North Atlantic Igneous Province: A Review of Models for its Formation

Romain Meyer
K.U. Leuven, Afd. Geologie, Celestijnenlaan 200E, 3001 Leuven-Heverlee, Belgium
romain.meyer@geo.kuleuven.be

Jolante van Wijk
Los Alamos National Laboratory, Earth and Environmental Sciences Division, Los Alamos, NM
87545, USA
jolante@lanl.gov

Laurent Gernigon
NGU, Geological Survey of Norway, leiv Erikssons vei 39, 7491 Trondheim, Norway,
Laurent.Gernigon@ngu.no

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 datasets 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 formation of the NAIP, 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 non-plume models need to overcome is the continuing, long-lived melt anomaly extending via the Greenland-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.

1. Introduction: challenging the mantle plume concept

Continental breakup at the Paleocene-Eocene transition marked the culmination of a ~350 My 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 breakup time. The magmatic events prior to and during continental separation, and the post-breakup continuous activity of the Iceland melting anomaly, have resulted in one of the largest Large Igneous Provinces (LIP) in the world: the North Atlantic Igneous Province (NAIP). The NAIP was long ago recognized by the significant regional onshore distribution of volcanic features including flood basalt traps and mafic and ultramafic complexes (Hutton, 1785). During the last 40 years, numerous seismic studies and commercial/scientific drilling have shown that this magmatic province also extends offshore. It is well developed along the Kolbeinsey and Reykjanes spreading ridges that are still anomalously productive, and the breakup axis of the NE Atlantic, that 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-dimensional picture of the mantle below the NAIP has emerged. The low-seismic-velocity anomaly beneath parts of the NAIP is now generally thought to be linked to its formation.

As a result of intense scientific and economic interest, the NAIP is the most thoroughly documented LIP 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 NAIP 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-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 onshore and offshore, may represent ~$1.3x10^6$ km^2 with a volume of ~$1.8x10^6$ km^3. Including magmatic underplating and other intrusions, it could reach $5x10^6$ to $1x10^7$ km^3 (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 NAIP 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 absence of a distinct lower mantle continuation of the upper-mantle seismic-wave-speed anomaly are arguments against the plume model as an explanation for NAIP formation (e.g. Foulger, 2005). Not only is a mantle plume source for NAIP formation challenged, the 'plume concept' self is topic of debate as well. We refer for a discussion on this aspect to Anderson and Natland (2005) and Foulger (2005).

Following Morgan (1971), most workers have explained the Early Paleogene volcanism of the NAIP 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 NAIP formation have been formulated over the last 10 years or so. These include moderately elevated mantle temperatures, fertile patches in the upper mantle, and small-scale convection (e.g., Boutillier and Keen, 1999; King and Anderson, 1995; 1998; van Wijk et al., 2001; Korenaga, 2004; Anderson and Natland, 2005; Foulger et al., 2005; Foulger and Anderson 2005; Lundin and Doré, 2005; http://www.mantleplumes.org).

The objective of this review paper is to test existing geodynamic models for NAIP 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 to test these model predictions. We summarize the datasets in the next sections. We then discuss the characteristic predictions of the main models for NAIP formation, and compare model predictions with observations. We conclude our study by exploring an alternative, non-mantle-plume model to explain NAIP formation.

2. Geological, geochemical and geophysical observations

2.1 Rifting episodes

The NE 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, northern UK, and in Norway (Séranne and Séguret, 1987; Strachan, 1994) as early as Devonian times. It continued with widespread Permo-Triassic rifting in Greenland, Norway, offshore UK, offshore 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 Greenland, the southwestern Olso

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 offshore mid-Norway (Blystad et al., 1995; Dancer et al., 1999; Koch and Heum, 1995; 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 period of broad uplift, and a non-breakup related magmatic event (Fig. 2). The Late Jurassic period is usually defined as a major rifting episode, which 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. This event possibly extends north to the Møre Basin and the Haltenbanken, offshore Norway (Koch and Heum, 1995), and 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 NE-SW oriented rift axis stretching from South Rockall to Lofoten in Norway and to the Barents Sea. At the same time, a NW-SE oriented rift develops from the Iberia-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 non-breakup magmatic event of Lower to Upper Cretaceous ages is documented in the Hopedale Basin and Svalbard areas, related to a period of uplift. This magmatic event is defined as an independent LIP (the so-called Cretaceous High Arctic Large Igneous Province) (Maher, 2000) (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 starts around Early Campanian time but is not necessarily synchronous 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 sea-floor spreading in the Labrador Sea started already at chron 33 in Late Cretaceous (Roest and Sirastava, 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, ~53 Ma). After breakup, early seafloor spreading immediately northeast of Iceland first occurred along the now extinct Aegir Ridge until anomaly C13, Mosar et al. (2002), or maybe longer, to 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.

2.2 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 break-up phase. The volcanic sequence is divided into an upper and lower series (US & LS). The US includes the Seaward Dipping Reflector Sequences (SDRS), interpreted as tilted subaerial and transitional-type tholeiitic MORB lava flows, with interbedded volcaniclastic sediments (Eldholm et al., 1987). The LS comprises a sequence of intermediate extrusive flow units and volcaniclastic sediments, erupted prior to the onset of MORB-type magmatism and derived, at least partially, from continental source material. A similar lithology, of an US basaltic SDRS and underlying LS of strongly crustally contaminated units has been sampled at the SE Greenland margin (ODP Leg 152, 1993, and Leg 163, 1995) (Saunders, et al. 1999; Larsen et al., 1999).

Available geochemical data for SE Greenland and the Vøring Plateau show that the Vøring Plateau US and the SE Greenland US are chemically and isotopically rather similar. The LS from both areas do not only differ from the corresponding US, but they are also fundamentally different from each other in many respects (e.g. LS SE Greenland $^{87}Sr/^{86}Sr < 0.702$ and the LS Vøring Plateau $^{87}Sr/^{86}Sr > 0.710$) (Meyer et al., 2005). The marked difference in the geochemical signatures of the SE Greenland and Vøring Plateau samples points to a substantial difference in either the pre-breakup crustal composition at the two localities, or to different styles of mantle-crust interaction.

West Greenland and Baffin Island

Igneous rocks are recorded from from Disko to Svartenhuk onshore 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 mid-Paleocene time in a subsiding marine environment, so that the earliest volcanic rocks are hyaloclastite breccias. After a significant Early Paleocene uplift, later volcanism was almost entirely sub-aerial (Dam et al., 1998). The volcanic rocks are divided into three formations (Gill et al., 1992): the lower formation mainly consists 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 ignembrites.

An extraordinary characteristic of the West Greenland and Baffin Island lavas in the NAIP is the high ratio of picrites to basalts of the erupted volumes (30 – 50 Vol.% compared to e.g. 15 Vol.% in E Greenland, Nielsen et al., 1981) (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) range between 15 to 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, 1978)? 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 British Paleogene Igneous Province (BIP) into M2 magmas with slight light-REE enrichment ($(La/Sm)_N$ of 1-1.2; Robillard et al., 1992) and M3 magmas ($(La/Sm)_N$ of 0.6-0.7; Robillard et al., 1992) (Fig. 3b). Most picrites have a radiogenic isotopic geochemistry ($\varepsilon Nd_{t=60} > +3.4$ and $^{86}Sr/^{87}Sr_{(Pd)} > 0.7031$; Holm et al., 1993) similar to the present-day Atlantic MORB and/or 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 SE Greenland margin is characterized by a well-developed package of SDRS in a wide zone across the shelf and in the adjacent offshore region. ODP Legs 152 and 163 drilling transects show that SDRS 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., 1988; Duncan et al., 1996). Site 917 penetrated basalts and dacites of Late Paleocene age (~61 Ma). These LS magmas represent the pre-breakup lava flows. The parent magmas evolved by assimilation-fractional crystallisation 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 N-MORB basalts with a few “Icelandic” basalt flows erupted during the pre-breakup phase, but the source of the post-breakup magmas was clearly an “Icelandic” mantle.

Offshore UK and British Igneous Province

The geochemistry and the mantle source of the British Igneous Province (BIP) has been discussed in several publications (e.g. Thompson et al., 1982, Kent and Fitton, 2000). The composition of the onshore, and to a lesser extent, offshore Scottish basalts is relatively well known. Geochemical studies defined three Paleogene successive magma types: M1-M3 (Kerr 1995; Kent and Fitton, 2000). A volumetrically insignificant fourth magma type (M4) is preserved as dykes and plugs. M1 and M2 are characterized by major element geochemistry similar to transitional alkali basalts, where 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 slightly light-REE enriched pattern (LREE) while the M2 (moderate Ce/Y) magmas have rather flat REE pattern (around 20 x chondritic), and the M3 (low Ce/Y) M3 magmas have a pattern similar to 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 again to an N-MORB source. Isotopic geochemistry of most BIP rocks confirms strong mantle-melt/crustal interaction 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 its distinctive isotopic signature (e.g. Geldmacher et al., 2002; Troll et al., 2004). Dickin (1981) even suggested that the Pb isotopic system provides no information in the BIP over the mantle source but mainly on the nature of the contaminating continental crust. Such crustal geochemical continental contamination/assimilation trends can be seen in all the subareas of the NAIP. Only after the deduction of these – sometimes still unknown – mantle/crust interaction processes, can precise information on possible mantle plume influences be deduced.

The NE-Irish basalts of the BIP 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 which 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.

The 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 being silica-oversaturated and being 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 formation. A mantle source change occurs at this transition; while the lower and middle formation tholeiites are entirely 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 non-volcanic margin to the SE and a Late Paleocene-Early Eocene volcanic margin to the NW which forms the southern edge of the NAIP, see Fig. 1 (Barton and White, 1995; 1997). The West Hatton volcanic margin exhibits a typical volcano-stratigraphic sequence similar to 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 centres, clearly characterized by a circular shaped gravity anomaly (e.g., Hitchen; 2004; Geoffroy et al., this volume). They were drilled recently 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.

Offshore volcanism at 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, 2000) (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 northwards beneath the Arctic Ocean. This Ridge is volcanic and partly of Cretaceous age with an alkaline rock sample dated using the Ar-Ar technique 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 have typical ages around 144 ± 5 Ma, and younger olivine-dolerites 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 Russian Barents Sea. Preliminary age data indicate that these widely distributed outcrops are part of the same event, but the data are not sufficiently precise to determine whether the occurrences are truly contemporaneous, or whether there is any systematic age progression from the Arctic region to the NAIP.

2.3 Post-breakup magmatism: Iceland and the oceanic part of NAIP

The seismic crust beneath Iceland reaches a thickness of 38 to 40 km in some places. Part of 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 (Smallwood et al., 1999; Richardson et al., 1998). Iceland is composed mainly of tholeitic basalts with smaller amounts of alkali basalts, rhyolites and obsidians. It is widely known, that the $^{87}Sr/^{86}Sr$ isotope data for Iceland (and the Reykjanes Ridge) are significantly higher than those of N-MORB (e.g. O'Nions and Pankhurst, 1974). The geochemical signature of Icelandic igneous rocks is characterized by high $^{3}He/^{4}He$ ratios relative to the atmospheric ratio Ra. The highest non-cosmogenic $^{3}He/^{4}He$ isotope ratios of ca. 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 above-described Paleogene successions (Fig. 3a, 3b), indicate that the upper mantle in most of the NE Atlantic has the same chemical characteristics as the current Iceland source (Saunders et al. 1997). The isotopic data of the whole NAIP show that most of the breakup igneous rocks and the Iceland magmas are derived from an enriched mantle source and not from a depleted mantle (e.g. N Atlantic MORB). The fact that such enriched magmas are limited with some exceptions, as Iceland, to the breakup time, strongly supports that the mantle source below the NAIP was heterogeneous. After the breakup magmatism, this source was depleted, and is producing now the typical N Atlantic MORB.

The oceanic crust formed at Kolbeinsey Ridge (Fig. 1) north of Iceland is 1–2.5 km thicker than normal oceanic crust (Kodaira et al., 1998). The crust is up to 10 km thick at the Reykjanes 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 in its northern part a rift valley. 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 (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; Jones et al., 2002). Alternatively, passive upper mantle heterogeneities could play a role in formation of the V-shaped structures (Vogt and Jung, 2005).

2.4 Magmatism: age-overview

The NAIP shows a wide range of magmatic ages of Paleogene volcanic rocks (Fig. 4). We used for this overview the compilation of geochronological NAIP data by Torsvik et al. (2001), and included data from Iceland (Moorbath et al., 1968; Ross and Mussett, 1976; Hardarson et al., 1997; Foulger, 2006). This compilation is a selection from the most reliable available data (Torsvik et al., 2001). 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 this lower series magmas are believed to be much younger, 56 to 55 Ma (Sinton et al., 1998). However, we note that there is currently debate on the reliability even of part of this dataset (Baksi, 2005, and this volume). The uncertainty in age determination in combination with logistical limitations has left a large part of the NAIP region unsampled or undersampled.

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

2.5 Volume of magmatism

Igneous rocks emplaced during the breakup event comprise three main units: (1) voluminous extrusive complexes, including the SDRS, (2) thick initial oceanic/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 SDRS, 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 ~12 - 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 ocean crust thickness (e.g., Skogseid and Eldholm, 1995). Packages of SDRS 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 LCB (e.g., Raum, 2000) and SDRS (e.g., Planke et al., 2000).

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

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

The thickness of the LCB 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 pre-existing high-velocity rocks such as eclogites or migmatites. Ebbing et al. (2006) proposed that the LCB could be remnants of the Caledonian root.

The non-magmatic hypothesis has significant implications. A non-magmatic interpretation of the LCB would lower the estimated NAIP melt volumes (Eldholm and Grue, 1994) significantly. This, in turn, would affect most conventional models for NAIP formation that 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 large oceanic crustal thickness there (Greenland-Iceland-Faeroe Ridges). 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 section 2.3).

2.6 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 into 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 wave speeds 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. Several plumes have been claimed to 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).

2.7 Uplift history of the margins

It is generally accepted that the NAIP experienced uplift and exhumation during Early Paleogene time, but a regional picture of these vertical movements and their amplitudes is far from being well constrained. The currently available information is summarized below and a regional overview of well-constrained Paleocene-Eocene uplifted areas in the North Atlantic domain is shown in Fig. 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 has affected the North Atlantic (Fig. 2). Locations of domes include southern and northern Norway, northern UK, Svalbard and Finnmark (e.g., Rohrman and van der Beek, 1994).

Regional Early Paleogene (pre-volcanic) 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 NAIP area, an epeirogenic event is well documented in the Latest Cretaceous-Earliest Paleocene before the breakup and the main volcanic phase. This pre-breakup 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 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 offshore 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).

West Greenland is not included in Fig. 5, but here, uplift has been documented 5-10 Ma before the onset of volcanism. The uplift (up to 1.3 km) was associated with fluvial peneplenation, 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 phase uplift is recognized and coincides with the Danian Maureen formation deposition in the North Sea. A mid-Paleocene phase associated with a major change in sediment provenance is recognized as well (Naylor et al., 1999).

At the onset of NE Atlantic breakup in Early Eocene, widespread volcanism and local erosion and uplift occur 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 occurs in Late Paleocene-Early Eocene time, followed by a rapid post-early Eocene subsidence (Nadin et al., 1997; Jones et al., 2001; Green et al., 2001; Mackay et al., 2005). In the Faeroe-Shetland Basin, the Late Paleocene-Early Eocene phase coincides with a strong unconformity and prograding sands and mudstone sequences offshore Faeroes (Sørensen et al., 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). Fig. 5 suggests a pattern of increased transient uplift toward the future breakup axis. Data are too sparse to definitely point to a concentration around the inferred paleo-position of the Iceland anomaly.

3. Geodynamic models for NAIP formation

The formation of the NAIP can only be related to geodynamic models explaining and predicting all the above-described observations. As the plume concept is today challenged, 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.

3.1 Lithosphere delamination

One mechanism that can explain the production of huge amounts of basalt involves a link between melt production and delamination of lower lithosphere (Fig. 6a). The mechanism of delamination that is considered here as a possible explanation for NAIP 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 processes may result in a sufficient increase in lithosphere-asthenosphere density contrast for delamination to occur (see e.g., Kay and Kay, 1993). These include a lithospheric mantle density increase by 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 heat flow and generation of delamination-related magmas, crustal subsidence during delamination preceding short-lived, post-delamination 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 My; 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 My) to expect any relationship between them. Moreover, the chemical contents of NAIP 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 NAIP (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 NAIP formation.

3.2 Impact

The idea that meteorite impacts may initiate volcanic eruptions and form Large Igneous Provinces 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 of 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; Jones et al., 2002) as well as oceanic plateau formation (e.g. Ingle and Coffin, 2004).

Igneous rocks are very common near large impacts craters. However, numerical simulations of a large asteroid impact in the last decades have produced contradicting predictions for the amount of melt that could result from an impact (Ivanov and Melosh, 2003; 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. 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 (that 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 NAIP. Deposits that are being related to impact events, such as quartz spherules, have been found near Disko Island in central west Greenland (Jones et al., 2005b). In the NAIP, melt eruptions took place over an elongated zone of ca. 3,200 km length following a long period of extension. After breakup, there is continuous melt production at Iceland. Even if a large projectile impacted this extended area with steep geotherms in 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 NAIP. 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 NAIP formation inhibits a definite rejection or acceptance of this scenario.

3.3 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 NAIP. Recycled oceanic crust, subducted during the closure of the Iapetus Ocean, and subsequently segregated at the 660 km discontinuity, is eventually brought toward the surface from the lower mantle in a quite complex mixing process. In this model, both the upper and lower mantle are 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 counter-upwelling 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 $^{3}He/^{4}He$ ratios, found in the NAIP, are expected.

Subducted slab material is suggested to have played a role in the scenario developed by Foulger et al. (2005) and Foulger and Anderson (2005) (Fig. 6d). Their model suggests that the Iapetus oceanic lithosphere was probably very young (~50 My) 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 is tapped, and excessive melt production is expected. The geochemical contents of igneous samples of the NAIP, including Iceland, are well predicted by this scenario. The melt volume produced at the latitude of Iceland is however such, that more than one “normal thickness” of oceanic crust is required, and Foulger et al. (2005) suggest that imbrication provides the necessary amount of oceanic crust. The longevity of anomalous volcanism at the Mid-Atlantic Ridge at the latitude of Iceland is in this model 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 NAIP. The model by Korenaga (2004) does not include a specific mechanism that explains the single short pulse of volcanism at the NAIP rifted margins; it implicitly assumes that the crustal inventory is drained quickly, while it continues beneath Iceland. It does predict time-varying melt productivity, because the amount of oceanic crustal material embedded in the mantle matrix is likely to vary.

A subducted slab is by nature inhomogeneous, as it includes altered N-MORB to OIB basalts 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, N 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 not needed anymore 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, where 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 NAIP magma series, e.g., the LS at the Vøring margin. Higher degrees of partial melting (10-30%) will produce ferrobasaltic melts (Ito and Kennedy, 1974), and 60-80% melting is required to produce Icelandic melts (Foulger et al., 2005). Such high degrees of melting might result 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 (see section 4), 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 pre-breakup uplift (Fig. 5). The low seismic-wave-speed anomaly beneath the Iceland region would, in this scenario, not be caused by a mantle plume but instead would result from plate-tectonic related processes such as a compositional heterogeneity or a trace of partial melt due to the presence of excess volatiles (Foulger et al., 2001).

3.4 Small-scale- and edge-driven convection

Many LIPs, including the NAIP, 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 un-melted 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 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, and be attributed to the effects of a thick cratonic lithosphere positioned next to hot asthenosphere below a rift (Vågnes and Amundsen, 1993; Kelemen and Holbrook, 1995).

The edge-driven convection scenario explains several NAIP 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 syn-rift) 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 described, e.g., by Bown and White (1995). This may lead to 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 pre-rift 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 syn-rift), 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 pre-breakup history of Atlantic-type passive rifted margins, and can thus not provide an explanation for NAIP post-breakup events or the continuous excessive melt production at Iceland. Application of this model to the NAIP, and especially the mid-Norwegian Vøring margin, suggest that characteristic pre-separation features (extension, vertical movements, timing and duration of magmatism) are well explained by it (van Wijk et al., 2004), provided (pre-) rift conditions are favorable.

Keen and Boutilier (2000) and Boutilier and Keen (1999) find that upwelling of upper mantle material by divergent plate motions is insufficient to explain observed melt volumes and post-breakup oceanic crustal thickness of the NAIP. A thin (~50 km) Iceland plume sheet layer, with a thermal anomaly of about 100˚C, is needed in these models to generate large thicknesses of post-breakup igneous crust on the North Atlantic volcanic margins. Small-scale convection continues in these models below the margin edge for some time after breakup. This suggests that vertical motions of the margins could be expected around breakup time. Because the plume sheet layer is soon depleted below the margins, Keen and Boutilier (2000) conclude that formation of the Greenland-Iceland and Iceland-Faeroe Ridges requires a deeper-sourced thermal anomaly.

Nielsen and Hopper (2002) also use an upper-mantle convection model to study the interaction of a sub-lithospheric 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 about 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 Boutilier and Keen (2000) of breakup-related magmatism do assume that the LCB 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 (sub-lithospheric sheet-like, or ambient) mantle temperatures, large extension rates or cratonic boundaries are necessary conditions for explaining the vertical movements and melt characteristics of the NAIP. 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 NAIP volcanic margin evolution, but the continuous large melt production on Iceland is difficult to explain.

3.5 Mantle plume

The mantle plume concept was first defined by Morgan (1971). In this concept, about 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 imposed thereby on the base of the lithosphere will drive plate tectonics. Morgan (1971) related the BIP to the Iceland plume, and suggested that breakup of the Atlantic could be 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 chapter to discuss all adapted scenarios; we will limit ourselves to important adaptations for the NAIP (Fig. 6e).

Griffiths and Campbell (1990; 1991) and Campbell and Griffiths (1990), for example, determined the thermal anomaly associated with upwelling plumes, as well as the area affected by the arrival of the plume below the lithosphere. Their starting plume model requires thermal anomalies of about 300±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 upon reaching the base of the lithosphere, it may spread out and affect an area 2000 to 2500 km across. The starting plume model also predicts vertical movements of the surface (Campbell, 2005). A maximum elevation of about 500-1000 m is predicted for a plume head with a temperature anomaly of about 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/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 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 pre-dates 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 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 pin-pointing the suggested plume locality.

Another aspect of the mantle plume concept, of importance to the NAIP, is stretching of the lithosphere above the plume. Vertical movements associated with plume impingement would place the lithosphere under stress, and zones of compression and extension may both 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; Griffiths and Campbell, 1990; 1991; Campbell and Griffiths, 1990; Farnetani and Samuel, 2005) assume that the plume originates at the core-mantle boundary. With 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 NAIP formation according to Foulger et al. (2005). Farnetani and Samuel (2005) recently calculated the wave-speed anomaly predicted from geodynamic models of thermo-chemical plumes. They find that a wide range of plume shapes and seismic wave speed anomalies are possible: a plume head is not always found in their models and also the head-tail structure can be absent. This great variety of plume shapes and sizes translates into a large variety of predicted styles of tomographic image according to this study. The wave-speed 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 could provide a mechanism for geological effects from plumes far beyond the location of impingement, and is proposed as a possible explanation for the huge area affected by NAIP volcanism, following the rift zones in the North Atlantic. This scenario is poorly supported by data according to Doré and Lundin (2005). Doré and Lundin (2005) find for example that the LCB has not filled pre-existing thin spots in the crust, but terminates abruptly against margin-perpendicular lineaments.

The geochemistry of the NAIP is consistent with the plume concept, and to a large extent with the two-stage model presented in Saunders et al. (1997). We refer to the study by Saunders et al. (1997) for an overview of present views of the genesis of the NAIP from the plume point of view. The plume scenario furthermore 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 prediction that is not supported by observations, and there is also debate about the continuation of the upper-mantle low seismic-wave velocity anomaly into the lower mantle. It is furthermore important to stress that recent studies suggest that the mantle plume scenario for NAIP 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 NAIP (Foulger, 2005). As a result, the concept cannot be disproved.

4. Exploring alternatives

Are the alternative (i.e. non-mantle plume) models that are to hand today able to explain the different aspects of NAIP formation? Delamination and impact models do not appear to be good candidates, and must at this stage be rejected to explain this LIP. 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 facilitates continuing excessive melting on Iceland. Alternatively, a mantle heterogeneity resulting from plate tectonic processes could act as a source for continuing igneous activity.

Some studies argue that alternative, non-plume explanations for the chemical signal of the NAIP melts may be valid. During the last 30 years, the prevailing geochemical model for the Earth’s mantle (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 only of 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 (Polve and Allègre, 1980; Suen and Frey, 1987). During 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; 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 meter to 10 kilometer length scales and spanning 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 only be generated from such a mantle 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 NAIP 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 NAIP have been interpreted on the basis of the classical layered-mantle or isolated-reservoirs mantle model. The chemical signatures either result from a plume mantle source,or 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 NAIP (Fig. 3a, 3b). In the BIP the proportion of melts with an "Icelandic" chemical fingerprint increases with time at the base and 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 NAIP 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 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 nowhere else in the NAIP were such a huge volume (30-50 vol.%) of picrites erupted. The "doughnut" shape of the Griffiths and Campbell (1990) model well explains the peripheral eruption of the NAIP. However, the model predicts that the high-temperature magmas can only be produced 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 to explain 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 only be short lived is to date not explained. The actual Iceland mantle anomaly provides little support for such plume-like temperatures (Foulger and Anderson, 2005).

A plausible alternative explanation for the formation of the picrites in Greenland and in other NAIP 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 to explain the geochemistry and large melt volumes in the Iceland region (Foulger et al., 2005). They 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 is 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 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 NAIP magmas, this is even more important as 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 with standard geochemical systems and models sub-continental and/or continental sources for OIB magmas.

Recently, the geochemistry of helium has been assumed to reflect evidence for mantle plumes. Helium has two isotopes: ^{3}He, a primordial isotope incorporated in the Earth during planetary accretion, and ^{4}He, an isotope largely produced by radioactive decay of U and Th isotopes. Basalts related to postulated mantle plumes have high $^{3}He/^{4}He$ ratios compared to the MORB. This observation is assumed to be an explicit indicator of a primitive, undegassed lower mantle source component, with a high ^{3}He content. However, deep-mantle sources are not the only possible explanation for high $^{3}He/^{4}He$ ratios. He concentrations in rocks believed to reflect a deep mantle sources should be higher compared to melts from the depleted MORB mantle. However the He content in OIB is often 2 to 3 orders lower than in MORB (Foulger et al. 2005). A key process in He geochemistry is oceanic crust formation, as the incompatible mother isotopes of ^{4}He (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 a part of the inhomogeneous mantle source proposed by Phipps Morgan and Morgan (1999), and might provide high He ratios to NAIP erupted basalts. The extreme He data from E Greenland picrites of Stuart et al. (2003) confirms this scenario, as 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 NAIP 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 tectonic processes (Korenaga, 2004; Foulger et al., 2005; Foulger and Anderson, 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. 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 is required to build a convincing case.

5. Conclusion

The mantle plume concept is currently most successful in explaining formation of the NAIP. 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 explain NAIP observations better. There are unexplained aspects of the concept that remain to be addressed, while alternative models also need to be matured further.

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 non-plume models need to overcome is the continuing, long-lived melt anomaly extending from the Greenland-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 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. 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 availability of increasingly more reliable data should help to resolve the problem of the challenged mantle plume concept in the near future.

Acknowledgments

We would like to thank P. Vogt, an anonymous reviewer, G. Foulger and D. Jurdy for their detailed and constructive comments, and Jan Hertogen for discussion and pre-reading. RM is supported by FWO-Vlaanderen (project G.0008.04) and BFR05/133 Luxembourg in the framework of the ESF EUROMARGINS program.

References

Abbott, D.H., and Isley, A.E., 2002, Extraterrestrial influences on mantle plume activity: Earth and Planetary Science Letters, v. 205, p. 53-62.

Ahmadi, Z., Sawyers, M., et al., 2003, Paleocene: The millennium atlas; petroleum geology of the central and northern North Sea, p. 235-249.

Albarède, F., 1998, Time-dependent models of U-Th-He and K-Ar evolution and the layering of mantle convection: Chemical Geology, v. 145, p. 413-429.

Albarède, F., 2005, The survival of mantle geochemical heterogeneities: in: Earth's deep mantle: structure, composition and evolution, Geophysical Monograph Series, v. 160, p. 27-46.

Allègre, C.J., and Lewin, E., 1995, Isotopic systems and stirring times of the earth's mantle:

Earth and Planetary Science Letters, v. 136, p. 629-646.
Allègre, C.J., and Turcotte, D.L., 1986, Implications of a two-component marble-cake mantle: Nature, v. 323, p. 123-127.
Anderson, D.L., 1998a, The EDGES of the mantle: in: The core-mantle boundary region, Gurnis, M.E., et al. (eds.), AGU, Washington D.C., p. 255-271.
Anderson, D.L., 1998b, The helium paradoxes: Proceedings of the National Academy of Sciences, v. 95, p. 4822-4827.
Anderson, D.L., 2000, The thermal state of the upper mantle; no role for mantle plumes: Geophysical Research Letters, v. 27, p. 3623-3626.
Anderson, D.L., 2005, Scoring hotspots: the plume and plate paradigms: Special Paper, Geological Society of America, v. 388, p. 31-54.
Anderson, D.L., and Natland, J.H., 2005, A brief history of the plume hypothesis and its competitors; concept and controversy: Special Paper, Geological Society of America, v. 388, p. 119-145.
Baksi, A.K., 2005, Evaluation of radiometric ages pertaining to rocks hypothesized to have been derived by hotspot activity, in and around the Atlantic, Indian, and Pacific Oceans: Geological Society of America Special Paper, v. 388, p. 55-70.
Baksi, A.K., this volume, The high solubility of argon in water: utilizing ^{36}Ar measurements in quantitative detection of alteration in rocks/minerals and investigating the role of water in subduction zone magmatism.
Barrat, J.A., and Nesbitt, R.W., 1996, Geochemistry of the Tertiary volcanism of Northern Ireland: Chemical Geology, v. 129, p. 15-38.
Barton, A.J., and White, R.S., 1995, The Edoras Bank margin; continental breakup in the presence of a mantle plume: Journal of the Geological Society of London, v. 152, p.971-974.
Barton, A.J., and White, R.S., 1997, Crustal structure of Edoras Bank continental margin and mantle thermal anomalies beneath the North Atlantic: Journal of Geophysical Research, v. 102, p. 3109-3129.
Bijwaard, H., and Spakman, W., 1999, Tomographic evidence for a narrow whole mantle plume below Iceland: Earth and Planetary Science Letters, v. 166, p. 121-126.
Bird, P., 1979, Continental delamination and the Colorado Plateau: Journal of Geophysical Research, v. 84, p. 7561-7571.
Bird, P. and J. Baumgardner, 1981, Steady propagation of delamination events: Journal of Geophysical Research, v. 86, p. 4891-4903.
Blystad, P., Brekke, H., Færseth, R.B., Larsen, B.T., Skogseid, J., and Tørudbakken, B., 1995, Structural elements of the Norwegian continental shelf, part II. The Norwegian Sea region: Norwegian Petroleum Directorate Bulletin, v. 8.
Boutilier, R.R., and Keen, C.C., 1999, Small-scale convection and divergent plate boundaries: Journal of Geophysical Research, v. 104, p. 7389-7403.
Bown, J.W., and White, R.S., 1995, Effect of finite extension rate on melt generation at rifted continental margins: Journal of Geophysical Research, v. 100, p. 18,011-18,029.
Breddam, K., 2002, Kistufell: primitive melt from the Iceland mantle plume: Journal of Petrology, v. 43, p. 344-373.
Breivik, A.J., Mjelde, R., Faleide, J.I., and Murai, Y., 2006, Rates of continental breakup magmatism and seafloor spreading in the Norway Basin-Iceland plume interaction: Journal of Geophysical Research, v. 111, doi:10.1029/2005JB004004.
Brooks, C.K., and Gleadow, A.J.W., 1977, A fission-track age for the Skeargaard intrusion and the age of the East Greenland basalts: Geology, v. 5, p. 539-540.
Bugge, T., Prestvik, T., and Rokoengen, K., 1980, Lower Tertiary volcanic rocks off Kristiansund-Mid Norway: Marine Geology, v. 35, p. 215-220.

Burov, Y.P., Krasil'scikov, A.A., Firsov, D.V., and Klubov, B.A., 1975, The age of Spitsbergen dolerites (from isotopic dating): Arbok- Norsk Polarinstitutt, v. 1975, p. 101-108.

Burov, E., and Guillo-Frottier, L., 2005, The plume head-continental lithosphere interaction using a tectonically realistic formulation for the lithosphere: Geophysical Journal International, v. 161, p. 469-490.

Campbell, I.H., 2005, Large igneous provinces and the mantle plume hypothesis: Elements, v. 1, p. 265-269.

Campbell, I.H., and Griffiths, R.W., 1990, Implications of mantle plume structure for the evolution of flood basalts: Earth and Planetary Science Letters, v. 99, p. 79-93.

Carlson, R.W., Pearson, D.G., and James, D.E., 2005, Physical, chemical, and chronological characteristics of continental mantle: Reviews of Geophysics, v. 43, RG1001, doi:10.1029/2004RG000156.

Ceramicola, S., Stoker, M., Praeg, D., et al., 2005, Anomalous Cenozoic subsidence along the 'passive' continental margin from Ireland to mid-Norway: Marine and Petroleum Geology, v. 22, p. 1045-1067.

Chalmers, J.A., and Laursen, K.H., 1995, Labrador Sea: the extent of continental crust and the timing of the start of sea-floor spreading: Marine and Petroleum Geology, v. 12, p. 205-217.

Chalmers, J.A., Whittaker, R.C., Skaarup, N., Pulvertaft, T.C.R., Geoffroy, L., Skuce, A.G., Angelier, J., Gelard, J.P., Lepvrier, C., and Olivier, P., 1999, The coastal flexure of Disko (West Greenland), onshore expression of the "oblique reflectors": discussion and reply: Journal of the Geological Society London, v. 156, p. 1051-1055.

Chapman, T.J., Broks, T.M., Corcoran, D.V., Duncan, L.A., and Dancer, P.N., 1999, The structural evolution of the Erris Trough, offshore Northwest Ireland, and implications for hydrocarbon generation: Petroleum Geology of Northwest Europe: proceedings of the 5th conference, v. 5, p. 455-469.

Chian, D., Keen, C., Reid, I., and Louden, K.E., 1995, Evolution of the nonvolcanic rifted margins: new results from the conjugate margins of the Labrador Sea: Geology, v. 23, p. 589-592.

Clarke, D.B., 1970, Tertiary basalts of Baffin Bay: possible primary magma from the mantle: Contributions to Mineralogy and Petrology, v. 25, p. 203-224.

Clarke, D.B., and O'Hara, M.J., 1979, Nickel, and the existence of high-MgO liquids in nature: discussion: Earth and Planetary Science Letters, v. 44, p. 153-158.

Clarke, D.B., and Pedersen, A.K., 1976, Tertiary volcanic province of West Greenland: in Geology of Greenland, Escher, A., and Watt, W.S., eds., p. 364-385, Groenlands Geol. Unders., Copenhagen, Denmark.

Coffin, M.F., and Eldholm, O., 1994, Large igneous provinces: crustal structure, dimensions, and external consequences: Reviews of Geophysics, v. 32, p. 1-36.

Corcoran, D.V., and Doré, A.G., 2005, A review of techniques for the estimation of magnitude and timing of exhumation in offshore basins: Earth-Science Reviews, v. 72, p. 129-168.

Corti, G., van Wijk, J., Bonini, M., Sokoutis, D., Cloetingh, S., Innocenti, F., and Manetti, P., 2002, Transition from continental breakup to seafloor spreading: how fast, symmetric and magmatic: Geophysical Research Letters, v. 30, doi:10.1029/2003GL017374.

Courtillot, V., Davaille, A., Besse, J., and Stock, J., 2003, Three distinct types of hotspots in the Earth's mantle: Earth and Planetary Science Letters, v. 205, p. 295-308.

Coward, M., 1995, Structural and tectonic setting of the Permo-Triassic basins of Northwest Europe: Boldy, S.A.R., ed., Permian and Triassic Rifting in Northwest Europe: Geological Society, London, Special Publications, v. 91, p. 7-39.

Coward, M.P., Enfield, M.A., and Fischer, M.W., 1989, Devonian basins of northern Scotland: extension and inversion related to Late Caledonian-Variscan tectonics: Geological Society Special Publications, v. 44, p. 275-308.

Dam, G., Larsen, M., and Sonderholm, M., 1998, Sedimentary response to mantle plumes: implications for Paleocene onshore successions, West and East Greenland: Geology, v. 26, p. 207-210.

Dancer, P.N., Algar, S.T., and Wilson, I.R., 1999, Structural evolution of the Slyne Trough: Petroleum Geology of Northwest Europe: proceedings of the 5th conference, v. 5, p. 445-453.

Davies, G.F., 1981, Earth's neodymium budget and structure and evolution of the mantle: Nature, v. 290, p.208-213.

Deptuck, M.E., MacRae, R.A., Shimeld, J.W., et al., 2003, Revised upper Cretaceous and lower Paleogene lithostratigraphy and depositional history of the Jeanne d'Arc Basin, offshore Newfoundland, Canada: American Association of Pet. Geol. Bulletin, v. 87, p. 1459-1483.

Dickin, A.P., 1981, Isotope geochemistry of Tertiary igneous rocks from the Isle of Skye, NW Scotland: Journal of Petrology, v. 22, p. 155-189.

Dickin, A.P., and Jones, N.W., 1983, Isotopic evidence for the age and origin of pitchstones and felsites, Isle of Eigg, NW Scotland: Journal of the Geological Society London, v. 140, p. 691-700.

Doré, A.G., and Lundin, E.R., 2005, Challenges and controversies in exploration of the NE Atlantic margin: 25th Annual Gulf Coast Section SEPM Foundation, Program and Abstracts, p. 18-21.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P.E., and Fichler, C., 1999, Principle tectonic events in the evolution of the Northwest European Atlantic margin: Petroleum Geology of Northwest Europe; proceedings of the 5th conference, v. 5, p.41-61.

Driscoll, N.W., Hogg, J.R., Christie-Blick, N., and Karner, G.D., 1995. Extensional tectonics in the Jeanne d'Arc Basin, offshore Newfoundland: implications for the timing of breakup between Grand Banks and Iberia: The tectonics, sedimentation and palaeoceanography of the north Atlantic region, Scrutton, R.A., Stoker, M.S., Shimmield, G.B., and Tudhope, A.W., Geological Society of London, London, p. 1-28.

Ducea, M. and Saleeby, J., 1998, A case for delamination of the deep batholithic crust beneath the Sierra Nevada, California: International Geology Review, v. 40, p. 78-93.

Duncan, R.A., Larsen, H.C., Allan, J.F., et al., 1996, Proceedings of the Ocean Drilling Program, Initial Reports, Southeast Greenland margin, covering Leg 163 of the cruises of the drilling vessel JOIDES Resolution: Proceedings of the Ocean Drilling Program, Initial Reports, v. 163, 623 pp.

Ebbing, J., Lundin, E., Olesen, O., and Hansen, E.K., 2006, The mid-Norwegian margin: a discussion of crustal lineaments, mafic intrusions, and remnants of the Caledonian root by 3D density modeling and structural interpretation: Journal of the Geological Society London, v. 163, p. 47-59.

Eldholm, O., Thiede, J., Taylor, E., et al., 1987, Summary and preliminary conclusions, ODP Leg 104: Proceedings of the Ocean Drilling Program, Initial Reports, v. 104, p. 751-771.

Eldholm, O., and Grue, K., 1994, North Atlantic volcanic margins: dimensions and production rates: Journal of Geophysical Research, v. 99, p. 2955-2968.

Elkins-Tanton, L.T., 2005, Continental magmatism caused by lithospheric delamination: Geological Society of America Special Paper, v. 388, p. 449-461.

Elkins-Tanton, L.T., and Hager, B.H., 2000, Melt intrusion as a trigger for lithospheric foundering and the eruption of the Siberian flood basalts: Geophysical Research Letters, v. 27, p. 3937-3940.
Elkins-Tanton, L.T., and Grove, T.L., 2003, Evidence for deep melting of hydrous, metasomized mantle: Pliocene high potassium magmas from the Sierra Nevadas: Journal of Geophysical Research, v. 108, doi:10.1029/2002JB002168.
Embry, A.F., 1991, Mesozoic history of the Arctic Islands: in: Trettin, H.P., ed., Geological Survey of Canada, p. 369-433.
England, P.C., and Houseman, G.A., 1989, Extension during continental convergence, with application to the Tibetan Plateau: Journal of Geophysical Research, v. 94, p. 17561-17579.
Erratt, D., Thomas, G.M., and Wall, G.R.T., 1999, The evolution of the central North Sea Rift: Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, v. 5, p. 63-82.
Estrada, S., 1998, Basaltic dykes in the Kap Washington and Frigg Fjord areas (North Greenland): Polarforschung, v. 68, p. 19-23.
Estrada, S., and Henjes-Kunst, F., 2004, Volcanism in the Canadian High Arctic related to the opening of the Arctic Ocean: Zeitschrift der Deutschen Geologische Gesellschaft, v. 154, p. 579-603.
Faleide, J.I., Vågnes, E., and Gudlaugsson, S.T., 1993, Late Mesozoic-Cenozoic evolution of the South-western Barents Sea in a regional rift-shear tectonic setting: Marine and Petroleum Geology, v. 10, p. 186-214.
Farmer, G.L., Glazner, A.F. and Manley, C.R., 2002, Did lithospheric delamination trigger late Cenozoic potassic volcanism in the southern Sierra Nevada, California?: Geological Society of America Bulletin, v. 114, p. 754-768.
Farnetani, C.G., and Samuel, H., 2005, Beyond the thermal plume paradigm: Geophysical Research Letters, v. 32, doi:10.1029/2005GL022360.
Fitton, J.G., Larsen, L.M., Saunders, A.D., Hardarson, B.S., and Kempton, P.D., 2000, Palaeogene continental to oceanic magmatism on the SE Greenland continental margin at 63°N: a review of the results of Ocean Drilling Program Legs 152 and 163: Journal of Petrology, v. 41, p. 951-966.
Foulger, G.R., 2005, Mantle plumes: why the current scepticism?: Chinese Science Bulletin, v. 50, p. 1555-1560.
Foulger, G.R., 2006, Older crust underlies Iceland: Geophysical Journal International, v. 165, p. 672-676.
Foulger, G.R., Pritchard, M.J., Julian, B.R., et al., 2001, Seismic tomography shows that upwelling beneath Iceland is confined to the upper mantle: Geophysical Journal International, v. 146, p. 504-530.
Foulger, G.R., and Anderson, D.L., 2005, A cool model for the Iceland hot spot: Journal of Volcanology and Geothermal Research, v. 141, p. 1-22.
Foulger, G.R., Natland, J.H., and Anderson, D.L., 2005, Genesis of the Iceland melt anomaly by plate tectonic processes: Special Paper, Geological Society of America, v. 388, p. 595-625.
Foulger, G.R., and Pearson, D.G., 2001, Is Iceland underlain by a plume in the lower mantle? Seismology and helium isotopes: Geophysical Journal International, v. 145, p. F1-F5.
Fowler, S.R., White, R.S., Spence, G.D., and Westbrook, G.K.,1989, The Hatton Bank continental margin: II, Deep structure from two-ship expanding spread seismic profiles: Geophysical Journal of the Royal Astronomical Society, v. 96, p. 295-309.
Fram, M.S., Lesher, C.E., and Volpe, A.M., 1998, Mantle melting systematics: transition

from continental to oceanic volcanism on the Southeast Greenland margin: Proceedings of the Ocean Drilling Program, Scientific Results, v. 152, p. 373-386.
Furlong, K.P., and Fountain, D.M., 1986, Continental crustal underplating: thermal considerations and seismic-petrologic consequences: Journal of Geophysical Research, v. 91, p. 8285-8294.
Gamble, J.A., 1979, The geochemistry and petrogenesis of dolerites and gabbros from Tertiary Central Complex of Slieve Gullion, North East Ireland: Contributions to Mineralogy and Petrology, v. 69, p. 5-19.
Gariépy, C., Ludden, J., and Brooks, C., 1983, Isotopic and trace element constraints on the genesis of the Faeroe lava pile: Earth and Planetary Science Letters, v. 63, p. 257-272.
Geldmacher, J., Troll, V.R., Emeleus, C.H., and Donaldson, C.H., 2002, Pb-isotope evidence for contrasting crustal contamination of primitive to evolved magmas from Ardnamurchan and Rum: implications for the structure of the underlying crust: Scottish Journal of Geology, v. 38, p. 55-61.
Geoffroy, L., Gelard, J.P., Lepvrier, C., and Olivier, P., 1998, The coastal flexure of Disko (West Greenland), onshore expression of the "oblique reflectors": Journal of the Geological Society London, v. 155, p. 463-473.
Geoffroy, L., Aubourg, C., Callot, J.P., and Barrat, A., Mechanisms of crustal growth in large igneous provinces: the North-Atlantic Province as a case study, this Volume.
Gernigon, L., Ringenbach, J.C., Planke, S., Le Gall, B., Jonquet-Kolsto, H., 2003, Extension, crustal structure and magmatism at the outer Vøring Basin, Norwegian margin: Journal of the Geological Society London, v. 160, p. 197-208.
Gernigon, L., Lucazeau, F., Brigaud, F., Ringenbach, J.-C., Le Gall, B., and Planke, S., 2006, Interpretation and integrated modelling along a volcanic rifted margin: deep structures and breakup processes along the Vøring margin (Norway): Tectonophysics, v. 412, p. 255-278.
Gibson, D., McCormick, A.G., Meighan, I.G., and Halliday, A.N., 1987, The British Tertiary Igneous Province: Young Rb-Sr ages for the Mourne Mountains granites: Scottish Journal of Geology, v. 23, p. 221-225.
Gill, R.C.O., Pedersen, A.K., and Larsen, J.G., 1992, Tertiary picrites in west Greenland: melting at the periphery of a plume?: Geological Society Special Publications, v. 68, p. 335-348.
Gleadow, A.J.W., and Brooks, C.K., 1979, Fission track dating, thermal histories and tectonics of igneous intrusions in East Greenland: Contributions to Mineralogy and Petrology, v. 71, p. 45-60.
Goes, S., Spakman, W., and Bijwaard, H., 1999, A lower mantle source for central European volcanism: Science, v. 286, p. 1928-1931.
Grachev, A.F., 2001, A new view on the origin of magmatism of the Franz Josef Land: Izvestiya- Russian Academy of Sciences, Physics of the Solid Earth, v. 137, p. 744-756.
Green, P.F., Thomson, K., and Hudson, J.D., 2001, Recognition of tectonic events in undeformed regions: contrasting results from the Midland Platform and East Midland Shelf, Central England: Journal of the Geological Society, v. 158, p. 59-73.
Griffiths, R.W., and Campbell, I.H., 1990, Stirring and structure in mantle starting plumes: Earth and Planetary Science Letters, v. 99, p. 66-78.
Griffiths, R.W., and Campbell, I.H., 1991, Interaction of mantle plume heads with the Earth's surface and onset of small-scale convection: Journal of Geophysical Research, v. 96, p. 18,295-18,310.
Grogan, P., Nyberg, K., Fotland, B., et al., 1998, Cretaceous magmatism south and east of

Svalbard: evidence from seismic reflection and magnetic data: Polarforschung, v. 68, p. 25-34.
Hamilton, M.A., Pearson, D.G., Thompson, R.N., Kelley, S.P., and Emeleus, C.H., 1998, Rapid eruption of Skye lavas inferred from precise U-Pb and Ar-Ar dating of the Rum and Cuillin plutonic complexes: Nature, v. 394, p. 260-263.
Hardarson, B.S., Fitton, J.G., Ellam, R.M., and Pringle, M.S., 1997, Rift relocation- a geochemical and geochronological investigation of a paleo-rift in northwest Iceland: Earth and Planetary Science Letters, v. 153, p. 181-196.
Harland, W.B., Anderson, L.M., and Manasrah, D., 1997, The geology of Svalbard: Memoir- Geological Society of London, v. 17, 521 pp.
Harland, W.B., and Kelly, S.R.A., 1997, Eastern Svalbard Platform: Memoir- Geological Society of London, v. 17, p. 75-95.
Harland, W.B., and Stephens, C.F., 1997, Neogene-Quaternary history: Memoir- Geological Society of London, v. 17, p. 418-435.
Harrison, R.K., and Merriman, R.J., 1984, Petrology, mineralogy, and chemistry of basaltic rocks: Leg 81: Initial Reports of the Deep Sea Drilling Project, v. 81, p. 743-774.
Hart, S.R., 1984, A large-scale isotope anomaly in the southern hemisphere mantle: Nature, v. 309, p. 753-757.
Hart, S.R., and Davis, K.E., 1978, Nickel, and the existence of high-MgO liquids in nature: reply: Earth and Planetary Science Letters, v. 44, p. 159-161.
Hart, S.R., and Zindler, A., 1989, Constraints on the nature and development of chemical heterogeneities in the mantle: The Fluid Mechanics of Astrophysics and Geophysics, v. 4, p. 261-387.
Henderson, P. and Gijbels, R., 1976, Trace element indicators of the Rhum layered intrusion, Inner Hebrides: Scottish Journal of Geology, v. 12, p. 325-333.
Hilton, D.R., Gronvold, K., Macpherson, C.G., and Castillo, P.R., 1999, Extreme $^{3}He/^{4}He$ ratios in Northwest Iceland; constraining the common component in mantle plumes: Earth and Planetary Science Letters, v. 173, p. 53-60.
Hirschmann, M.M., Renne, P.R., and McBirney, A.R., 1997, ^{40}Ar-^{39}Ar dating of the Skaergaard intrusion: Earth and Planetary Science Letters, v. 146, p. 645-658.
Hitchen, K., 2004, The geology of the UK Hatton-Rockall margin: Marine and Petroleum Geology, v. 21, p. 993-1012.
Hitchen, K., and Ritchie, J.D., 1993, New K-Ar ages, and a provisional chronology, for the offshore part of the British Tertiary Igneous Province: Scottish Journal of Geology, v. 29, 73-85.
Hitchen, K., Stoker, M.S., Evans, D., Beddoe-Stephens, B., 1995, Permo-Triassic sedimentary and volcanic rocks in basins to the north and west of Scotland: Geological Society Special Publications, v. 91, p. 87-102.
Hofmann, A.W., 1988, Chemical differentiation of the Earth: the relationship between mantle, continental crust and oceanic crust: Earth and Planetary Science Letters, v. 90, p. 297-314.
Holbrook, W.S., Larsen, H.C., Korenaga, J., et al., 2001, Mantle thermal structure and active upwelling during continental breakup in the North Atlantic: Earth and Planetary Science Letters, v. 190, p. 251-266.
Holm, P.M., Gill, R.C.O., Pedersen, A.K., Larsen, J.G., Hald, N., Nielsen, T.F.D., and Thirlwall, M.F., 1993, The Tertiary picrites of West Greenland: contributions from “Icelandic” and other sources: Earth and Planetary Science Letters, v. 115, p. 227-244.
Hooper, P.R., 1990, The timing of crustal extension and the interruption of continental flood basalts: Nature, v. 345, p. 246-249.

Hutton, J., 1785. Theory of the Earth: published in Transactions of the Royal Society of Edinburgh.

Ingle, S., and Coffin, M.F., 2004, Impact origin of the greater Ontong Java Plateau?: Earth and Planetary Science Letters, v. 218, p. 123-134.

Ito, G., 2001, Reykjanes “V”-shaped ridges originating from a pulsing and dehydrating mantle plume: Nature, v. 411, p. 681-684.

Ito, K., and Kennedy, G.C., 1974, The composition of liquids formed by partial melting of eclogites at high temperatures and pressures: Journal of Geology, v. 82, p.383-392.

Ivanov, B.A., and Melosh, H.J., 2003, Impacts do not initiate volcanic eruptions: eruptions close to the crater: Geology, v. 31, p. 869-872.

Jokat, W., 2003, Seismic investigations along the western sector of Alpha Ridge, central Arctic Ocean: Geophysical Journal International, v. 152, p. 185-201.

Jones, S.M., White, N., and Lovell, B., 2001, Cenozoic and Cretaceous transient uplift in the Porcupine basin and its relationship to a mantle plume: Geological Society of London Special Publications, v. 188, p. 345-360.

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

Jones, S.M., and White, N., 2003, Shape and size of the starting Iceland plume swell: Earth and Planetary Science Letters, v. 216, p. 271-282.

Jones, A.P., Price, G.D., Price, N.J., DeCarli, P.S., and Clegg, R.A., 2002, Impact induced melting and the development of large igneous provinces: Earth and Planetary Science Letters, v. 202, p. 551-561.

Jones, A.P., Wünemann, K., and Price, G.D., 2005a, Modeling impact volcanism as a possible origin for the Ontong Java Plateau: Foulger, G.R., Natland, J.H., Presnall, D.C., and Anderson, D.L., eds., Plates, plumes and paradigms: Geological Society of America Special Paper, v. 388, p. 711-720.

Jones, A.P., Kearsley, A.T., Friend, C.R.L., Robin, E., Beard, A., et al., 2005b, Are there signs of a large Palaeocene impact, preserved around Disko bay, W. Greenland?: Nuussuaq spherule beds origin by impact instead of volcanic eruption?: Geological Society of America Special Paper, v. 384, p. 281-298.

Jurine, D., Jaupart, C., Brandeis, G., and Tackley, P.J., 2005, Penetration of mantle plumes through depleted lithosphere, Journal of Geophysical Research, v. 110, doi:10.1029/2005JB003751.

Kay, S.M., Coira, B., and Viramonte, J., 1994, Young mafic back arc volcanic rocks as indicators of continental lithospheric delamination beneath the Argentine Puna plateau, central Andes: Journal of Geophysical Research, v. 99, p. 24,323-24,339.

Kay, R.W. and S. M. Kay, 1993, Delamination and delamination magmatism: Tectonophysics, v. 219, p. 177-189.

Keen, C.E., and Boutilier, R.R., 2000, Interaction of rifting and hot horizontal plume sheets at volcanic margins: Journal of Geophysical Research, v. 105, p. 13,375-13,387.

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

Kellogg, J.B., Jacobsen, S.B., and O’Connell, R.J., 2002, Modeling the distribution of isotopic ratios in geochemical reservoirs: Earth and Planetary Science Letters, v. 204, p. 183-202.

Kent, R.W., and Fitton, J.G., 2000, Mantle sources and melting dynamics in the British Paleogene igneous province: Journal of Petrology, v. 41, p. 1023-1040.

Kerr, A.C., 1995, The geochemistry of the Mull-Morvern lava succession, NW Scotland: an assessment of mantle sources during plume-related volcanism: Chemical Geology, v. 122, p. 43-58.

King, S.D., 2005, North Atlantic topographic and geoid anomalies: the result of a narrow ocean basin and cratonic roots?: Foulger, G.R., Natland, J.H., Presnall, D.C., and Anderson, D.L., eds., Plates, plumes and paradigms: Geological Society of America Special Paper, v. 388, p. 653-664.

King, S.D., and Anderson, D.L., 1995, An alternative mechanism for flood basalt formation: Earth and Planetary Science Letters, v. 136, p. 269-279.

King, S.D. and Anderson, D.L., 1998, Edge-driven convection: Earth and Planetary Science Letters, v. 160, p. 289-296.

Koch, J.O., and Heum, O.R., 1995, Exploration trends of the Halten Terrace: 25 years of Petroleum Exploration in Norway, NPF Special Publication, v. 4, p. 235-251.

Kodaira, S., Mjelde, R., Gunnarsson, K., Shiobara, H., and Shimamura, H., 1998, Evolution of oceanic crust on the Kolbeinsey Ridge, north of Iceland, over the past 22 Myr: Terra Nova, v. 10, p. 27-31.

Kontak, D.J., Jensen, S.M., Dostal, J., Archibald, D.A., and Kyser, T.K., 2001, Cretaceous mafic dyke swarm, Peary Land, northernmost Greenland: geochronology and petrology: The Canadian Mineralogist, v. 39, p. 997-1020.

Korenaga, J., 2004, Mantle mixing and continental breakup magmatism: Earth and Planetary Science Letters, v. 218, p. 463-473.

Korenaga, J., Holbrook, W.S., Kent, G.M., Detrick, R.S., Larsen, H.C., Hopper, F.R., and Dahl-Jensen, T., 2000, Crustal structure of the Southeast Greenland margin from joint refraction and reflection seismic tomography: Journal of Geophysical Research, v. 105, p. 19163-19184.

Knox, R.W.O.'B., 1998, The tectonic and volcanic history of the North Atlantic region during the Paleocene-Eocene transition: implications for NW European and global biotic events: in Late Paleocene-Early Eocene climatic and biotic events in the marine and terrestrial records, Aubrey, M.P., et al. (eds.), Columbia University Press, p. 91-102.

Larsen, L.M., Fitton, J.G., and Saunders, A.M., 1999, Composition of volcanic rocks from the Southeast Greenland margin, Leg 163; major and trace element geochemistry: Proceedings of the Ocean Drilling Program, Scientific Results, v. 163, p. 63-75.

Larsen, H.C., Saunders, A.D., Clift, P.D., et al., 1994, Proceedings of the ocean Drilling Program: initial reports; East Greenland margin: covering Leg 152 of the cruises of the drilling vessel JOIDES Resolution: Proceedings of the Ocean Drilling Program, Initial Reports, v. 152, 977 pp.

Larsen, L.M., and Pedersen, A.K., 1988, Investigations of Tertiary volcanic rocks along the south coast of Nuussuaq and in eastern Disko, 1987: Report- Geological Survey of Greenland, v. 140, p. 28-32.

Larsen, L.M., and Pedersen, A.K., 2000, Processes in high-Mg, high-T magmas: evidence from olivine, chromite and glass in Paleogene picrites from West Greenland: Journal of Petrology, v. 41, p. 1071-1098.

Larsen, L.M., Pedersen, A.K., Pedersen, G.K., and Piasecki, S., 1992, Timing and duration of early Tertiary volcanism in the north Atlantic: new evidence from West Greenland: Geological Society Special Publications, v. 68, p. 321-333.

Lawver, L.A., and Müller, R.D., 1994, Iceland hotspot track: Geology, v. 22, p. 311-314.

Le Bas, M.J., 2000, IUGS reclassification of the high-Mg and picritic volcanic rocks: Journal of Petrology, v. 41, p. 1467-1470.

LeHuray, A.P., and Johnson, E.S., 1989, Rb-Sr systematics of Site 642 volcanic rocks and

alteration minerals: Proceedings of the Ocean Drilling Program Scientific Results, v. 104, p. 437-448.
Lund, J., 1983, Biostratigraphy of interbasaltic coals: Bott, M.H.P., et al. (eds.), Structure and development of the Greenland-Scotland Ridge; new methods and concepts. Plenum Press, p. 417-423.
Lundin, E.R., and Doré, A.G., 2005, Fixity of the Iceland "hotspot" on the Mid-Atlantic Ridge: observational evidence, mechanisms, and implications for Atlantic volcanic margins: Special Paper, Geological Society of America, v. 388, p. 627-651.
Mackay, L.M., Turner, J., Jones, S.M., and White, N.J., 2005, Cenozoic vertical motions in the Moray Firth Basin associated with initiation of the Iceland Plume: Tectonics, v. 24, n. 5., 23 pp.
Maher, H.D., 2000, Manifestations of the Cretaceous High Arctic Large Igneous Province in Svalbard: The Journal of Geology, v. 109, p. 91-104.
Martinsen, O.J., Boen, F., Charnock, M.A., Mangerud, G., and Nottvedt, A., 1999, Cenozoic development of the Norwegian margin 60-64°N: sequences and sedimentary response to variable basin physiography and tectonic setting: Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, v. 5, p. 293-304.
McKenzie, D., and Bickle, M.J., 1988, The volume and composition of melt generated by extension of the lithosphere: Journal of Petrology, v. 29, p. 625-679.
McKenzie, D., Stracke, A., Blichert-Toft, J., Albarède, F., Gronvold, K., and O'Nions, R.K., 2004, Source enrichment processes responsible for isotopic anomalies in oceanic island basalts: Geochimica et Cosmochimica Acta, v. 68, p. 2699-2724.
Meibom, A., and Anderson, D.L., 2004, The statistical upper mantle assemblage: Earth and Planetary Science Letters, v. 217, p. 123-139.
Meibom, A., Anderson, D.L., Sleep, N.H., Frei, R., Chamberlain, C.P., Hren, M.T., and Wooden, J.L., 2003, Are high $^{3}He/^{4}He$ ratios in oceanic basalts an indicator of deep mantle-plume components?: Earth and Planetary Science Letters, v. 208, p. 197-204.
Meyer, R., Hertogen, J., Pedersen, R.B., Viereck-Götte, L., and Abratis, M., 2005, Geochemical signatures of rift-related volcanism in the Vøring Plateau and the S.E. Greenland margin: Geophysical Research Abstracts, v. 7, 05734.
Mjelde, R., Raum, T., Myhren, B., et al., 2005, Continent-ocean transition on the Vøring Plateau, NE Atlantic, derived from densely sampled ocean bottom seismometer data: Journal of Geophysical Research, v. 110, no. B5, 19 pp.
Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., Engdahl, R.E., and Hung, S.-H., 2004, Finite-frequency tomography reveals a variety of plumes in the mantle: Science, v. 303, p. 338-343.
Moorbath, S., and Thompson, R.N., 1980, Strontium isotope geochemistry and petrogenesis of the early Tertiary lava pile of the Isle of Skye, Scotland, and other basic rocks of the British Tertiary Province: an example of magma-crust interaction: Journal of Petrology, v. 21, p. 295-321.
Moore, W.B., Schubert, G., and Tackley, P.J., 1998, Three-dimensional simulations of plume-lithosphere interaction at the Hawaii swell: Science, v. 279, p. 1008-1011.
Moore, W.B., Schubert, G., and Tackley, P.J., 1999, The role of rheology in lithospheric thinning by mantle plumes: Geophysical Research Letters, v. 26, p. 1071-1076.
Moreira, M., and Sarda, P., 2000, Noble gas constraints on degassing processes: Earth and Planetary Science Letters, v. 176, p. 375-386.
Morency, C., and Doin, M.P., 2004, Numerical simulations of the mantle lithosphere delamination: Journal of Geophysical Research, v. 109, doi:10.1029/2003JB002414.
Morgan, W.J., 1971, Convection plumes in the lower mantle: Nature, v. 230, p. 42-43.
Mosar, J., Lewis, G., and Torsvik, T.H., 2002, North Atlantic sea-floor spreading rates:

implications for the Tertiary development of inversion structures of the Norwegian-Greenland Sea: Journal of the Geological Society, London, v. 159, p. 503-515.

Mussett, A.E., 1986, ^{40}Ar-^{39}Ar step-heating ages of the Tertiary igneous rocks of Mull, Scotland: Journal of the Geological Society London, v. 143, p. 887-896.

Nadin, P.A., Kusznir, N.J., and Cheadle, M.J., 1997, Early Tertiary plume uplift of the North Sea and Faeroe-Shetland basins: Earth and Planetary Science Letters, v. 148, p. 109-127.

Natland, J.H., 2003, Capture of helium and other volatiles during the growth of olivine phenocrysts in picritic basalts from the Juan Fernandez Islands: Journal of Petrology, v. 44, p. 421-456.

Nevle, R.J., Brandriss, M.E., Bird, D.K., McWilliams, M.O., and O'Neil, J.R., 1994, Tertiary plutons monitor climate change in East Greenland: Geology, v. 22, p. 775-778.

Nielsen, T.K., and Hopper, J.R., 2002, Formation of volcanic rifted margins: are temperature anomalies required?: Geophysical Research Letters, v. 29, doi:10.1029/2002GL015681.

Noble, R.H., Macintyre, R.M., and Brown, P.E., 1988, Age constraints on Atlantic evolution: timing of magmatic activity along the E Greenland continental margin: Journal of the Geological Society Special Publications, v. 39, p. 201-214.

Nunns, A.G., 1983, Plate tectonic evolution of the Greenland-Scotland Ridge and surrounding regions: NATO Conference Series IV; Marine Sciences, v. 8, p. 11-30.

O'Nions, R.K., and Pankhurst, R.J., 1974, Rare-earth element distribution in Archaean gneisses and anorthosites, Godthab area, West Greenland: Earth and Planetary Science Letters, v. 22, p. 328-338.

Oskarsson, N., Sigvaldason, G.E., and Steinthorsson, S., 1982, A dynamic model of rift zone petrogenesis and the regional petrology of Iceland: Journal of Petrology, v. 23, p. 28-74.

Ozima, M., and Igarashi, G., 2000, The primordial noble gases in the Earth: a key constraint on Earth evolution models: Earth and Planetary Science Letters, v. 176, p. 219-232.

Pascal, C., van Wijk, J.W., Cloetingh, S.A.P.L., and Davies, G.R., 2002, Effect of lithosphere thickness heterogeneities in controlling rift localization: numerical modeling of the Oslo Graben: Geophysical Research Letters, v. 29, doi:10.1029/2001GL014354.

Pearson, D.G., Emeleus, C.H., and Kelley, S.P., 1996, Precise $^{40}Ar/^{39}Ar$ age for the initiation of Palaeogene volcanism in the Inner Hebrides and its regional significance: Journal of the Geological Society of London, v. 153, p. 815-818.

Phipps Morgan, J., and W.J. Morgan, 1999, Two-stage melting and the geochemical evolution of the mantle: a recipe for mantle plum-pudding: Earth and Planetary Science Letters, v. 170, p. 215-239.

Planke, S., Symonds, P.A., Alvestad, E., and Skogseid, J., 2000, Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins: Journal of Geophysical Research, v. 105, p. 19,335-19,351.

Prestvik, T., 1978, Cenozoic plateau lavas of Spitsbergen: a geochemical study: Arbok-Norsk Polarinstitutt, v. 1977, p. 129-142.

Price, S., Brodie, J., Whitham, A., and Kent, R, 1997, Mid-Tertiary rifting and magmatism in the Traill Ø region, East Greenland: Journal of the Geological Society London, v. 154, p. 419-434.

Pumhösl, H., 1998, Petrographische und geochemische Untersuchungen an den Basalten der Insel Salisbury, Franz Josef-Land, Russische Arktis: Mitteilungen der Oesterreichischen Mineralogischen Gesellschaft, v.143, p.218-219.

Raum, T., 2000, Crustal structure and evolution of the Faeroe, more and Vøring margins from wide-angle seismic and gravity data. Thesis, University of Bergen, Norway.

Ren, S., Faleide, J.I., Eldholm, O., Skogseis, J., and Gradstein, F., 2003, Late Cretaceous-Paleocene tectonic development of the NW Vøring Basin: Marine and Petroleum Geology, v. 20, p. 177-206.

Ribe, N.M., and Christensen, U.R., 1994, Three-dimensional modeling of plume-lithosphere interaction: Journal of Geophysical Research, v. 99, p. 669-682.

Richardson, K.R., Smallwood, J.R., White, R.S., Snyder, D., and Maguire, P.K.H., 1998, Crustal structure beneath the Faeroe Islands and the Faeroe-Iceland Ridge: Tectonophysics, v. 300, p. 159-180.

Ritsema, J., van Heijst, H.J., and Woodhouse, J.H., 1999, Complex shear wave velocity structure imaged beneath Africa and Iceland: Science, v. 286, p. 1925-1928.

Robillard,, I., Francis, D., and Ludden, J.N., 1992, The relationship between E- and N-type magmas in the Baffin Bay lavas: Contributions to Mineralogy and Petrology, v. 112, p. 230-241.

Roest, W.R., and Srivastava, S.P., 1989, Sea-floor spreading in the Labrador Sea; a new reconstruction: Geology, v. 17, p. 1000-1003.

Rohrman, M. and van der Beek, P., 1994, Cenozoic postrift domal uplift of North Atlantic margins: an asthenospheric diapirism model: Geology, v. 24, p. 901-904.

Rogers, G.C., 1982, Oceanic plateaus as meteorite impact signatures: Nature, v. 299, p. 341-342.

Ross, J.G., and Mussett, A.E., 1976, ^{40}Ar/^{39}Ar dates for spreading rates in eastern Iceland: Nature, v. 259, p. 36-38.

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J., and Kent, R.W., 1997, The North Atlantic Igneous Province. In: Large Igneous Provinces: continental, oceanic and planetary flood volcanism. Geophysical Monograph, v. 100, p. 45-93.

Saunders, A.D., Kempton, O.D., Fitton, J.G., and Larsen, L.M., 1999, Sr, Nd, and Pb isotopes and trace element geochemistry of basalts from the Southeast Greenland margin: Proceedings of the Ocean drilling Program, Scientific Results, v. 163, p. 77-93.

Schilling, J.G., Meyer, P.S., and Kingsley, R.H., 1983, Rare earth geochemistry of Iceland basalts: spatial and temporal variations: NATO Conference Series IV, Marine Sciences, v.8, p. 319-342.

Schott, B., Yuen, D. and Schmeling, H., 2000, The significance of shear heating in continental delamination: Physics of the Earth and Planetary Interiors, v. 118, p. 273-290.

Séranne, M., and Séguret, M., 1987, The Devonian basins of western Norway: tectonics and kinematics of an extending crust: Geological Society Special Publications, v. 28, p. 537-548.

Sinton, C.W., and Duncan, R.A., 1998, ^{40}Ar-^{39}Ar ages of lavas from the Southeast Greenland margin, ODP Leg 152, , and the Rockall Plateau, DSDP Leg 81: Proceedings of the Ocean Drilling Program, Scientific Results, v. 152, p. 387-402.

Sinton, C.W., Hitchen, K., and Duncan, R.A., 1998, ^{40}Ar-^{39}Ar geochronology of silicic and basic volcanic rocks: Geological Magazine, v. 135, p. 161-170.

Skaarup, N., Jackson, H.R., and Oakey, G., 2006, Margin segmentation of Baffin Bay/Davis Strait, eastern Canada based on seismic reflection and potential field data: Marine and Petroleum Geology, v. 23, p. 127-144.

Skogseid, J., and Eldholm, O., 1989, Vøring Plateau continental margin: seismic interpretation, stratigraphy and vertical movements: Proceedings of the Ocean Drilling Program, Scientific Results, v. 104, p. 993-1030.

Skogseid, J., Pedersen, T., and Larsen, V.B., 1992, Vøring Basin: subsidence and tectonic evolution: NPF Special Publication, v. 1, p. 55-82.

Skogseid, J., and Eldholm, O., 1995, Rifted continental margin off mid-Norway: Rifted ocean-continent boundaries, Banda, E., et al. (eds), Kluwer, p. 147-153.
Sleep, N.H., 1996, Lateral flow of hot plume material ponded at sublithospheric depths: Journal of Geophysical Research, v. 101, p. 28,065-28,083.
Sleep, N.H., 1997, Lateral flow and ponding of starting plume material: Journal of Geophysical Research, v. 102, p. 10,001-10,012.
Smallwood, J.R., Staples, R.K., Richardson, K.R., and White, R.S., 1999, Crust generated Above the Iceland mantle plume; from continental rift to oceanic spreading center: Journal of Geophysical Research, v. 104, p. 22,885-22,902.
Sørensen, A.B., 2003, Cenozoic basin development and stratigraphy of the Faeroes area: Petroleum Geoscience, v. 9, p. 189-207.
Storey, M., Duncan, R.A., Pedersen, A.K., Larsen, L.M., and Larsen, H.C., 1998, $^{40}Ar/^{39}Ar$ geochronology of the West Greenland Tertiary volcanic province: Earth and Planetary Science Letters, v. 160, p. 569-586.
Strachan, R.A., 1994, Evidence in North-east Greenland for Late Silurian-Early Devonian regional extension during the Caledonian Orogeny: Geology, v. 22, p. 913-916.
Stuart, F.M., Lass-Evans, S., Fitton, J.G. and Ellam, R.M., 2003, Extreme 3He/4He in picritic basalts from Baffin Island: the role of a mixed reservoir in mantle plumes: Nature, v. 424, p. 57-59.
Sun, S.S., and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes: Geological Society Special Publications, v. 42, p. 313-345.
Surlyk, F., 1990, Timing, style and sedimentary evolution of late Palaeozoic-Mesozoic extensional basins of East Greenland: Geological Society Special Publications, v. 55, p. 107-125.
Tate, M.P., 1993, Structural framework and tectono-stratigraphic evolution of the Porcupine Seabight Basin, offshore western Ireland: Marine and Petroleum Geology, v. 10, p. 95-123.
Taylor, P.N., and Morton, A.C., 1989, Sr, Nd and Pb isotope geochemistry of the upper and lower volcanic series at Site 642: Proceedings of the Ocean Drilling Program Scientific Results, v. 104, p. 429-435.
Taylor, S.R., and McLennan, S.M., 1985, The continental crust: its composition and evolution: Blackwell Scientific Publications, 312 pp.
Tegner, C., and Duncan, R.A., 1999, 40Ar-39Ar chronology for the volcanic history of the Southeast Greenland rifted margin: Proceedings of the Ocean Drilling Program, Scientific Results, v. 163, p. 53-62.
Tegner, C., Duncan, R.A., Bernstein, S., et al., 1998, ^{40}Ar-^{39}Ar geochronology of Tertiary mafic intrusions along the east Greenland rifted margin;: relation to flood basalt and the Iceland hotspot track: Earth and Planetary Science Letters, v. 156, p. 75-88.
Thompson, R., and Gibson, S., 1991, Sub-continental mantle plumes, hot-spots and pre-existing thinspots: Journal of the Geological Society London, v. 148, p. 973-977.
Thompson, P., Mussett, A.E., and Dagley, P., 1987, Revised ^{40}Ar-^{39}Ar age for granites of the Mourne Mountains, Ireland: Scottish Journal of Geology, v. 23, p. 215-220.
Thompson, R.N., Dickin, A.P., Gibson, I.L., and Morrison, M.A., 1982, Elemental fingerprints of isotopic contamination of Hebridean Palaeocene mantle-derived magmas by Archaen sial: Contributions to Mineralogy and Petrology, v 79, p. 159-168.
Thoraval, C., Tommasi, A., and Doin, M.P., 2006, Plume-lithosphere interaction beneath a fast moving plate: Geophysical Research Letters, v. 33, doi:10.1029/2005GL024047.
Torsvik, T.H., Mosar, J., and Eide, E.A., 2001, Cretaceous-Tertiary geodynamics: a North

Atlantic exercise: Geophysical Journal International., v. 146, p. 850-866.
Troll, V.R., Donaldson, C.H., and Emeleus, C.H., 2004, Pre-eruptive magma mixing in ash-flow deposits of the Tertiary Rum Igneous Centre, Scotland: Contributions to Mineralogy and Petrology, v. 147, p. 722-739.
Tsikalas, F., Eldholm, O., and Faleide, J.I., 2005, Crustal structure of the Lofoten-Vesterålen continental margin, off Norway: Tectonophysics, v. 404, p. 151-174.
Turner, S., Hawkesworth, C., Gallagher, K., Stewart, K., Peate, D., and Mantovani, M., 1996, Mantle plumes, flood basalts, and thermal models for melt generation beneath continents: assessment of a conductive heating model and application to the Paraná: Journal of Geophysical Research, v. 101, p.11,503-11,518.
Upton, B.G.J., 1988, History of Tertiary igneous activity in the N Atlantic borderlands: Geological Society Special Publications, v. 39, p. 429-453.
Upton, B.G.J., Emeleus, C.H., Rex, D.C., and Thirlwall, M.F., 1995, Early Tertiary magmatism in NE Greenland: Journal of the Geological Society of London, v. 152, p. 959-964.
Upton, B.G.J., Skovgaard, A.C., McClurg, J., Kirstein, L., Cheadle, M., Emeleus, C.H., Wadsworth, W.J., and Fallick, A.E., 2002, Picritic magmas and the Rum ultramafic complex, Scotland: Geological Magazine, v. 139, p. 437-452.
Vågnes, E. and Amundsen, H., 1993, Late Cenozoic uplift and volcanism on Spitsbergen-caused by mantle convection. Geology, v. 21, p. 251-254.
van der Hilst, R.D., and de Hoop, M.V., 2005, Banana-doughnut kernels and mantle tomography: Geophysical Journal International., v. 163, p. 956-961.
van Wijk, J.W., Huismans, R.S., Ter Voorde, M., and Cloetingh, S.A.P.L., 2001, Melt generation at volcanic continental margins: no need for a mantle plume?: Geophysical Research Letters, v. 28, p. 3995-3998.
van Wijk, J.W., van der Meer, R., and Cloetingh, S.A.P.L., 2004, Crustal thickening in an extensional regime: application to the mid-Norwegian Vøring margin: Tectonophysics, v. 387, p. 217-228.
Vogt, P.R., 1971, Asthenosphere motion recorded by the ocean floor south of Iceland: Earth and Planetary Science Letters, v. 13, p. 153-160.
Vogt, P.R., and Avery, O.E., 1974, Detailed magnetic surveys in the Northeast Atlantic and Labrador Sea: Journal of Geophysical Research, v. 79, p. 363-389.
Vogt, P.R., Johnson, G.L., and Kristjansson, L., 1980, Morphology and magnetic anomalies north of Iceland: Journal of Geophysics, v. 47, p. 67-80.
Vogt, U., Makris, J., O'Reilly, B.M., et al., 1998, The Hatton bank and continental margin: crustal structure from wide-angle seismic and gravity data: Journal of Geophysical Research, v. 103, p. 12545-12566.
Vogt, P.R., and Jung, W.-Y., 2005, Paired basement ridges: spreading axis migration across mantle heterogeneities?: Geological Society of America Special Paper, v. 388, p. 555-579.
Waagstein, R., 1988, Structure, composition and age of the Faeroe basalt plateau: Geological Society Special Publications, v. 39, p. 225-238.
White, R.S., and McKenzie, D.P., 1989, Magmatism at rift zones: the generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, p. 7685-7729.
White, R.S., Bown, J.W., and Smallwood, J.R., 1995, The temperature of the Iceland plume and origin of outward-propagating V-shaped ridges: Journal of the Geological Society of London, v. 152, p. 1039-1045.
Yasuda, A., Fujii, T., and Kurita, K., 1994, Melting phase relations of an anhydrous mid-ocean ridge basalt from 3 to 20 GPa: implications for the behaviour of subducted

oceanic crust in the mantle: Journal of Geophysical Research, v. 99, p. 9401-9414.
Ziegler, P.A., 1988, Evolution of the Arctic-North Atlantic and the western Tethys: AAPG Memoir, v. 43, Tulsa, Okla., 198 pp.
Zindler, A., Staudigel, H., and Batiza, R., 1984, Isotope and trace element geochemistry of young Pacific seamounts: implications for the scale of upper mantle heterogeneity: Earth and Planetary Science Letters, v. 70, p. 175-195.

Fig. 1 The North Atlantic Igneous Province. Tertiary onshore and offshore 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= Mohns 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.

Fig. 2 Schematic overview of tectonic history of the 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 offshore 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 is related to a period of magmatism; several magmatic episodes (relatively minor in volume) have preceded the formation of the NAIP. Continental breakup in the Northeast Atlantic follows the Paleocene rift event. See text for references.

Fig. 3 Geochemical overview of NAIP magmas. (a) $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ diagram for igneous NAIP products. 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 $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ in crustal rocks are related to age and the contrasting geochemical behaviour of Sm and Nd relative to Rb and Sr. The mantle plume model suggests that the correlation of initial Nd and Sr isotopes represent mixing lines, between “mantle zoo” reservoirs of distinct chemistry and age. DMM = Depleted MORB Mantle; DMM = Depleted MORB Mantle; HIMU = High _ (subducted oceanic crust); EM1 and EM2 = Enriched Mantle 1 (recycled pelagic ocean floor sediments / sub-continental lithosphere) and 2 (subducted continental material); fields from Hart (1984) and Hart and Zindler (1989). Alternatively, the trend may result from mixing by assimilation / 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 sub-NAIP areas (Scotland). See section 4 for a discussion. Data are from the Max Planck Institut für Chemie, Geochemistry Division GeoRoc database.

(b) Masuda-Coryell diagram comparing REE compositions of the sub-NAIP areas. The REE patterns are controlled by the source geochemistry and crystal-melt equilibrias. 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 sub-NAIP areas include both; melts from an enriched mantle source and magmas generated from a depleted mantle. Data are from the Max Planck Institut fŸr Chemie, Geochemistry Division GeoRoc database and the N-MORB, EMORB and OIB line 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).

Fig. 4 Cenozoic ages of NAIP 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. Dataset: Brooks and Gleadow (1977), Gleadow and Brooks (1979), Bugge et al. (1980), Dickin (1981), Dickin and Jones (1983), Mussett (1986), Thompson et al. (1987), Gibson et al. (1987), Noble et al. (1988), Hitchen and Ritchie (1993), Nevle et al. (1994), Upton et al. (1995), Pearson et al. (1996), 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), Moorbath et al. (1968), Ross and Mussett (1976), Hardarson et al. (1997), and Foulger (2006).

Fig. 5 Transient Paleocene-Eocene boundary uplift in the NAIP. 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), Deptuck et al. (2003), Ceramicola et al. (2005), Jones et al. (2001), Ren et al. (2003), Jones and White (2003), Mackay et al. (2005) and Knox (1998).

Fig. 6 Schematic overview of different models suggested for LIP or NAIP 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 non-craton 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 existing thin spot in the lithosphere, causing uplift, and excessive melting.

Fig1 Meyer et al. (P4)

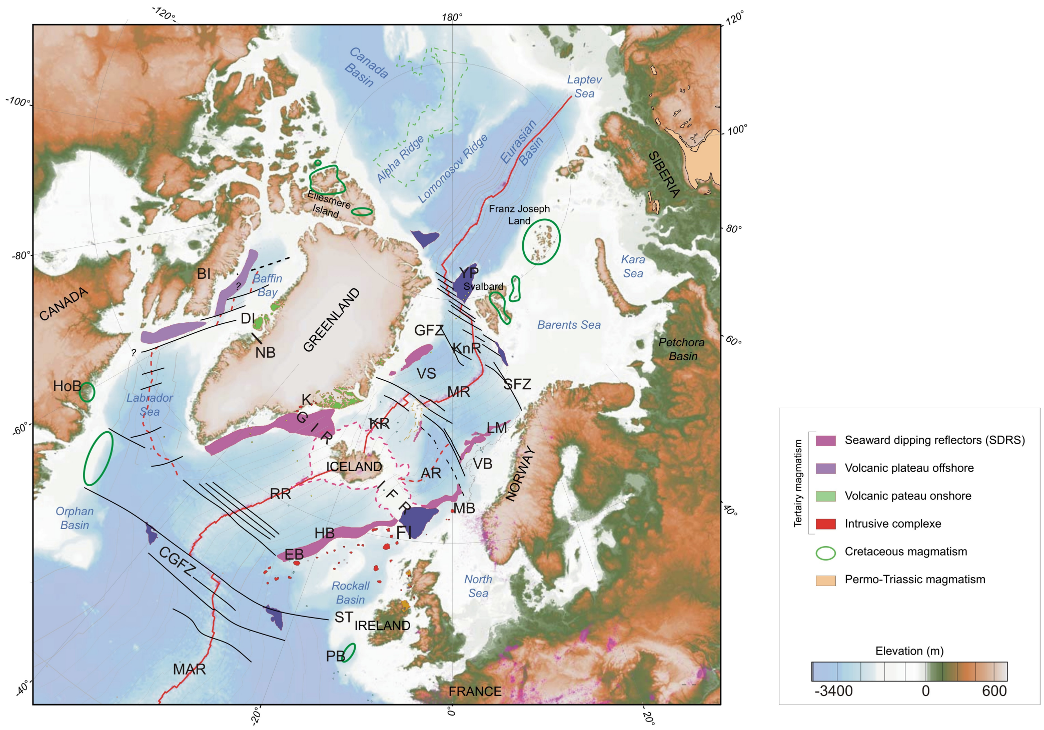

Fig2 Meyer et al. (P4)

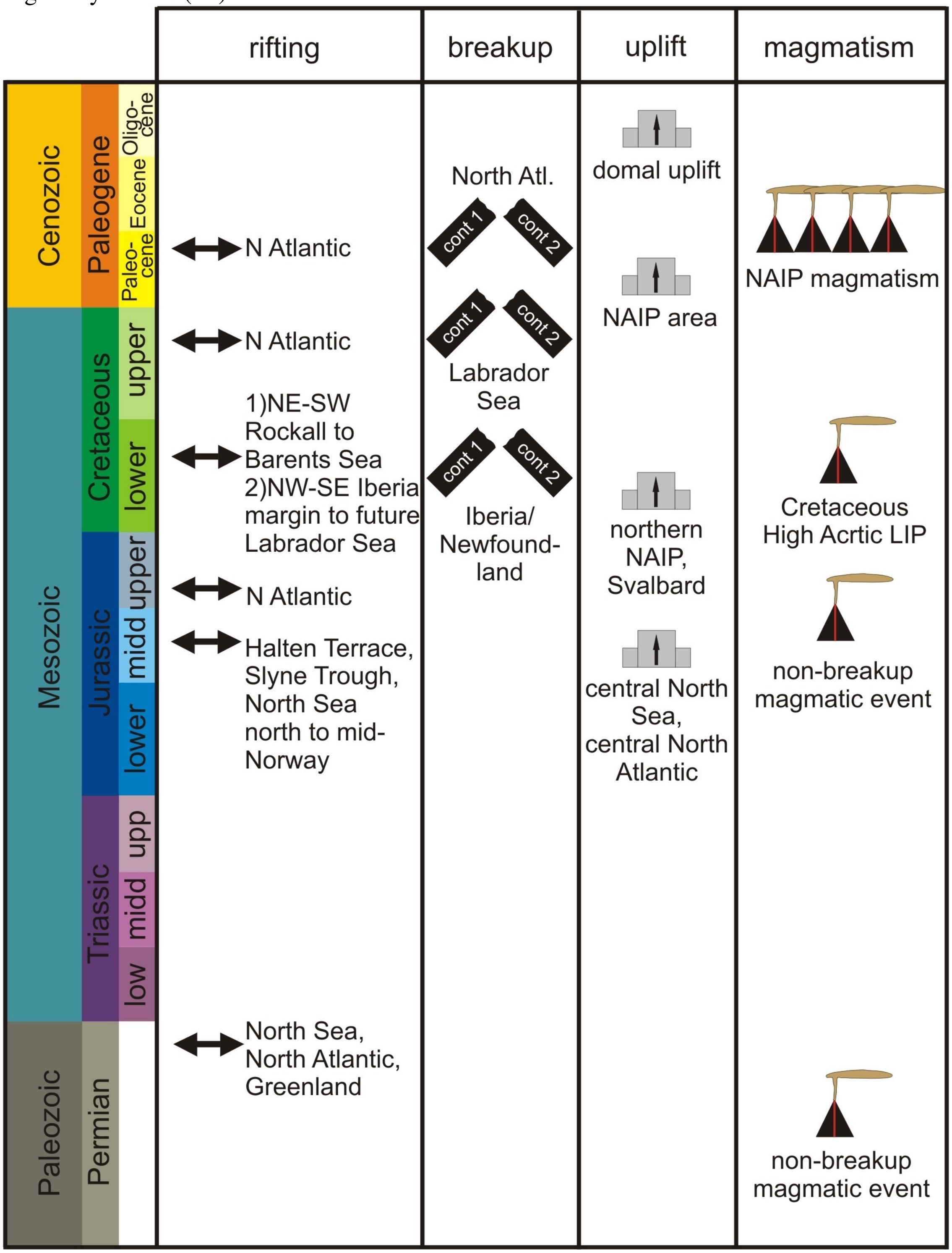

Fig3a Meyer et al. (P4)

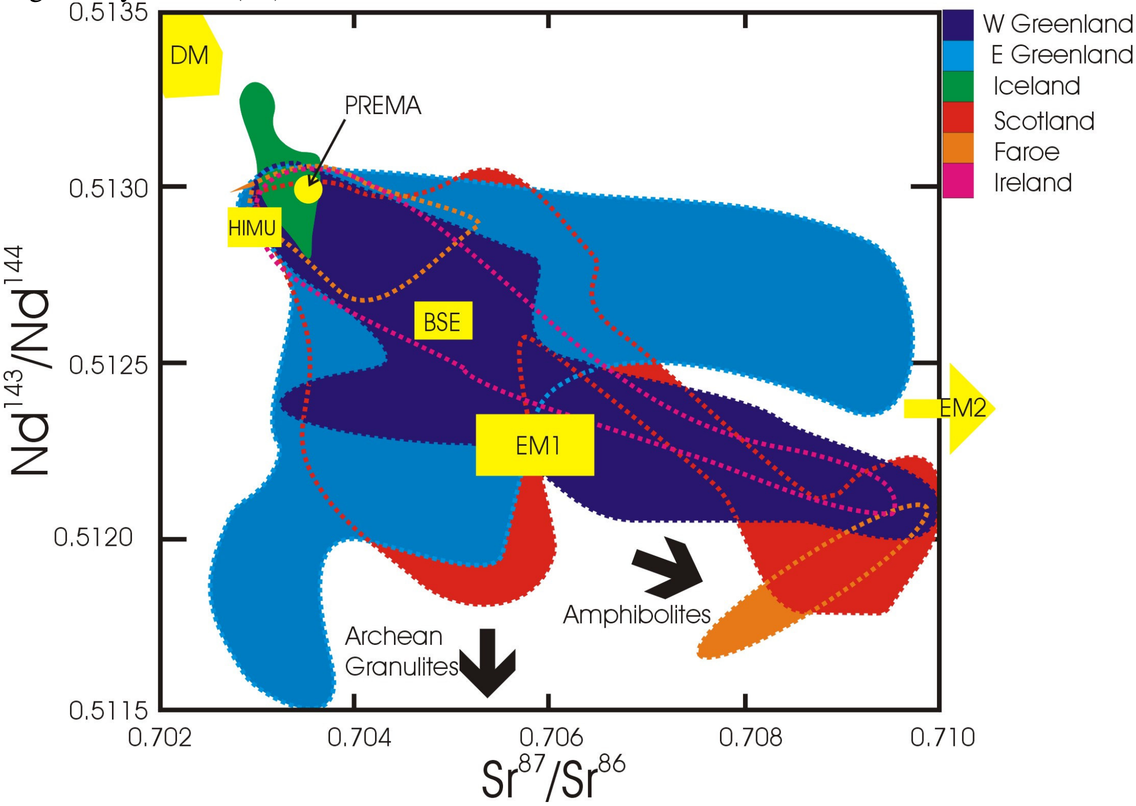

Fig3b Meyer et al (P4)

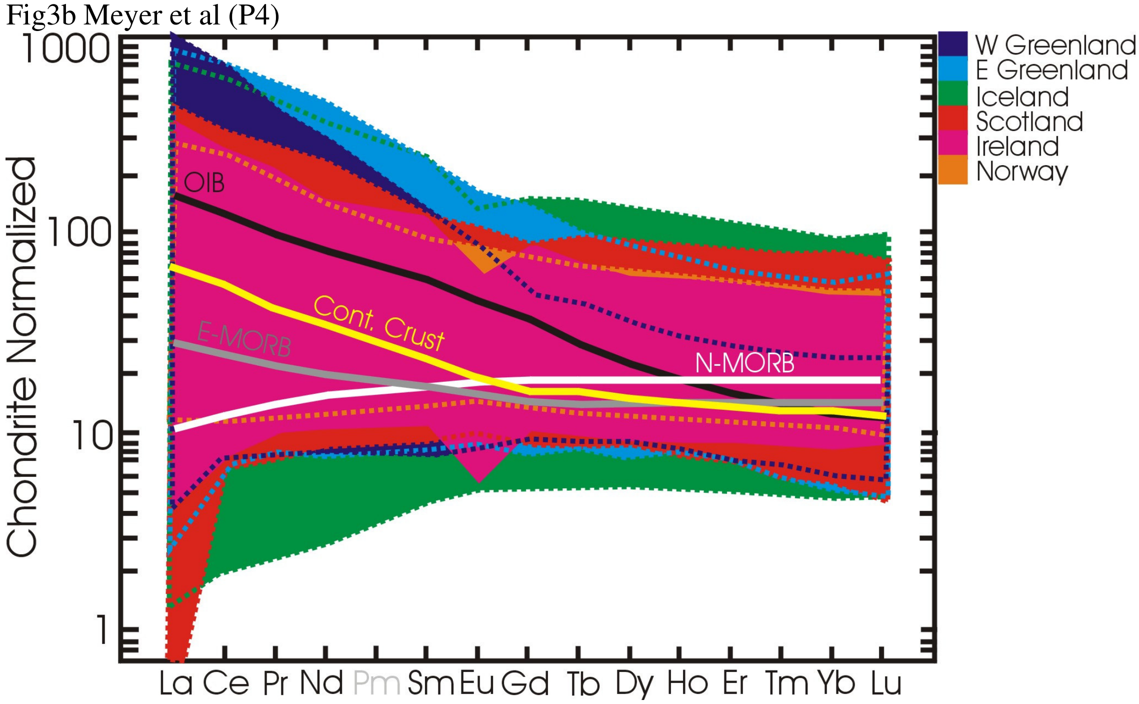

Fig4 Meyer et al. (P4)

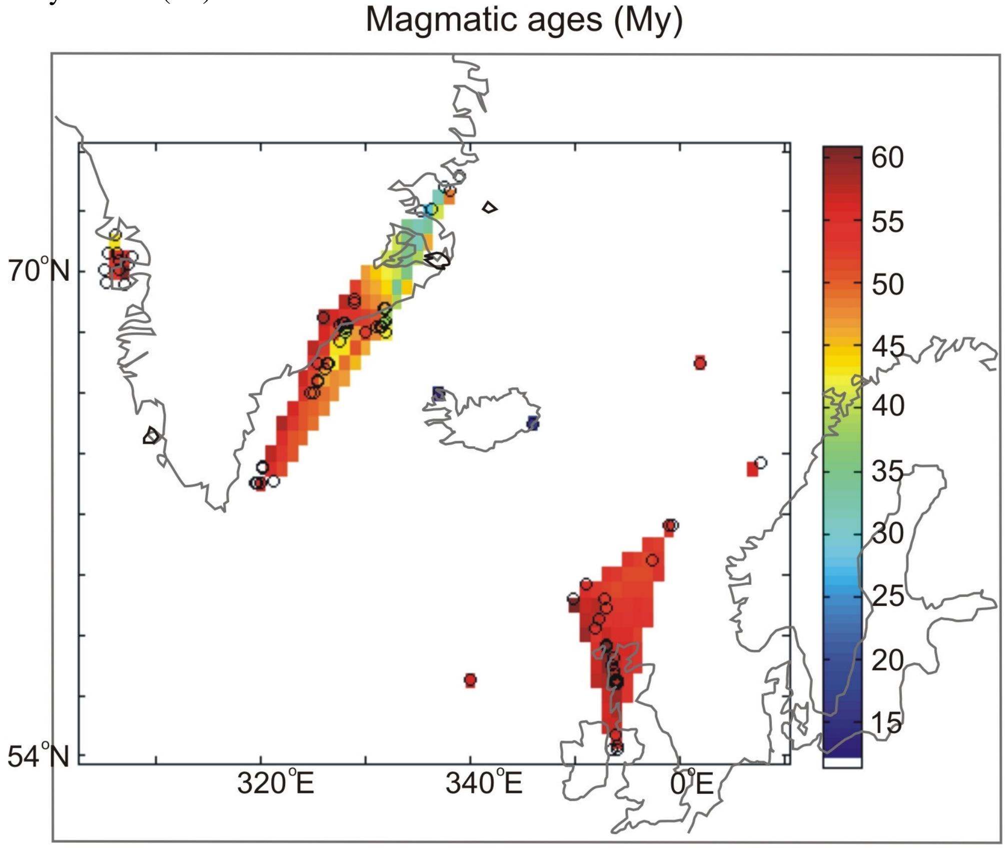

Fig5 Meyer et al. (P4)

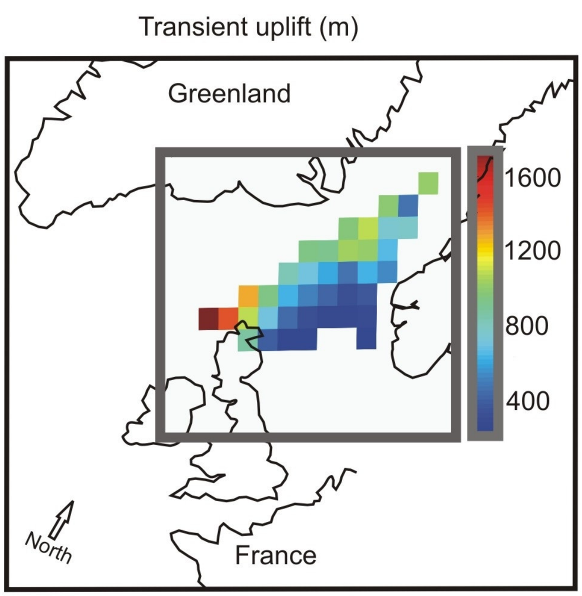

Fig6 Meyer et al. (P4)