimbrites.

An extraordinary characteristic of the West Greenland and Baffin Island lavas in the North Atlantic Igneous Province is the high ratio of picrites to basalts of the erupted volumes (30–50 vol% compared to, e.g., 15 vol% in East Greenland) (Gill et al., 1992; Larsen et al., 1992; Holm et al., 1993). Definitions of picrites are not always unambiguous (Le Bas, 2000); Gill et al. (1992) defined all basaltic rocks with MgO concentrations higher than 10 wt% as picrites. The MgO content of the rocks analyzed by Gill et al. (1992) ranges between 15 and 30 wt%. Petrologists debate the nature of these rocks: Do the melts represent unmodified high-MgO mantle melts (e.g., Clarke, 1970; Clarke and O'Hara, 1979), or are they derived from a primary mantle magma modified by one or more subsequent processes, e.g., olivine accumulation (Hart and Davis, 1979)? There is no doubt that the high-MgO (up to 30 wt%) picrites have been influenced by olivine accumulation (Gill et al., 1992). The picrites on Baffin Island can be classified according to the Kent and Fitton (2000) classification scheme for the Paleogene British igneous province (BIP) into M2 magmas with slight enrichment in light rare earth elements ($[\text{La}/\text{Sm}]_{\text{N}}$ of 1–1.2; Robillard et al., 1992) and M3 magmas ($[\text{La}/\text{Sm}]_{\text{N}}$ of 0.6–0.7; Robillard et al., 1992) (Fig. 3B). Most picrites have a radiogenic isotopic geochemistry ($\epsilon\text{Nd}_{t=60} > +3.4$ and $^{86}\text{Sr}/^{87}\text{Sr}_{(\text{Pd})} > 0.7031$; Holm et al., 1993), similar to the present-day Atlantic MORB and/or the Iceland basalts (Fig. 3A).

East Greenland Margin. Prior to breakup and opening of the Iceland basin, the southeast Greenland margin formed one system with the West Hatton volcanic margin. The southeast Greenland margin is characterized by a well-developed package of SDRSs in a wide zone across the shelf and in the adjacent off-shore region. ODP legs 152 and 163 drilling transects show that SDRSs were formed by subaerial or shallow marine lavas. Drilling during ODP legs 152 and 163 sampled the feather edge and the central part of the SDRS, recovering mainly basaltic lavas (Larsen et al., 1994; Duncan et al., 1996). Site 917 penetrated basalts and dacites of Late Paleocene age (ca. 61 Ma). These LS magmas represent the prebreakup lava flows. The parent magmas evolved by assimilation- and fractional crystallization-type processes in continental crustal reservoirs. Trace element and radiogenic isotope compositions indicate that the contaminant changed through time, from lower-crustal granulite to a mixture of granulite and amphibolite (Fitton et al., 2000) (Fig. 3A). The degree of contamination decreased rapidly after continental separation. Dominantly normal MORB (N-MORB) basalts with a few “Icelandic” basalt flows erupted during the prebreakup phase, but the source of the postbreakup magmas was clearly an “Icelandic” mantle.

Off-Shore U.K. and the British Igneous Province. The geochemistry and the mantle source of the British Igneous Province have been discussed in several publications (e.g., Thompson et al., 1982; Kent and Fitton, 2000). The composition of the on-shore and, to a lesser extent, off-shore Scottish basalts is relatively well known. Geochemical studies defined three successive Paleogene magma types: M1–M3 (Kerr, 1995;

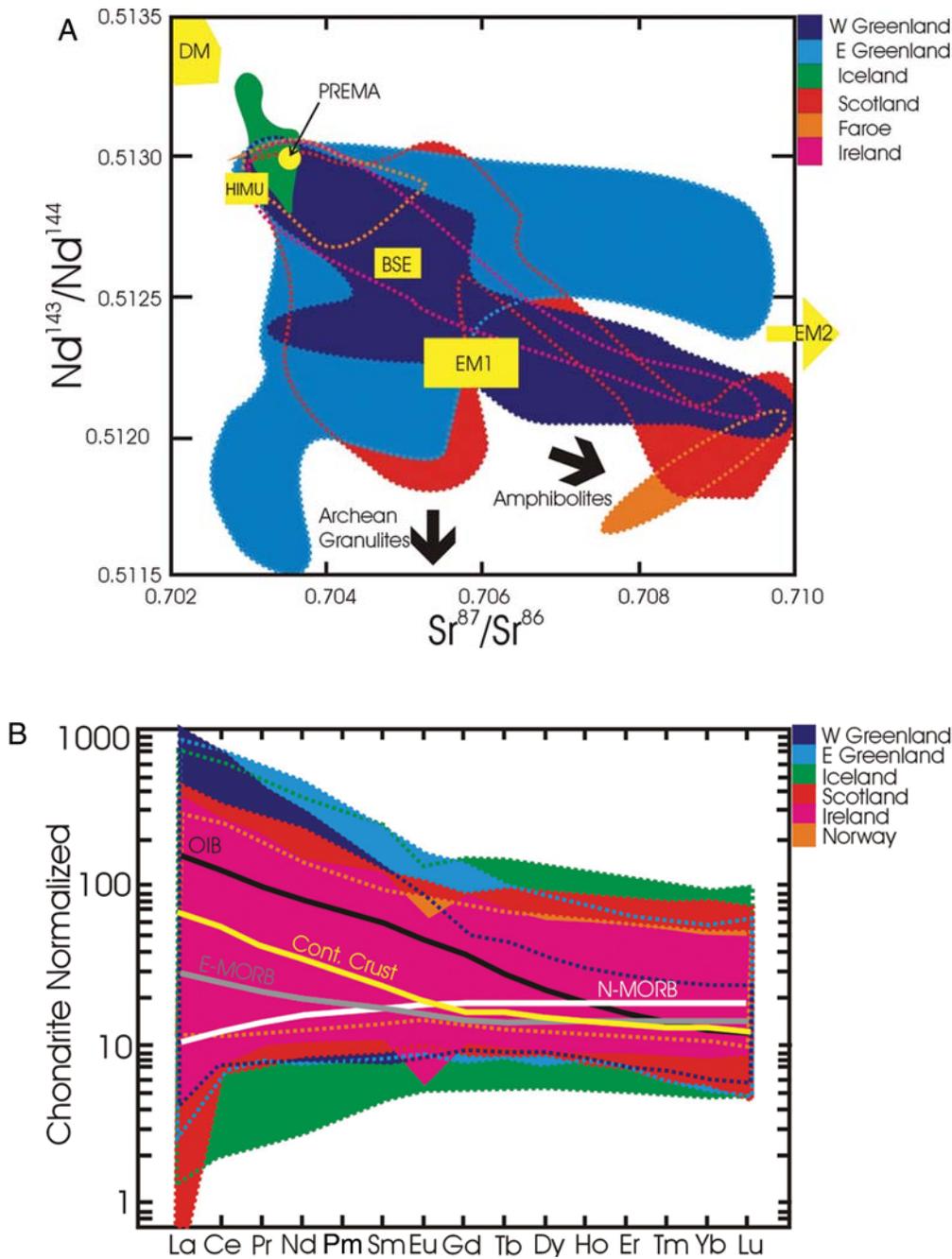


Figure 3. Geochemical overview of North Atlantic Igneous Province magmas. (A) $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ diagram for igneous products of the province. Isotopic differences are due to the contrast in Nd and Sr isotopic composition between old continental crust (e.g., gneiss, amphibolites) and mantle magma sources. Variations of $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ in crustal rocks are related to age and the contrasting geochemical behavior of Sm and Nd relative to Rb and Sr. The mantle plume model suggests that the correlation of initial Nd and Sr isotopes represents mixing lines between “mantle zoo” reservoirs of distinct chemistry and age. BSE—bulk silicate earth; DM—depleted MORB (mid-ocean ridge basalt) mantle; HIMU—high μ (i.e., high U/Pb subducted oceanic crust); EM1 and EM2—enriched mantle 1 (recycled pelagic ocean floor sediments or subcontinental lithosphere) and 2 (subducted continental material); PREMA—prevalent mantle. Fields from Hart (1984) and Hart and Zindler (1989). Alternatively, the trend may result from mixing by assimilation or contamination of high-Sm/Nd, low-Rb/Sr mantle melts with old low-Sm/Nd, high-Rb/Sr crustal material, as has been shown in some areas below the North Atlantic Igneous Province (Scotland). See the section headed “Exploring Alternatives” for a discussion. Data are from the Max Planck Institut für Chemie, Geochemistry Division, GeoRoc database. (B) Masuda-Coryell diagram comparing the rare earth element (REE) compositions of the areas below the North Atlantic Igneous Province. The REE patterns are controlled by the source geochemistry and crystal-melt equilibria. Melting processes (e.g., partial melting) affect the content of REE but not the shape of the C1 normalized pattern, reflecting the source composition. All areas below the North Atlantic Igneous Province include both melts from an enriched mantle source and magmas generated from a depleted mantle. Data are from the Max Planck Institut für Chemie, Geochemistry Division, GeoRoc database, and the lines for normalized mid-ocean ridge basalt (N-MORB), enriched MORB (E-MORB), and ocean island basalt (OIB) are representative patterns from Sun and McDonough (1989). The continental crust pattern is from Taylor and McLennan (1985). Data are normalized to the C1 chondrite composition of Sun and McDonough (1989).

Kent and Fitton, 2000). A volumetrically insignificant fourth magma type (M4) is preserved as dikes and plugs. M1 and M2 are characterized by major element geochemistry similar to that of transitional alkali basalts, whereas the M3 magmas have tholeiitic basalt major element chemistry (Kent and Fitton, 2000). The rare earth element (REE) geochemistry of the M1 (high Ce/Y) magmas is defined by a pattern of slight enrichment in light REE (LREE), while the M2 (moderate Ce/Y) magmas have a rather flat REE pattern (around 20 × chondritic), and the M3 (low Ce/Y) magmas have a pattern similar to that of N-MORB (Fig. 3B). Chambers and Fitton (2000) showed that the earliest tapped mantle source on Mull was N-MORB, followed by an “Icelandic” mantle, before returning to an N-MORB source. The isotopic geochemistry of most British Igneous Province rocks confirms strong interaction between mantle melt and crust during the formation of these magmas (Fig. 3A). Sr, Nd, Hf, and Pb isotopic compositions not only shed light on crust-mantle interactions but are also able to reveal the crustal contaminant (lower crustal gneisses, upper crustal amphibolites, upper crustal sediments) by means of their distinctive isotopic signatures (e.g., Geldmacher et al., 2002; Troll et al., 2004). Dickin (1981) even suggested that in the British Igneous Province the Pb isotopic system provides no information on the mantle source but mainly provides information on the nature of the contaminating continental crust. Such crustal geochemical continental contamination or assimilation trends can be seen in all the subareas of the North Atlantic Igneous Province. Only after the deduction of these mantle-crust interaction processes, some of which are still unknown, can precise information on possible mantle plume influences be deduced.

The northeast Irish basalts of the British Igneous Province have also been divided into three formations. The volcanic activity there was episodic, and the majority of the mantle magmas were contaminated by assimilation of crustal rocks (Fig. 3A) (Kerr, 1995; Barrat and Nesbitt, 1996). With the exception of the Causeway Member, most have convex-up REE patterns. These are interpreted as being due to residual garnet in the mantle source (Fig. 3B). This suggests that at the start of Paleogene volcanism, the melt regime was controlled by a thick lithosphere that thinned with time such that the Causeway tholeiitic MORB-like basalts were produced at shallower levels. Barrat and Nesbitt (1996) suggest that the return to the convex-up patterns of the Upper Formation shows that simple models of lithospheric stretching and rifting are not able to explain the Antrim situation.

Faeroe Islands. The Faeroe Islands rest on top of the subsided, continental Faeroe-Rockall Plateau, which is separated from the British Isles by the deep rift basins of the Faeroe-Shetland Channel and the Rockall Trough (Fig. 1). The islands expose up to 3 km of flood basalts—the Faeroe Plateau Lava Group—which is also divided into three basalt formations (Waagstein, 1988). All basaltic lavas have been erupted subaerially and are tholeiitic (Fig. 3A). The lowermost formation differs from the olivine tholeiites in the upper and middle formations in-

ing silica-oversaturated and more crust-contaminated (Fig. 3A). The lower formation is capped by a coal-bearing sequence, dated as Paleocene (Lund, 1983), which is evidence for a break or decrease in volcanic activity. So far, no hiatus has been documented between the middle and upper formations. A mantle source change occurs at this transition; while all of the lower and middle formation tholeiites are slightly LREE enriched, the upper formation is a mixture of LREE-depleted and LREE-enriched tholeiites (Gariépy et al., 1983).

Irish Volcanic Margin. The Irish margins are characterized by a nonvolcanic margin to the southeast and by a Late Paleocene–Early Eocene volcanic margin to the northwest, which forms the southern edge of the North Atlantic Igneous Province (see Fig. 1) (Barton and White, 1995, 1997). The West Hatton volcanic margin exhibits a typical volcanostratigraphic sequence similar to that of the Norwegian volcanic margin.

DSDP leg 81 sampled the Irish SDRS tholeiitic basalt lava flows, extruded under subaerial or very shallow marine conditions. The lavas are all consistently MORB-like in composition (Harrison and Merriman, 1984).

The Hatton Basin and the West Hatton margin are part of the Rockall-Hatton Plateau, a continental fragment between the Rockall Basin and the oceanic crust, east of the C24 magnetic anomaly. From Hitchen (2004) we know that Albian sediments are present beneath the thin Cenozoic section in the western part of the Hatton Basin. These sediments are on-lapped by Paleocene lava flows that issued from igneous centers, clearly characterized by a circular-shaped gravity anomaly (e.g., Hitchen, 2004; Geoffroy et al., this volume). They were recently drilled by the British Geological Survey and comprise basalt, gabbro, and andesite (Hitchen, 2004).

Arctic, Svalbard, and Barents Sea. Svalbard contains a record of magmatic events dating back to the Mesozoic. The only direct evidence for Paleogene volcanic activity at Svalbard is minor tuff input in the Central Basin.

Off-shore volcanism at the Yermak Plateau (Fig. 1) of northern Spitsbergen may be Paleogene (Harland et al., 1997). Neogene to Recent volcanism can be divided, after Harland and Stephens (1997), into two distinct groups: Miocene plateau lavas and Pleistocene volcanics with hydrothermal activity. Ages of 10–12 Ma for the plateau basalts are based on K-Ar dating (Prestvik, 1978).

In this area, an older volcanic episode has been recognized and defined as an independent LIP (the so-called Cretaceous High Arctic Large Igneous Province) (Maher, 2001) (Fig. 2). Flood basalts, dikes, and sills with Early to Late Cretaceous ages are found in the Canadian Arctic Island (Estrada, 1998). Recent Ar-Ar dating from northernmost Greenland suggests an age of ca. 80–85 Ma for the magmatism, which is older than previous whole-rock K-Ar measurements indicated (Kontak et al., 2001; Estrada and Henjes-Kunst, 2004).

The aseismic Alpha Ridge extends northward beneath the Arctic Ocean. This ridge is volcanic and partly of Cretaceous age, with an alkaline rock sample dated using the Ar-Ar tech-

nique at 82 ± 1 Ma (C33r) (Jokat, 2003). Lower Cretaceous basaltic rocks are known in Svalbard, Kongs Karl Land, and Franz Josef Land (Bailey and Rasmussen, 1997). Tholeiitic basalts in Franz Josef Land have been dated at 117 ± 2.5 Ma (C34n) by Pumhösl (1998) using Ar-Ar techniques. Also at Svalbard, abundant doleritic Jurassic and Cretaceous intrusions are known with a few volcanic lava flows. Burov et al. (1975) suggest that quartz dolerites typically have ages around 144 ± 5 Ma, and younger olivine dolerites have ages around 105 ± 5 Ma. However, like the Prestvik (1978) ages, they need to be confirmed with state-of-the-art dating methods. From seismic data it is known that sills are present in the central and northern part of the Russian Barents Sea. Preliminary age data indicate that these widely distributed outcrops were formed as part of the same event, but the data are not sufficiently precise to allow us to determine whether the occurrences were truly contemporaneous or whether there is any systematic age progression from the Arctic region to the North Atlantic Igneous Province.

Postbreakup Magmatism: Iceland and the Oceanic Part of the North Atlantic Igneous Province

The seismic crust beneath Iceland is estimated to reach a thickness of 38–46 km in some places. Part of the Icelandic crust is possibly continental (Foulger et al., 2005). Two thick-crust ridges flank Iceland: the Greenland-Iceland and Iceland-Faeroe ridges (Fig. 1), with a Moho depth of ~25–30 km (Richardson et al., 1998; Smallwood et al., 1999). Iceland is composed mainly of tholeiitic basalts with smaller amounts of alkali basalts, rhyolites, and obsidians. It is widely known that the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope data for Iceland (and the Reykjanes Ridge) show significantly higher concentrations than those of N-MORB (e.g., O’Nions and Pankhurst, 1974). The geochemical signature of Icelandic igneous rocks is characterized by high $^3\text{He}/^4\text{He}$ ratios relative to the atmospheric ratio, Ra. The highest noncosmogenic $^3\text{He}/^4\text{He}$ isotope ratios of ~42 Ra are found in Iceland (Hilton et al., 1999; Breddam, 2002). The major geochemistry of basalts from the nearby ridge segments, Vesteris seamount, the Jan Mayen area, and the previously described Paleogene successions (Fig. 3A and B) indicate that the upper mantle in most of the Northeast Atlantic has the same chemical characteristics as the current Iceland source (Saunders et al., 1997). The isotopic data of the whole North Atlantic Igneous Province show that most of the breakup igneous rocks and the Iceland magmas derived from an enriched mantle source and not from a depleted mantle (e.g., North Atlantic MORB). The fact that such enriched magmas are limited, with some exceptions, such as Iceland, to the breakup time strongly supports the idea that the mantle source below the North Atlantic Igneous Province was heterogeneous. After the breakup magmatism, this source was depleted, and it is now producing the typical North Atlantic MORB.

The oceanic crust formed at Kolbeinsey Ridge (Fig. 1) north of Iceland is 1.0–2.5 km thicker than normal oceanic crust (Kodaira et al., 1998). The crust is up to 10 km thick at the Reyk-

janes Ridge axis south of Iceland (Smallwood et al., 1995), which is also anomalously thick for this slow-spreading ridge. The Reykjanes Ridge shows further remarkable features. While it is slow spreading, it lacks a rift valley in its northern part. Furthermore, basement ridges are observed that cut obliquely across lines of equal age. They are arranged symmetrically about the spreading boundary and form a V-shaped pattern (Vogt, 1971; Ito, 2001). These features have also been documented at the Kolbeinsey Ridge, north of Iceland (S.M. Jones et al., 2002; Vogt and Jung, 2005). Lateral transport of plume-derived material from Iceland southward along the Reykjanes Ridge has been suggested to explain the ridge bathymetry (which slopes up toward Iceland) and the V-shaped ridges (e.g., White et al., 1995; Ito, 2001). Alternatively, passive upper-mantle heterogeneities could have played a role in the formation of the V-shaped structures (S.M. Jones et al., 2002; Vogt and Jung, 2005).

Magmatism: Age and Overview

The North Atlantic Igneous Province shows a wide range of magmatic ages of Paleogene volcanic rocks (Fig. 4). For this overview we used the most reliable available data, the compilation of geochronological data on the province by Torsvik et al. (2001), and included data from Iceland (Moorbath et al., 1968; Ross and Mussett, 1976; Hardarson et al., 1997; Foulger, 2006). Note, for example, the single data point of the mid-Norwegian margin, where several publications suggest a range of ages. The Vøring plateau magmas have been inconsistently dated by Rb-Sr isochrones to 57.8 ± 1.0 Ma (LeHuray and Johnson, 1989) and 63 ± 19 Ma (Taylor and Morton, 1989). Since recent Ar-Ar geochronology investigations, these LS magmas are believed to be much younger, 56–55 Ma (Sinton et al., 1998). However, we note that there is currently debate on the reliability even of part of this data set (Baksi, 2005 and this volume, both chapters). The uncertainty in age determination, in combination with logistical limitations, has left a large part of the North Atlantic Igneous Province region unsampled or undersampled.

The present data set (Fig. 4) suggests several robust patterns: (1) there is evidence of prolonged magmatism after continental separation on Iceland and in the northern parts of the West and East Greenland margins, while the southern part of the Northeast Atlantic margins seem devoid of postbreakup magmatism, and (2) Paleogene, prebreakup magmatism (ca. 60 Ma) occurs in all regions (except for Iceland) and is middle to late synrift (Fig. 2). The absence of postbreakup magma samples along most of the northwest Atlantic margins away from the Greenland, Iceland, and Faeroe ridges is in concert with the rapidly decreasing oceanic crustal thickness after breakup. It indicates that the melting source was depleted at this time.

Volume of Magmatism

Igneous rocks emplaced during the breakup event comprise three main units: (1) voluminous extrusive complexes, includ-

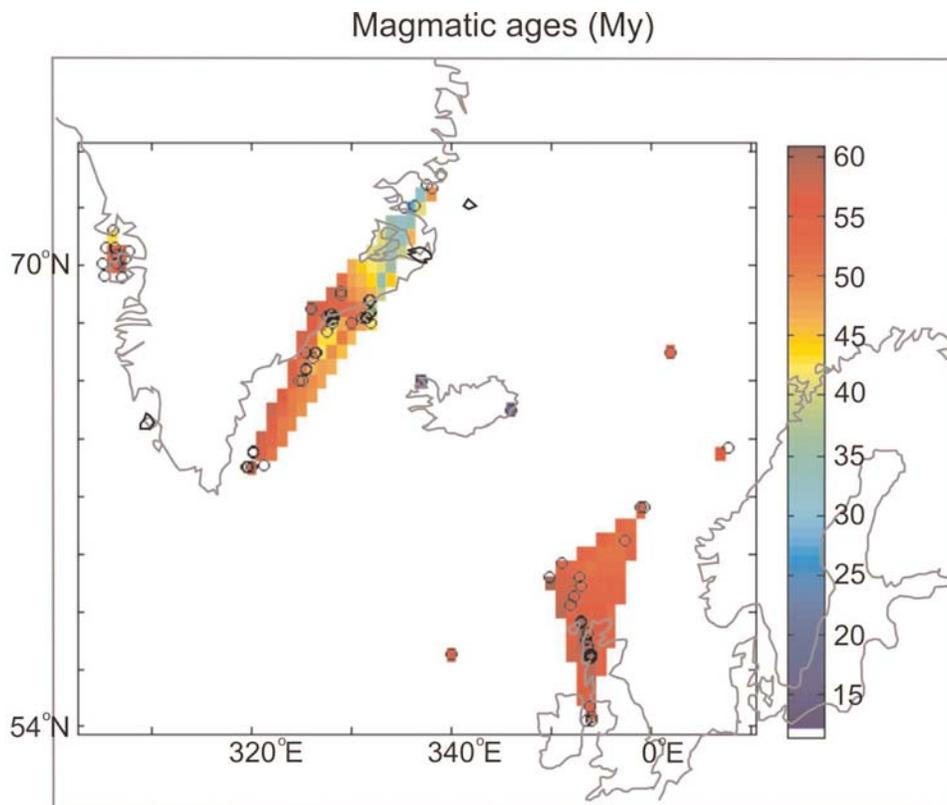


Figure 4. Cenozoic ages of North Atlantic Igneous Province igneous rocks. See text for references and explanation. This is a linear interpolation of the data points onto a regular grid with a 1° by 0.25° resolution. Data set: Moorbath et al. (1968), Ross and Mussett (1976), Brooks and Gleadow (1977), Gleadow and Brooks (1979), Bugge et al. (1980), Dickin (1981), Dickin and Jones (1983), Mussett (1986), Gibson et al. (1987), Thompson et al. (1987), Noble et al. (1988), Hitchen and Ritchie (1993), Nevle et al. (1994), Upton et al. (1995), Pearson et al. (1996), Hardarson et al. (1997), Hirschmann et al. (1997), Price et al. (1997), Sinton and Duncan (1998), Sinton et al. (1998), Storey et al. (1998), Tegner et al. (1998), Gamble et al. (1999), Tegner and Duncan (1999), and Foulger (2006).

ing the SDRS; (2) thick initial oceanic or transitional crust, often with a high-velocity lower-crustal body (LCB); and (3) intrusives. Between individual margin segments, there is variability in the extent and volume of these magmatic features. For example, the thickness and surface area covered by SDRSs, the thickness of the LCB, and the thickness of the initially formed oceanic crust vary considerably.

At the northern Norwegian Lofoten-Vesterålen margin, for example (Fig. 1), the initial oceanic crust is $\sim 12\text{--}15$ km thick (Tsikalas et al., 2005). A LCB is documented seaward of the shelf edge. To the south, the mid-Norwegian Vøring margin is characterized by an increased but along-strike-variable initial oceanic crust thickness (e.g., Skogseid and Eldholm, 1995). Packages of SDRSs are commonly present at this margin, and the thickness of the LCB varies along strike (Mjelde et al., 2005; Ebbing et al., 2006). At the Møre margin (Fig. 1), there is evidence of a LCB (e.g., Raum, 2000) and SDRS (e.g., Planke et al., 2000).

The volcanic central region of Baffin Island is characterized by SDRSs. To the north the margin is nonvolcanic, and SDRSs are absent (Skaarup et al., 2006). In the south, Baffin magmatism is limited and the margin is interpreted as nonvolcanic (Skaarup et al., 2006). The conjugate margins of the Labrador Sea, southern Labrador, and southern West Greenland are nonvolcanic (Chian et al., 1995). The existence of SDRSs at Disko Island remains controversial (Geoffroy et al., 1998; Chalmers et al., 1999).

Along the East Greenland margin, transects image LCBs (Korenaga et al., 2000; Holbrook et al., 2001). The crustal thickness varies (Holbrook et al., 2001) from 30 to 33 km at the postulated hotspot-proximal zone to $10\text{--}20$ km away from the region. Maximum crustal thickness (~ 30 km) decreases over the period $10\text{--}12$ Ma just after the C24 magnetic anomalies to only $8\text{--}9$ km. On a crustal scale, massive and scattered LCBs are recognized in several parts of the Hatton Basin and along the West Hatton margin, but are not present everywhere (Fowler et al., 1989; Barton and White, 1997; Vogt et al., 1998).

The thickness of the LCBs not only varies laterally (Tsikalas et al., 2005; Ebbing et al., 2006), but there is also discussion regarding its magmatic nature (Ebbing et al., 2006; Gernigon et al., 2006). A widely accepted interpretation of these bodies is magmatic underplating, representing both ponded magmatic material trapped beneath the Moho and magmatic sills injected into the lower crust (Furlong and Fountain, 1986; White and McKenzie, 1989). Some recent studies, however, suggest an alternative explanation. Gernigon et al. (2006) propose that the LCB characteristics may be partly explained by the presence of preexisting high-velocity rocks such as eclogites or migmatites. Ebbing et al. (2006) propose that the LCBs could be remnants of the Caledonian root.

The nonmagmatic hypothesis has significant implications. A nonmagmatic interpretation of the LCBs would lower the estimated North Atlantic Igneous Province melt volumes (Eld-

holm and Grue, 1994) significantly. This, in turn, would affect most conventional models for LIP formation, which generally link melt volumes to potential mantle temperature (White and McKenzie, 1989).

From available seismic, gravity, and magnetic data, a picture emerges of a melt volume that varies significantly along strike of the North Atlantic margins, but that is clearly largest near the Iceland anomaly, as shown by the great oceanic crustal thickness there (Greenland–Iceland–Faeroe ridges). The post-breakup oceanic crustal thickness shows a similar pattern of excessive magma production at the Greenland–Iceland–Faeroe ridges and present-day Iceland and increased crustal production at the Reykjanes and Kolbeinsey spreading ridges (see the earlier section on postbreakup magmatism).

Mantle Seismic Velocity Structure

Tomographic studies agree on an upper-mantle low-seismic-velocity anomaly beneath Iceland (e.g., Bijwaard and Spakman, 1999; Ritsema et al., 1999; Foulger et al., 2001; Montelli et al., 2004). This anomaly is centered beneath east central Iceland and is approximately cylindrical in the top 250 km but tabular in shape at greater depth (Foulger et al., 2001). A narrow anomaly seems to be embedded in a wider (1000 km or more), weaker anomaly beneath the Iceland region. In the lower mantle the strong anomaly is no longer present; anomalies there are only a fraction of the strength of the upper-mantle anomaly and in most studies are discontinuous with the upper-mantle anomaly (Ritsema et al., 1999). Although the temperature dependence of wavespeeds in the mantle decreases with depth, making plumes more difficult to image deeper down, a sharp change is not expected at the base of the upper mantle. It has been claimed that several plumes have been observed extending into the deep mantle elsewhere, suggesting that the lack of continuity at Iceland is real (Montelli et al., 2004). The tomographic images thus provide no evidence for an upwelling, deep-mantle plume (Montelli et al., 2004).

Uplift History of the Margins

It is generally accepted that the North Atlantic Igneous Province experienced uplift and exhumation during Early Paleogene time (cf. Saunders et al., 2007), but a regional picture of these vertical movements and their amplitudes is far from well constrained. The currently available information is summarized later, and a regional overview of well-constrained Paleocene–Eocene uplifted areas in the North Atlantic domain is shown in Figure 5. We note that this compilation is far from being complete; we omitted poorly constrained data as well as subsidence patterns along the incipient margin. The breakup-related phase of uplift was preceded by several other periods of uplift (Fig. 2) in the North Atlantic domain since collapse of the Caledonian orogeny. After continental separation, domal uplift affected the North Atlantic (Fig. 2). The locations of domes in-

clude southern and northern Norway, the northern United Kingdom, Svalbard, and Finnmark (e.g., Rohrman and van der Beek, 1996).

Regional Early Paleogene (prevolcanic) uplift has been demonstrated by field and/or seismic data in West Greenland (Dam et al., 1998), the Faeroes-Shetland Basin (Nadin et al., 1997; Sørensen, 2003), the North Sea Basin (Mudge and Jones, 2004), the Porcupine Basin (Jones et al., 2001), the Celtic and Central Irish Sea (Murdoch et al., 1995; Corcoran and Doré, 2005), the Hatton Basin (Hitchen, 2004), and the Norwegian margin (Skogseid and Eldholm, 1989).

Along the North Atlantic Igneous Province, an epeirogenic event is well documented in the latest Cretaceous–earliest Paleocene before the breakup and the main volcanic phase. This prebreakup event coincides with a regional hiatus and erosion features along the outer Vøring Basin (Skogseid et al., 1992). During this period, the Møre Basin experienced the rapid and episodic influx of coarse sediment in response to regional exhumation and denudation of the mainland (Martinsen et al., 1999). In East Greenland, isolated outcrops show Upper Cretaceous and Lower Paleocene off-shore shales and submarine channel turbidites that are unconformably overlain by fluvial conglomerate and sandstones, implying a similar dramatic shallowing there as well (Larsen et al., 1999).

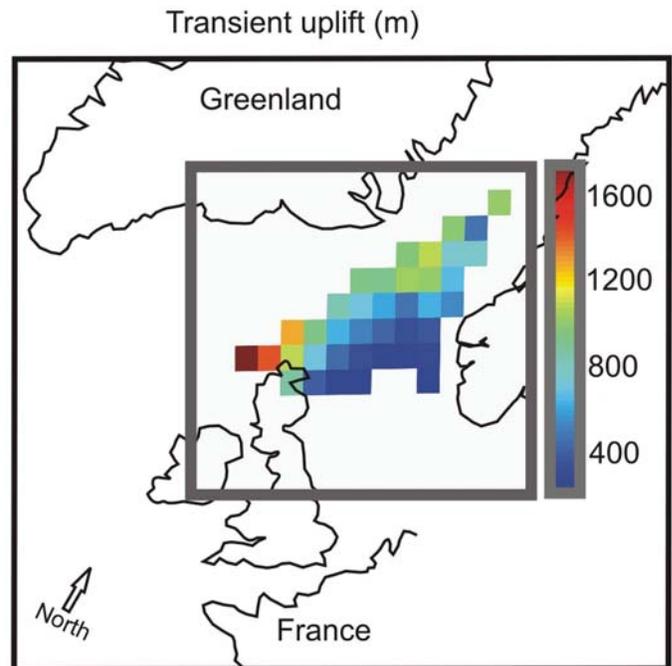


Figure 5. Transient Paleocene–Eocene boundary uplift in the North Atlantic Igneous Province. The East Greenland uplift is not shown here, nor are several locations that were insufficiently well constrained. Linear interpolation of the selected data points onto a regular grid with a 2° by 2° resolution. Compilation of data shown here from Nadin et al. (1997), Knox (1998), Jones et al. (2001), Deptuck et al. (2003), Jones and White (2003), Ren et al. (2003), Ceramicola et al. (2005), and Mackay et al. (2005).

West Greenland is not included in Figure 5, but there uplift has been documented 5–10 Ma before the onset of volcanism. The uplift (up to 1.3 km) was associated with fluvial penneplanation, exhumation of deep marine sediments, valley incision, and catastrophic deposition (Dam et al., 1998). Around the British Isles, apatite fission track studies have identified two exhumation events: an early Cenozoic and a late Cenozoic episode (Green et al., 2001). Subsidence analysis in the Moray Firth Basin (Mackay et al., 2005) suggests transient uplift initiated in Early Paleocene time. The basin records contemporaneous changes from hemipelagic to clastic sedimentation in the northern North Sea and coincides with a marine regression (Ahmadi et al., 2003). In the Faeroe-Shetland Basin, the Early Paleocene uplift is recognized and coincides with the Danian Maureen formation deposition in the North Sea. A Middle Paleocene phase associated with a major change in sediment provenance is recognized as well (Naylor et al., 1999).

At the onset of Northeast Atlantic breakup in the Early Eocene, widespread volcanism and local erosion and uplift occurred along the breakup axis of the Mid-Norwegian margin. Tectonic subsidence curves show uplift around the time of rift-drift transition on the western side of the Vøring Basin and the Vøring Marginal High (Skogseid et al., 1992). Around Ireland and in the North Sea, a maximum transient uplift occurred in Late Paleocene–Early Eocene time, followed by a rapid post–Early Eocene subsidence (Nadin et al., 1997; Green et al., 2001; Jones et al., 2001; Mackay et al., 2005). In the Faeroe-Shetland Basin, the Late Paleocene–Early Eocene phase coincided with a strong unconformity and prograding sands and mudstone sequences off-shore Faeroes (Sørensen, 2003). Along the Northeast Greenland shelf, five sequences of eastward-prograding wedges document a strong uplift of the Greenlandic mainland from Paleocene to Early Eocene time (Tsikalas et al., 2005). Figure 5 suggests a pattern of increased transient uplift toward the future breakup axis. The data are too sparse to definitely point to a concentration around the inferred paleoposition of the Iceland anomaly.

GEODYNAMIC MODELS FOR NORTH ATLANTIC IGNEOUS PROVINCE FORMATION

The formation of the North Atlantic Igneous Province can be related only to geodynamic models explaining and predicting all the previously described observations. Because the plume concept is challenged today, alternative models have been proposed as sources for LIPs. In this section we discuss the most prominent models, including delamination, impact, fertile mantle, small-scale convection, and mantle plume.

Lithosphere Delamination

One mechanism that can explain the production of huge amounts of basalt involves a link between melt production and delamination of the lower lithosphere (Fig. 6A). The mechanism

of delamination that is considered here as a possible explanation for North Atlantic Igneous Province formation involves the rapid foundering of the mantle part of the lithosphere into the convective mantle. Under specific conditions, the lithospheric mantle can become insufficiently buoyant or viscous to survive as lithosphere, and detach (Bird, 1979; Bird and Baumgardner, 1981). There are two conditions that must be met before delamination can occur: the lithospheric mantle has to be gravitationally unstable, and its viscosity must be low enough to allow flow (Elkins-Tanton and Hager, 2000; Schott et al., 2000). Several conditions may result in a sufficient increase in lithosphere–asthenosphere density contrast for delamination to occur (e.g., see Kay and Kay, 1993). These include melt intrusions that subsequently freeze, cooling of mantle lithosphere by shortening and mountain building, or a compositional difference. Viscosity decrease can be caused by melt intrusions (Carlson et al., 2005).

Gentle removal of the base of the lithospheric mantle would probably have no expression in the overlying crust or vertical movements, but rapid delamination is expected to influence the remaining overlying part of the lithosphere. Potential consequences are increased heatflow and generation of delamination-related magmas; crustal subsidence during delamination preceding short-lived, postdelamination rapid uplift of the surface; and changes in tectonic style to an extensional stress regime (e.g., England and Houseman, 1989; Elkins-Tanton and Hager, 2000; Morency and Doin, 2004; Carlson et al., 2005). The geochemical content of igneous rocks related to delamination is characterized by high-potassium magmas such as lamprophyres, leucitites, and absarokites (Kay et al., 1994; Ducea and Saleeby, 1998; Farmer et al., 2002; Elkins-Tanton and Grove, 2003). Delamination will not result in steady-state melting for tens of m.y.; instead, a short pulse is expected (Elkins-Tanton, 2005). Delamination can occur over a range of scales, and modeling studies suggest that a wide range of melt volumes may result (Elkins-Tanton, 2005).

As far as we know, the amount of crustal subsidence and subsequent uplift that can be expected from delamination has not yet been quantified. We assume that the size and area of delamination will influence the amount and distribution of vertical movements and melt production (Elkins-Tanton, 2005). The sequence of events during delamination are thus different (opposite) from that typically proposed to accompany the arrival of a mantle plume: subsidence is followed by uplift and magmatism, while a mantle plume is expected to cause uplift prior to volcanism.

The long extensional phases that ultimately resulted in continental separation between Norway and East Greenland were preceded by a mountain-building phase, the Caledonian orogeny. So the circumstances that could lead to a gravitational unstable lithospheric root and possibly delamination were present. However, there is no documentation of substantial magmatism following the orogeny, and the time lapse between the mountain-building phase and the Paleocene–Eocene volcanic event is too large (several 100 m.y.) to expect any relationship between

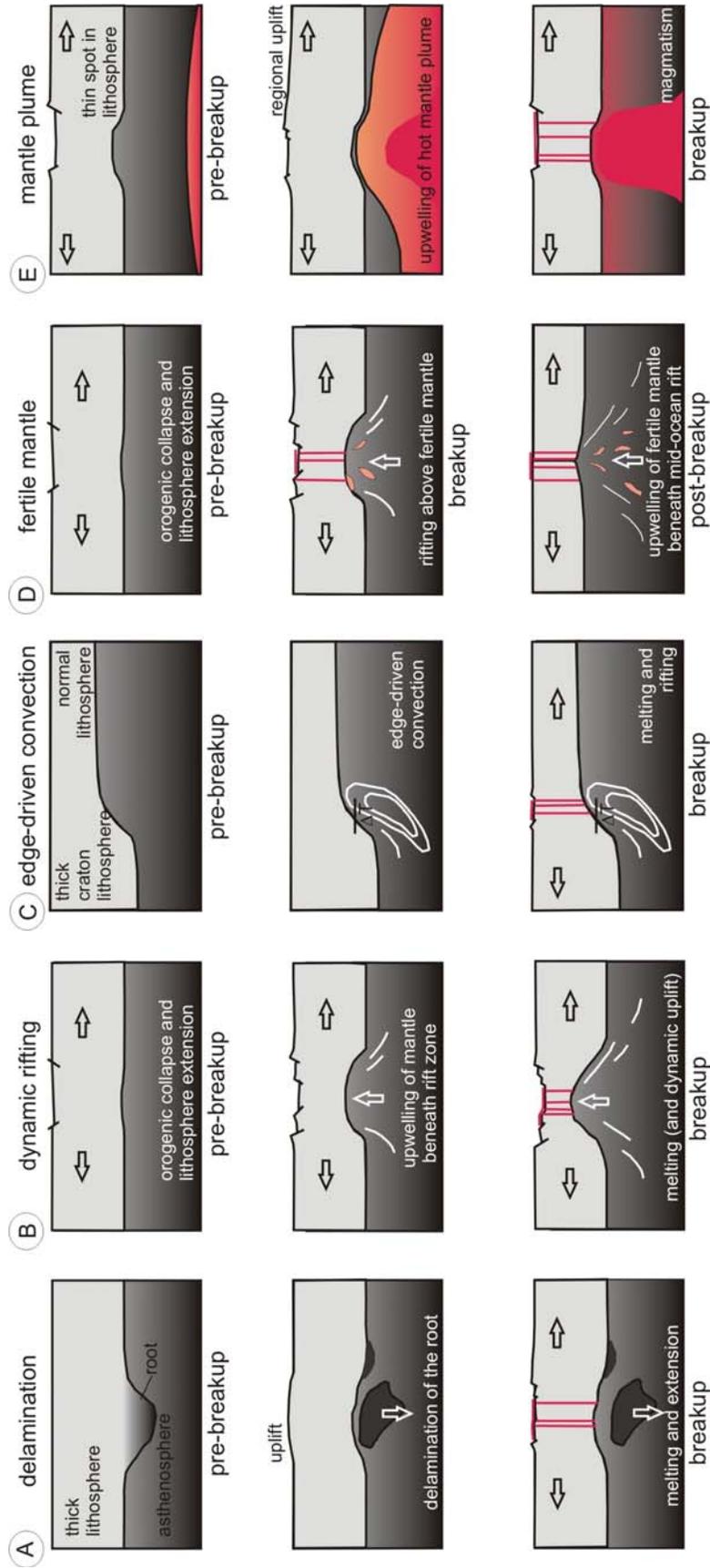


Figure 6. Schematic overview of different models suggested for large igneous province or North Atlantic Igneous Province formation. (A) Delamination of thick lithosphere root. Uplift is a response to the delamination, followed by magmatism and extension. (B) Dynamic rift model. Passive rifting follows Caledonian collapse. Warm mantle material wells up beneath the rift zone to fill the space created by extension, resulting in decompression melting. (C) Edge-driven convection model. Convection occurs due to lateral temperature differences between craton and noncraton lithosphere. This brings large volumes of mantle material into the melt window. (D) Fertile mantle concept. Rifting occurs above a patch of fertile mantle material (a remnant of subducted oceanic lithosphere), resulting in volcanic margins and later in continued magmatism at Iceland. (E) Mantle plume model. Mantle plume material fills an existing thin spot in the lithosphere, causing uplift and excessive melting.

them. Moreover, the chemical contents of North Atlantic Igneous Province igneous rocks are not in agreement with the expected chemical signature of lavas following from the mechanism of delamination, and the tectonic evolution of the North Atlantic Igneous Province (mountain building, extension, uplift, magmatic phase) is not in concert with delamination (mountain building, magmatism and uplift, extension). We therefore reject the delamination mechanism as an explanation for formation of the North Atlantic Igneous Province.

Extraterrestrial Body Impact

The idea that meteorite impacts may initiate volcanic eruptions and form LIPs on Earth was first proposed by Rogers (1982). He suggested that the collision of a large extraterrestrial body with Earth could cause the formation of an impact crater with a diameter on the order of 100 km and penetrate the lithosphere into the asthenosphere. Massive volcanism would result and extend to outside the crater, so the crater would be obliterated. Another consequence of an impact is that it could cause the formation of a long-lived mantle plume, with an extended, secondary period of additional melting (see also Abbott and Isley, 2002). This concept has been applied to continental flood basalt provinces (for example, the Siberian Traps; A.P. Jones et al., 2002) as well as oceanic plateau formation (e.g., Ingle and Coffin, 2004).

Igneous rocks are very common near large impact craters. However, numerical simulations of a large asteroid impact in the last decades have produced contradicting predictions regarding the amount of melt that could result from an impact (Ivanov and Melosh, 2003; A.P. Jones et al., 2005a). Ivanov and Melosh (2003) find that impact-induced melt volume is limited and cannot explain LIPs unless a large impact occurs on very warm lithosphere, such as a mid-ocean ridge, which is unlikely. A.P. Jones et al. (2005a), on the other hand, using a different set of geotherms and melt calculation methods, find impact melt volumes that are large enough to explain the origin of the largest LIPs on Earth.

Apart from the impact crater (which can be obliterated) and possible subsequent top-down-induced plume formation, there are no tectonic processes related to the impact scenario that we can compare with observations of the North Atlantic Igneous Province. Deposits that are being related to impact events, such as quartz spherules, have been found near Disko Island in central West Greenland (A.P. Jones et al., 2005b). In the North Atlantic Igneous Province, melt eruptions took place over an elongated zone of ~3200 km length following a long period of extension. After breakup, there was continuous melt production at Iceland. Even if a large projectile impacted this extended area with steep geotherms in the Late Paleocene just prior to breakup, the elongated shape of the eruption zone does not support an impact scenario for the rifted margins of the North Atlantic Igneous Province. The Iceland hotspot would, in this scenario, represent the top-down-induced mantle plume. Lack of more data and

model development to support an impact scenario for formation of the North Atlantic Igneous Province inhibits a definite rejection or acceptance of this scenario.

Fertile Mantle: Chemical Anomalies

A heterogeneous mantle source has been suggested by several authors to explain the variation in rift-related melt production and geochemical contents of igneous rocks along rifted margins. Korenaga (2004) suggests a fertile mantle heterogeneity as the source of the North Atlantic Igneous Province. Recycled oceanic crust subducted during the closure of the Iapetus Ocean and subsequently segregated at the 660 km discontinuity was eventually brought toward the surface from the lower mantle in a quite complex mixing process. In this model, both the upper and lower mantle were involved in mantle mixing. Fertile material may have accumulated near the upper-lower mantle boundary during subduction. During continental rifting, plate-driven flow assists the entrainment process, and upwelling of the fertile mantle will result in a high degree of melting and emplacement of flood basalts. This process of counterupwelling fertile material could continue for tens of millions of years according to Korenaga (2004). Because recycled oceanic crust with possibly ultramafic cumulates is involved in the convection process, high $^3\text{He}/^4\text{He}$ ratios such as those found in the North Atlantic Igneous Province are expected.

Subducted slab material is suggested to have played a role in the scenario developed by Foulger and Anderson (2005) and Foulger et al. (2005) (Fig. 6D). Their model suggests that the Iapetus oceanic lithosphere was probably very young (~50 m.y.) at the time of subduction, and therefore buoyant, and that subduction was flat. Subducted oceanic crust might have been trapped within the continental lithosphere. Subsequently, a metamorphic transformation could have transformed the subducted material to eclogite (Foulger and Anderson, 2005). Upon extension of the lithosphere, the fertile material would have been tapped, and excessive melt production would be expected. The geochemical contents of igneous samples of the North Atlantic Igneous Province, including Iceland, are well predicted by this scenario. The melt volume produced at the latitude of Iceland, however, is such that more than one "normal thickness" of oceanic crust is required, and Foulger et al. (2005) suggest that imbrication would have provided the necessary amount of oceanic crust. In this model, the longevity of anomalous volcanism at the Mid-Atlantic Ridge at the latitude of Iceland is attributed to its location on a Caledonian suture, which could run transversely across the North Atlantic. The Mid-Atlantic Ridge near Iceland could have been migrating transversely over this structure since breakup time, which could explain the continuous production of large volumes of melt below Iceland and the shorter period of high melt generation at the volcanic margins of the North Atlantic Igneous Province. The model by Korenaga (2004) does not include a specific mechanism that explains the single short pulse of volcanism at the rifted margins of the North

Atlantic Igneous Province; it implicitly assumes that the crustal inventory was drained quickly, while it continued beneath Iceland. It does predict time-varying melt productivity, because the amount of oceanic crustal material embedded in the mantle matrix is likely to have varied.

A subducted slab is by nature inhomogeneous, because it includes altered N-MORB to ocean island basalts (OIB) and gabbros, depleted oceanic lithospheric mantle, and continental sediments. The model of Foulger et al. (2005) finds support in the inference of McKenzie et al. (2004) that correlations between isotope ratios and elemental concentrations point to the presence of subducted OIB of Caledonian age beneath Theistareykir, North Iceland. Similar to the model of Phipps Morgan and Morgan (1999), the enriched OIB-like components could have been heterogeneously distributed in the mantle by veins etc. in the underlying lherzolite. A separate geochemical mantle reservoir in the deeper mantle is no longer needed to explain OIB-like magmas from Iceland (McKenzie et al., 2004; Foulger et al., 2005).

These eclogite models offer alternative explanations for the genesis of ferrobasalts. These are difficult to explain using classical mantle models, in which they are considered to be the products of remelting of the thick Icelandic crust (Oskarsson et al., 1982). Yasuda et al. (1994) show that initial melts produced by small degrees of partial melting of an eclogite will have an andesitic composition. Basaltic andesites are reported from several initial North Atlantic Igneous Province magma series, e.g., the LS at the Vøring margin. Higher degrees of partial melting (10%–30%) will produce ferrobaltic melts (Ito and Kennedy, 1974), and 60%–80% melting is required to produce Icelandic melts (Foulger et al., 2005). In the present case, such high degrees of melting might have resulted after a long time, when the Caledonian slab was thermally relaxed and so was closer to its solidus (and perhaps even partially molten) than the surrounding lherzolite (Foulger et al., 2005).

Fertile mantle models could explain the chemistry of Iceland magmas and the longevity of the Iceland melt anomaly, although there is still much uncertainty about the ancient suture and subducted slab. Rifting-induced upwelling of fertile mantle material would explain the coexistence of rifting and magmatism in the North Atlantic. The models do not present a mechanism for prebreakup uplift (Fig. 5). The low seismic wavespeed anomaly beneath the Iceland region, in this scenario, would not have been caused by a mantle plume but instead would have resulted from plate tectonic-related processes such as compositional heterogeneity or a trace of partial melt due to the presence of excess volatiles (Foulger et al., 2001).

Small-Scale and Edge-Driven Convection

Many LIPs, including the North Atlantic Igneous Province, can be related to Archean craton boundaries and lithospheric discontinuities, according to King and Anderson (1995) and Anderson (2005). The edge-driven convection scenario (King and

Anderson, 1995, 1998; King, 2005) suggests that thick cratonic lithosphere adjacent to thinner or normal lithosphere may control edge-driven convection cells, which produce flood basalt province formations. This step in lithosphere thickness and corresponding variations in thermal structure would induce small-scale convection of mantle material and flow of previously unmelted mantle into the melting zone (Fig. 6C). Several numerical modeling studies suggest that such a step in lithosphere thickness indeed results in small-scale convection below the edge of the craton (King and Anderson, 1995, 1998) and in increased and focused upwelling (Pascal et al., 2002), and thus in decompression melting. When the melts are formed, a mechanism is required in order for the melts to reach the surface. A favored mechanism for this process is plate separation (King and Anderson, 1995); extension and faulting of the lithosphere will facilitate melt transport toward the surface.

King and Anderson (1995, 1998) find that the amount of upwelling and melting depends on the thickness contrast between the craton and normal or thinner lithosphere, the rate of plate separation, and the thermal structure of the mantle. Material may flow into the melt zone from large depths (>400 km; King, 2005). Detailed melt calculations are not incorporated in the models, and it is therefore not known to what extent the chemical signature of edge-induced melts would differ from or agree with mantle plume related melts. The models by King (2005) and King and Anderson (1995, 1998) do not consider vertical movements of the crust, so we do not know the pattern of uplift/subsidence that can be expected from this scenario. Other studies, however, suggest that uplift of the margins of the extended zone can be expected, which can be attributed to the effects of a thick cratonic lithosphere positioned next to hot asthenosphere below a rift (Våagnes and Amundsen, 1993; Kelemen and Holbrook, 1995).

The edge-driven convection scenario explains several North Atlantic Igneous Province characteristics well. It explains its location (close to the Baltica and Laurentian cratons), its elongated shape, and relation to the rift structure. It also provides a mechanism for generating more melt than is expected from passive rifting alone (White and McKenzie, 1989). It does not directly explain the short period of eruptions; this should be a lithospheric extension-controlled aspect. Also, the timing of volcanism (middle to late synrift) is extension-related and not a component of the edge-driven convection process alone. The scenario has problems explaining the continuous excessive melt production on Iceland.

Modeling experiments (van Wijk et al., 2001) suggest that excess igneous crustal thickness at rifted margins may result from active upwelling rates that are larger than the plate separation rates during breakup, so that more mantle material flows into the melting zone than in passive rift models such as that described, e.g., by Bown and White (1995). This may lead to the melting of large amounts of normal-temperature mantle around breakup time. Buoyancy-driven upwelling is inherent to the rifting process in this model, but is strongly influenced by how the

lithosphere deforms during rifting, which, in turn, is influenced by factors such as prerift lithosphere structure, rheology, thermal structure of the lithosphere and mantle, and extension rates (van Wijk et al., 2001, 2004; Corti et al., 2002). This rifting model predicts high eruption rates starting a short time before continental separation (middle to late synrift), with most of the melting taking place in a short period of time around breakup (Fig. 6B). The model does not incorporate the entire upper mantle, but is restricted to the lithosphere and a thin layer of asthenosphere material, so it is not known from what depth material might flow into the rift zone. Dependent on the inherited lithosphere architecture, dynamic uplift of the margin induced by small-scale convection may occur prior to breakup in this model (van Wijk et al., 2004). This rift-related, small-scale convection model has been designed to study the prebreakup history of Atlantic-type passive rifted margins and can thus not provide an explanation for North Atlantic Igneous Province postbreakup events or the continuous excessive melt production at Iceland. Application of this model to the North Atlantic Igneous Province, especially the mid-Norwegian Vøring margin, suggests that characteristic pre-separation features (extension, vertical movements, timing and duration of magmatism) are well explained by it (van Wijk et al., 2004), provided that (pre-)rift conditions were favorable.

Boutillier and Keen (1999) and Keen and Boutillier (2000) have found that upwelling of upper-mantle material by divergent plate motions is insufficient to explain the observed melt volumes and postbreakup oceanic crustal thickness of the North Atlantic Igneous Province. A thin (~50 km) Iceland plume sheet layer with a thermal anomaly of ~100 °C is needed in these models to generate large thicknesses of postbreakup igneous crust on the North Atlantic volcanic margins. In these models, small-scale convection continued below the margin edge for some time after breakup. This suggests that vertical motions of the margins could have been expected around breakup time. Because the plume sheet layer would soon have been depleted below the margins, Keen and Boutillier (2000) conclude that formation of the Greenland-Iceland and Iceland-Faeroe ridges requires a more deeply sourced thermal anomaly.

Nielsen and Hopper (2002) also use an upper-mantle convection model to study the interaction of a sublithospheric hot plume sheet with rift-driven flow. They specifically focus on how weak the mantle must be in order to induce small-scale convection and enhance melt production during breakup, while after breakup a stable system with realistic oceanic crustal thickness is established. Their models confirm that small-scale convection can occur during rifting and breakup. To produce thick oceanic crust, the model requires a thin layer of hot material underlying the lithosphere. The temperature anomalies associated with this layer are ~100–200 °C, and after breakup the layer must be quickly exhausted so that a steady-state oceanic spreading ridge system is established. The model by Nielsen and Hopper (2002) thus requires the passive influence of a mantle plume and spread of a plume head for rapid emplacement of

warm mantle material in lithospheric thin spots. However, the estimated melt volumes predicted in this study and in the studies of breakup-related magmatism by Boutillier and Keen (1999) assume that the LCBs represent magmatic material, an idea that is presently challenged.

Convection models agree on a possible increased melt volume around breakup in comparison with prior kinematic modeling studies. They disagree on whether fertile mantle, elevated (sublithospheric sheetlike, or ambient) mantle temperatures, large extension rates, or cratonic boundaries are necessary conditions for explaining the vertical movements and melt characteristics of the North Atlantic Igneous Province. They have focused on different aspects of the rift system and rift evolution, but are still being developed. We find that all models provide an explanation for North Atlantic Igneous Province volcanic margin evolution, but the continuous large melt production on Iceland is difficult to explain.

Mantle Plume

The mantle plume concept was first defined by Morgan (1971). In this concept, ~20 mantle plumes originating in the deep mantle bring warm material from the core-mantle boundary to the base of the lithosphere. Once arrived, mantle material flows radially away from the plume. Stresses thereby imposed on the base of the lithosphere will drive plate tectonics. Morgan (1971) related the British Igneous Province to the Iceland plume and suggested that breakup of the Atlantic could have been caused by the line-up of hotspots in this basin (Tristan, Azores, Iceland). He also recognized the regional high topography around each hotspot and suggested a relation with the upwelling material. In the decades following this proposal, the mantle plume concept has been refined and adapted frequently (for an overview see Courtillot et al., 2003; Anderson and Natland, 2005). It is beyond the scope of this article to discuss all adapted scenarios; we will limit ourselves to important adaptations for the North Atlantic Igneous Province (Fig. 6E).

Campbell and Griffiths (1990) and Griffiths and Campbell (1990, 1991), for example, determined the thermal anomaly associated with upwelling plumes, as well as the area affected by the arrival of a plume below the lithosphere. Their starting plume model requires thermal anomalies of $\sim 300 \pm 100$ °C at the source of the plume, the core-mantle boundary.

Plume head temperatures at the top of the mantle are then up to 250 °C. The plume head may have a diameter of up to 1200 km in the upper mantle, but when the plume head collapses on reaching the base of the lithosphere, it may spread out and affect an area 2000–2500 km across. The starting plume model also predicts vertical movements of the surface (Campbell, 2005). A maximum elevation of ~500–1000 m is predicted for a plume head with a temperature anomaly of ~100 °C. Uplift thus precedes volcanism. This uplift is expected to be followed by subsidence as the plume head spreads beneath the lithosphere. At the margins of the spreading plume head, uplift continues at

this time, and the pattern of uplift and subsidence might thus be quite complex. This is also predicted by numerical modeling experiments described by Burov and Guillou-Frottier (2005). They show that upon interaction with the lithosphere, the plume head may cause both small- and large-scale vertical movements of the surface, and uplift as well as subsidence. The resulting topography may be asymmetric and is influenced by lithosphere structure and rheology: a very thick and cold lithosphere will result in different topographic wavelengths from a warm, thin lithosphere.

An important aspect of the mantle plume concept is the mechanism by which the plume penetrates the lithosphere, or decompression melting actually reaches the surface. White and McKenzie (1989) proposed that this can be accomplished by the coincidence between lithosphere extension and thinning and plumes. In the North Atlantic, a period of lithosphere extension predated the arrival of the postulated Iceland plume. Griffiths and Campbell (1991) and Thoraval et al. (2006) suggest that small-scale instabilities that develop in plume heads might ease penetration. Turner et al. (1996) suggest that plume penetration is not a necessary mechanism, but that melting may occur by heating the lithosphere above a mantle plume instead of in the mantle plume itself. Other studies have shown that it is difficult to erode the lower lithosphere with a hot mantle plume (e.g., Ribe and Christensen, 1994; Moore et al., 1998, 1999; Jurine et al., 2005).

The plume concept also predicts a trail of volcanism that reflects the relative motions of the plume and the lithospheric plates. If a plume originates at the core-mantle boundary, it is assumed to have a fixed position with respect to the moving plates and to cause a volcanic trail at the surface of the Earth. Several studies have estimated the position of the Iceland proto-plume through time (e.g., Lawver and Müller, 1994; Torsvik et al., 2001). Details of the timing, location, structure, and composition of the postulated plume in the Early Paleogene, however, remain controversial. Lundin and Doré (2005) questioned the validity of the idea of pinpointing the suggested plume locality.

Another aspect of the mantle plume concept, of importance to the study of the North Atlantic Igneous Province, is stretching of the lithosphere above the plume. Vertical movements associated with plume impingement would place the lithosphere under stress, and zones of both compression and extension may result above the plume head (Burov and Guillou-Frottier, 2005). Whether this rift zone would be elongated, as in the North Atlantic, is not known.

Some descriptions of the plume concept (e.g., Morgan, 1971; Campbell and Griffiths, 1990; Griffiths and Campbell, 1990, 1991; Farnetani and Samuel, 2005) assume that the plume originates at the core-mantle boundary. Because of a clear head-tail structure, tomographic images are expected to show this structure, and some plumes can actually be traced to the deep mantle (Montelli et al., 2004), although there is debate on this finding (van der Hilst and de Hoop, 2005). The Iceland anomaly is not one of this group of deep plumes, which detracts from the plume concept as an explanation for North Atlantic Igneous

Province formation according to Foulger et al. (2005). Farnetani and Samuel (2005) recently calculated the wavespeed anomaly predicted from geodynamic models of thermochemical plumes. They found that a wide range of plume shapes and seismic wavespeed anomalies is possible: a plume head is not always found in their models, and the head-tail structure can be absent. The great variety of plume shapes and sizes translates into a large variety of predicted styles of tomographic image according to this study. The wavespeed anomaly below Iceland would be consistent with a deep-seated plume if such variations in plume shape and style are indeed possible. Some authors have suggested that upper-mantle plumes can be fed by lower-mantle upwellings (e.g., Goes et al., 1999). This would be an alternative explanation for the discontinuous anomaly beneath Iceland.

Material may flow away from the postulated mantle plume laterally over large distances according to the starting plume model of Sleep (1996, 1997) (Fig. 6E). This model proposes that plume material flows underneath the lithosphere and prefers to follow thin spots. Thin spots are formed, for example, by rifting of the lithosphere that might leave relief on its underside (Thompson and Gibson, 1991). This model could provide a mechanism for geological effects of plumes far beyond the location of impingement, and it is proposed as a possible explanation for the huge area affected by North Atlantic Igneous Province volcanism following the rift zones in the North Atlantic. This scenario is poorly supported, though, by the data reported by Doré and Lundin (2005). These authors find, for example, that the LCB has not filled preexisting thin spots in the crust, but terminates abruptly against margin-perpendicular lineaments.

The geochemistry of the North Atlantic Igneous Province is consistent with the plume concept, and to a large extent with the two-stage model presented by Saunders et al. (1997). We refer to their study for an overview of present views of the genesis of the North Atlantic Igneous Province from the plume point of view. The plume scenario further explains uplift history, the upper mantle tomographic results and the distribution and timing of melting. Lack of a time-progressive volcanic track in the Iceland region is a scenario that is not supported by observations, and there is also debate about the continuation of the upper-mantle low seismic wavespeed anomaly into the lower mantle. Furthermore, it is important to stress that recent studies suggest that the mantle plume scenario for North Atlantic Igneous Province formation cannot be tested (e.g., Foulger et al., 2005). This is because many of the adaptations that mantle plume models have undergone in the past decades seem designed specifically to achieve a better fit with observations of the North Atlantic Igneous Province (Foulger, 2005). As a result, the concept cannot be disproved.

EXPLORING ALTERNATIVES

Are the alternative (i.e., non-mantle-plume) models that are at hand today able to explain the different aspects of North At-

lantic Igneous Province formation? Delamination and impact models do not appear to be good candidates to explain this LIP, and must at this stage be rejected. The small-scale convection and dynamic rift models do not address the ongoing melt production on Iceland, and therefore need to be combined with other hypotheses. This role could be filled by a mantle plume that has had limited influence in creating the volcanic margins but has facilitated continuing excessive melting on Iceland. Alternatively, a mantle heterogeneity resulting from plate tectonic processes could have acted as a source of continuing igneous activity.

Some studies argue that alternative, nonplume explanations for the chemical signal of the North Atlantic Igneous Province melts may be valid. The geochemical model for the Earth's mantle that has prevailed over the past thirty years (e.g., Morgan, 1971; Hofmann, 1988) involves an enriched deep mantle reservoir (the OIB source) overlain by an undepleted lower primordial mantle on top of which lies the depleted upper mantle reservoir (the MORB source). These chemically isolated reservoirs are genetically connected through the early evolution of the Earth. During melt extraction to form the incompatible element-rich continental crust, the upper mantle was depleted in these elements compared to the primordial mantle (e.g., Hofmann, 1988). In earlier models, the mantle was of only lherzolite composition (harzburgite as a restite of MORB), but studies of mantle peridotites on surface outcrops have pointed to a basalt-pyroxenite-veined harzburgite-lherzolite rock as the major mantle component (Polvé and Allègre, 1980; Suen and Frey, 1987). For the last two decades, several varieties of the alternative "plum-pudding" or "marble-cake" mantle model have been suggested (e.g., Davies, 1981; Zindler et al., 1984; Allègre and Turcotte, 1986; Allègre and Lewin, 1995; Phipps Morgan and Morgan, 1999; Kellogg et al., 2002; Meibom and Anderson, 2004; Albarède, 2005). These models suggest that a high degree of chemical and isotopic heterogeneity characterizes many regions of the mantle. The mantle is, in these models, a heterogeneous assemblage of depleted residues and enriched, recycled subducted oceanic crust, lithosphere, and sediments. Primordial material may still be present in the mantle in small, strongly sheared, and refolded domains (Albarède, 2005). The models differ in various aspects, including whether separate mantle reservoirs exist (the upper and lower mantle).

Phipps Morgan and Morgan (1999) proposed that the mantle contains pyroxenite veins on scales of 1 m to 10 km that span the entire global isotopic range of Nd, Pb, and Os data in erupted OIB and MORB. They concluded that it is possible to produce enriched OIB-like melts in the upper mantle provided the source has enough embedded veins. However, in such a veined (enriched) mantle, the melting of a depleted MORB is much more problematic. MORB-like magmas can be generated from such a mantle only after a prior melting process that produced OIB melts. This primary melting phase has to subtract vein components from the source and deplete the mantle (Phipps Morgan and Morgan, 1999). The North Atlantic Igneous Province offers

the opportunity to test competing chemical mantle models, because it is an area where the mantle source contributed not only to flood magmatism (often considered to be related to mantle plumes) but also to magmatism associated with continental breakup.

Most of the Paleogene magmas erupted in the North Atlantic Igneous Province have been interpreted on the basis of the classical layered mantle or the isolated reservoirs mantle model. The chemical signatures result either from a plume mantle source or from the N-MORB mantle reservoir at the outer envelope of the postulated plume (Fig. 3A) (e.g., Saunders et al., 1997). A diffuse chemical "bipolar" trend can be seen in most of the sub-areas of the North Atlantic Igneous Province (Fig. 3A and B). In the British Igneous Province, the proportion of melts with an "Icelandic" chemical fingerprint increases with time at the base, then later reverts to lavas with N-MORB chemistry (e.g., Hamilton et al., 1998; Kent and Fitton, 2000).

Other petrological and geochemical data commonly attributed to a mantle plume during the formation of the North Atlantic Igneous Province are the picritic, high-Mg magmas (Gill et al., 1992; Larsen and Pedersen, 2000; Upton et al., 2002). Most of the picritic magmas can be associated with continental breakup and with the opening of the Labrador Sea and the North Atlantic at Greenland, Scotland, and Baffin Island. The eruption of large volumes of picrite in West Greenland has generally been related to an abnormally hot local mantle. A problem with this interpretation is that such a huge volume (30–50 vol%) of picrites erupted nowhere else in the North Atlantic Igneous Province. The "doughnut" shape of the Griffiths and Campbell (1990) model well explains the peripheral eruption of the North Atlantic Igneous Province. However, the model predicts that the high-temperature magmas can be produced only by the 150-km-wide hot central plume jet, which is not in agreement with the fixed plume position (Gill et al., 1992). Different explanations have been proposed for the huge amount of picrites, such as a separate, short-lived "Davis Strait plume" (McKenzie and Bickle, 1988). However, why such a hotter plume should be short-lived has not been explained to date. The actual Iceland mantle anomaly provides little support for such plumelike temperatures (Foulger and Anderson, 2005).

A plausible alternative explanation for the formation of the picrites in Greenland and in other North Atlantic Igneous Province regions was suggested by Fram et al. (1998). They proposed that the high Mg content of the magmas reflected their generation at moderately high average pressure as a result of the thick lithosphere at that time. This, combined with the clear evidence for olivine accumulation in some West Greenland high-MgO magmas, weakens the case for the two-stage plume pulse model of Saunders et al. (1997). However, the Fram et al. (1998) interpretation cannot rule out the Saunders et al. (1997) model. The accumulation of olivine in the source points to a possible scenario recently published by Foulger et al. (2005) to explain the geochemistry and large melt volumes in the Iceland region. These authors point out that the expected radial symmetry of

geochemical signatures predicted for a plume (e.g., Schilling et al., 1983) is not observed in Iceland. Geochemical discontinuities occur in Iceland across relatively minor structures, and the melting temperatures of the most primitive Icelandic melts are calculated to be similar to MORB formation temperatures (Breddam, 2002).

Major geochemical problems in relating LIPs to postulated mantle plumes are the identification and quantitative estimation of the contribution of crustal and lithospheric sources to the magmatism. However, such studies are essential for us to ultimately understand which of the geochemical variations observed in basalts reflect the expected intrinsic variations of deep-mantle sources. Cautious isotopic studies (see Fig. 3A) showed that for most classical isotopic systems (Rb, Sr, Pb) the differences between mixing lines of depleted MORB source with enriched mantle reservoirs and mixing lines between mantle sources with continental crust signatures are not visible. For North Atlantic Igneous Province magmas, this is even more important, because many lavas erupted through continental crust and show contamination by the crust (Fig. 3A). The OIB paradox (Fitton, this volume) illustrates the problem of distinguishing subcontinental and/or continental sources for OIB magmas using standard geochemical systems and models.

Recently the geochemistry of helium has been assumed to reflect evidence for mantle plumes. Helium has two isotopes: ^3He , a primordial isotope incorporated in the Earth during planetary accretion, and ^4He , an isotope largely produced by radioactive decay of U and Th isotopes. Basalts related to postulated mantle plumes have high $^3\text{He}/^4\text{He}$ ratios compared to MORB. This observation is assumed to be an explicit indicator of a primitive, undegassed lower-mantle source component with a high ^3He content. However, deep-mantle sources are not the only possible explanation for high $^3\text{He}/^4\text{He}$ ratios (Meibom et al., 2003). He concentrations in rocks believed to reflect deep mantle sources should be higher compared to melts from the depleted MORB mantle. However, the He content in OIB is often two to three orders of magnitude lower than in MORB (Foulger et al., 2005). A key process in He geochemistry is oceanic crust formation, because the incompatible mother isotopes of ^4He (U and Th) are extracted from the source mantle (e.g., Albarède, 1998; Anderson, 1998). Thus, ultramafic cumulates are possibly low-U + Th sources. Ultramafic cumulates could be part of the inhomogeneous mantle source proposed by Phipps Morgan and Morgan (1999) and might provide high He ratios to North Atlantic Igneous Province erupted basalts. The extreme He data of Stuart et al. (2003) from East Greenland picrites confirms this scenario, because rocks with the highest MgO content have the highest He ratios.

Can the volume and timing of magmatic activity be explained by alternative models? Both the volume and timing (middle to late synrift) observed along the North Atlantic Igneous Province volcanic margins can be explained by dynamic rift-related processes (King and Anderson, 1995, 1998; van Wijk et al., 2001). Mantle heterogeneities resulting from plate tec-

tonic processes (Korenaga, 2004; Foulger and Anderson, 2005; Foulger et al., 2005) have been proposed to account for the ongoing excessive melt production at the Mid-Atlantic, Reykjanes, and Kolbeinsey ridges and Iceland, but there are still uncertainties concerning the location of the proposed ancient suture zone and old slab distribution. Uplift of the surface might be explainable by dynamic rift processes as well, but more work is needed to investigate that issue. The low seismic velocity anomaly in the upper mantle beneath the Iceland region has been suggested to result from plate tectonic processes (Foulger et al., 2001), but further investigation of this issue, too, is required to build a convincing case.

CONCLUSION

The mantle plume concept is currently most successful in explaining the formation of the North Atlantic Igneous Province. However, it has been suggested that this is largely due to the adaptations that have been made to the site-specific model over the years to better explain observations of the province. There are unexplained aspects of the concept that remain to be addressed, while alternative models also need to be further matured.

Alternative models (e.g., rift-related small-scale convection) are being developed that appear to be able to explain volcanic rifted margin volcanism well. However, the most important problem that nonplume models need to overcome is the continuing, long-lived melt anomaly extending from the Greenland and Faeroe ridges to Iceland. Mantle heterogeneities resulting from ancient subducted slabs are invoked in plate tectonic models to explain the continuing melt production, but further proof of this is required.

Existing data sets and geodynamic concepts are incomplete, which hinders a more conclusive statement on whether the mantle plume or alternative models can be accepted or rejected. For example, (1) the lateral distribution of magmatic material is poorly known, and there is still debate regarding the composition of the LCB; (2) there is uncertainty regarding several characteristics of the melts, such as the source temperatures for the picritic melts; and (3) the degree of homogeneity of the mantle is controversial. Ongoing development of the different models and the availability of increasingly more reliable data should help to resolve the problem of the challenged mantle plume concept in the near future.

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DISCUSSION

31 January 2007, Laurent Geoffroy

Any effort to summarize the available data from the north Atlantic igneous province is welcome, and we should thank Meyer et al. (this volume) for their valuable contribution. However, I would like to make the following comments, the first on a minor aspect and the second concerning a much more general point.

The South-East Baffin Controversy. Meyer et al. (this volume) refer to the argument concerning the existence of an onshore exposed seaward dipping reflector (SDR) along the west Green-

land margin north of ~70°N (Chalmers et al., 1999). I do not think that this is a matter of debate any longer. Geoffroy et al. (1998, 2001) were correct in recognizing that the Disko-Svartenhuk west Greenland coastal area exposes a thick fan-shaped inner prism of syntectonic seaward-dipping basalts and tuffs that essentially forms an upper crustal structure typical of volcanic passive margins worldwide. The recent confirmation of an SDR located on the conjugate margin offshore from Baffin Island fully supports the view that the south Baffin Bay margins are of volcanic type (Skaarup et al., 2006). However, Chalmers et al. (1999) rightly point out the geodynamic importance of the Ungava transform

splay faults in the tectonic structure of the Disko and Nuussuaq areas. The west Greenland controversy was compounded by a general misunderstanding about the tectonic setting of SDR wedges across volcanic margins. According to Chalmers et al. (1999), if we consider the west Greenland coastal flexure to be an SDR, this implies a transition to the oceanic crustal domain across the coastline (conflicting with hopes for the petroleum potential of this area). This ignores the fact that, at volcanic margins, the innermost SDR prisms are often continental, as suggested by Roberts et al. (1979) and confirmed in later studies (e.g., Tard et al., 1991). One can truly consider the west Greenland volcanic margin at the latitude of Ubekendt-Ejland and Svartenhuk (Geoffroy et al., 2001, Plate 3) as representing the most suitable place to study in detail the development of a partly eroded continental inner-SDR and the relationships linking the pre-breakup and breakup-related volcanic formations with pre-existing sedimentary basins. More generally, in discussing this aspect, we might add that there is little point in interpreting offshore geology at margins without a detailed examination of adjacent onshore data. By the same token, offshore observations (when available) are just as crucial for interpreting onland geology.

Distribution and Timing of the North Atlantic Large Igneous Province Volcanism. The authors proposed that the distribution of large igneous province (LIP)-related magmatism in the North Atlantic (their Fig. 1) is somewhat surprising compared to former views, suggesting a much wider geographical extent (see, for example, Fig. 8 in White and McKenzie, 1989). Could they specify the range of data used for this otherwise quite useful compilation? Did they take into account the extensively sill-intruded basins that are fully part of the LIP? This is not merely a point of detail because the authors' diagram appears to confine most of the magmatism to the breakup area, in good agreement with the mantle-melting model developed by Van Wijk et al. (2001). This distribution is also discussed in the text, where the authors state that the "Paleocene magmatism is middle or late syn-rift." From this, we can understand that they are referring to previous Cretaceous rifting in the North Atlantic (their Fig. 2). According to such a presentation of the data, magmatic activity would be a direct and natural consequence of a late-stage stretching of the lithosphere. This would be surprising because, apart from the breakup zones where Eocene SDR are developed, very little extension took place during the emplacement of most of the North Atlantic Paleocene-related extrusives. These formations are mainly associated with horizontal dilatation caused by dike injection and thus have no relation to tectonic stretching and thinning. In many cases, traps at LIPs can be seen to seal former sedimentary rifts and basins. For example, this is exactly the pattern observed in the Afar area, where the Ethiopian and Yemen traps form thick horizontal piles over wide areas, lying directly on top of the basement or capping the older Mesozoic rifts. I do not think that we can so easily discount such a robust and generalized observation.

Whatever the mantle-melting mechanism (and mantle plumes are certainly not the only possible explanation, as the au-

thors rightly state), we still need to explain why a major and sudden pulse of magmatism occurred simultaneously over such a wide area. At the same time, this magmatism is coeval with a stress pattern that is unrelated to the regime acting during premagmatic Mesozoic tectonic events (Geoffroy et al., this volume). This type of scenario strongly resembles a major dynamic plate-scale perturbation of a metastable system, i.e., the buoyant mantle located beneath the rigid and heterogeneous lithosphere.

1 February 2007, Stephen Jones

Postbreakup Magmatism: Iceland and the Oceanic Part of the North Atlantic Igneous Province. Several authors have pointed out that the geometry of the V-shaped ridges might be explained by passive upwelling of a thermal halo surrounding Iceland and containing outward-dipping thermal/compositional anomalies instead of by lateral advection of thermal/compositional anomalies within a plume head (Jones et al., 2002a; Vogt and Jung, 2005). Previously, the main difficulty in deciding between the lateral and vertical transport models was a lack of seismic images with sufficient vertical resolution to distinguish a slow sublithospheric plume head layer about 100 km thick from a slow thermal halo filling the entire upper mantle (Jones et al., 2002a). The situation is now improving. Pilidou et al. (2005) presented a Rayleigh wave tomography model that resolves a regional sublithospheric slow layer whose base lies at a depth of less than 300 km. The balance of the seismic evidence now appears to favor the lateral outflow model.

Lithospheric Delamination. Constraints on the degree of lithospheric delamination and regional uplift are available for the British igneous province. The top of the melting region that supplied the British igneous province has been estimated at about 70 km from modeling of rare earth element distributions (Brodie and White, 1995; White and McKenzie, 1995). The British igneous province was emplaced within the Sea of the Hebrides Trough, which formed by modest rifting (total strain less than 2) in the Jurassic, and no significant rifting occurred coeval with British igneous province emplacement (Emeleus and Bell, 2005). Lithospheric thinning to 70 km is not easily attributed to mild Jurassic rifting, making it more likely that some lithospheric erosion was associated with the mantle circulation that led to British igneous province emplacement during the Middle Paleocene. Field observations show that uplift of the British igneous province itself occurred before and during emplacement, and some of this uplift could be related to lithospheric erosion. However, uplift histories interpreted from sedimentary basins surrounding the British igneous province show relatively little regional uplift coeval with British igneous province emplacement. Instead, most of the regional uplift (up to 1 km) occurred after British igneous province activity, peaking close to the Paleocene-Eocene boundary and Europe-Greenland breakup time (a summary and references can be found in MacLennan and Jones, 2006; Saunders et al., 2007). Thus, in the case of the British igneous province, it is likely that

some delamination did occur, but it was not directly associated with major uplift outside the province itself.

Fertile Mantle. The authors point out that models involving fertile mantle and no thermal anomaly cannot explain pre-breakup uplift. An equally important problem is that such models cannot explain the present-day north Atlantic bathymetric swell, which has a diameter of around 2000 km and a central amplitude of 2 km (excluding the contribution of unusually thick crust; Jones et al., 2002b; Conrad et al., 2004). The topographic swell also correlates with a positive free-air gravity anomaly. It has long been recognized that such broad swells with correlated gravity anomalies must be supported by low-density material within the mantle (e.g., Anderson et al., 1973). Even the more skeptical workers agree that it is difficult to explain the 2000-km topographic swell without a thermal anomaly of up to about 100 °C (Foulger and Anderson, 2005).

Small-Scale and Edge-Driven Convection. The conclusion that small-scale convection by itself cannot explain the north Atlantic igneous province is supported by the regional uplift history. Although the uplifted swell that developed close to the Paleocene-Eocene boundary is not well constrained over its entire area, data from the well-explored basins around the British Isles clearly show that uplift of 100 m to 1 km occurred at a distance of 1000 km from the Europe-Greenland breakup zone (Maclennan and Jones, 2006). Such regional uplift is not easily explained by small-scale convection centered on the breakup zone.

Mantle Plume. It is true that mantle plume models applied to the north Atlantic igneous province differ in many details. However, one common proposal is that a large amount of hot mantle was convectively emplaced beneath the entire north Atlantic igneous province during the Middle Paleocene. The hot asthenosphere first generated the British and West Greenland igneous provinces and then remained beneath the area to generate the Europe-Greenland volcanic margins (Larsen and Saunders, 1998). This model implies major regional uplift at or before the Middle Paleocene and persisting until the Early Eocene. The well-resolved uplift history surrounding shows that the model cannot be correct because major regional uplift (up to 1–2 km over a diameter comparable to the north Atlantic igneous province) is not observed until the Late Paleocene, after emplacement of both the British and Greenland provinces (Maclennan and Jones, 2006; Saunders et al., 2007). It is very difficult to explain both the igneous and the sedimentary record of uplift by a single plume head impact. Whatever model for the north Atlantic igneous province is accepted in future, it must explain both the igneous record and the record of uplift. My view is that it will be very difficult to do so without advection of hot mantle beneath the lithosphere.

6 February 2007, Romain Meyer, Jolante van Wijk, and Laurent Gernigon

We thank Geoffroy and Jones for their constructive comments on our chapter. The comments confirm the conclusion of the re-

view, i.e., “existing datasets and geodynamic concepts are incomplete, which hinders a more conclusive statement on whether or not the mantle plume or alternative models can be accepted or rejected.” The second comment from Geoffroy concerns the distribution and timing of north Atlantic igneous province magmatism, (Fig. 1 in Meyer et al., this volume). We initially chose a conservative approach while constructing this figure (map of the north Atlantic igneous province with distribution of volcanism) and used only published, strongly founded data for its compilation. Following an e-mail discussion with Geoffroy, we decided to modify the map; in some areas, the volcanic rocks are likely more extensive than our initial map suggested. Note that the boundaries for the localities of the Rockall, Faeroes, and Baffin magmatism are still uncertain.

In our chapter we have related north Atlantic igneous province magmatism to the timing of the pre-breakup rift phase (Fig. 2 in Meyer et al., this volume). By doing so we did, however, not intend to relate all magmatism to the process of rifting, and we agree with Geoffroy that such a relation is far from well constrained. The origin of such magmatic formations away from the breakup zone (as in the UK–Rockall area) is not discussed in detail in our chapter; we refer to Geoffroy et al. (this volume) for a discussion on and possible explanation for this phenomenon.

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