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The onset of the North Atlantic Igneous Province in a rifting perspective

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Abstract – The processes that led to the onset and evolution of the North Atlantic Igneous Province (NAIP) have been a theme of debate in the past decades. A popular theory has been that the impingement on the lower lithosphere of a hot mantle plume (the 'Ancestral Iceland' plume) initiated the first voluminous outbursts of lava and initiated rifting in the North Atlantic area in Early Palaeogene times. Here we review previous studies in order to set the NAIP magmatism in a time–space context. We suggest that global plate reorganizations and lithospheric extension across old orogenic fronts and/or suture zones, aided by other processes in the mantle (e.g. local or regional scale upwellings prior to and during the final Early Eocene rifting), played a role in the generation of the igneous products recorded in the NAIP for this period. These events gave rise to the extensive Paleocene and Eocene igneous rocks in W Greenland, NW Britain and at the conjugate E Greenland–NW European margins. Many of the relatively large magmatic centres of the NAIP were associated with transient and geographically confined doming in Early Paleocene times prior to the final break-up of the North Atlantic area.

Keywords: flood basalts, rifting, orogenic sutures, North Atlantic.

1. Introduction

The North Atlantic Igneous Province (NAIP) is a classic Large Igneous Province associated with a volcanic rifted margin. It has traditionally been considered to comprise the voluminous Palaeogene igneous rocks occurring at the conjugate E Greenland–NW European margins and in the W Greenland–Baffin Bay area (Upton, 1988; Saunders *et al.* 1997; Meyer, Van Wijk & Gernigon, 2007 and references therein). Other contemporaneous magmatism occurred in the northernmost parts of Greenland (Kap Washington Group at *c.* 64 ± 3 Ma, (Estrada, Höhndorf & Henjes-Kunst, 2001) and in the W Barents Sea (Vestbakken Volcanic Province, *c.* 54 Ma, (Tsikalas, Eldholm & Faleide, 2002) (Fig. 1).

The major Early Palaeogene NAIP rocks can be regionally divided into: W Greenland–Baffin Island, SE Greenland, (central–east) CE Greenland, NE Greenland, Vøring margin, Møre margin, Faroe Islands, Rockall–Hatton area, Faroe–Shetland Basin, Rockall Trough and the NW British Isles (Saunders *et al.* 1997) (Fig. 1). Other contemporaneous, smaller and more isolated parts of the NAIP are also shown in Figure 1. The CE Greenland–Faroe Islands Ridge and Iceland formed subsequent to the onset of seafloor spreading in the area (Meyer, Van Wijk & Gernigon, 2007). Exposed and submerged basaltic rocks of the NAIP extend roughly NE–SW for more than 2000 km along the conjugate East Greenland–NW European margins (Saunders *et al.* 1997) (Fig. 1).

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The extrusive rocks of the province cover a surface area of at least $\sim 1.3 \times 10^6$ km^2, while the extrusive and intrusive rocks of the NAIP are together estimated to comprise a volume of $\sim 6.6 \times 10^6$ km^3 (Eldholm & Grue, 1994). The majority of the extrusive rocks at the conjugate E Greenland–NW European margins (the Faroe Islands; Rockall–Hatton and Vøring–Møre) were extruded in subaerial or shallow-marine environments onto continental crust (e.g. Natland & Winterer, 2005). Similarly, the vast majority of the Early Palaeogene W Greenland igneous products were emplaced in continental crust (e.g. Larsen *et al.* 1999*a*) in a subaerial and/or in a shallow marine environment (Storey *et al.* 1998).

Here we use published studies to show that the formation of the NAIP could have been aided by the combined actions of a number of magmatic centres, whose initial actions in part were governed by regional and/or provincial plate tectonic reorganizations.

2. Geological setting prior to and during magmatism

In the context of a large igneous province such as the NAIP, it is pertinent to consider relevant tectonic events prior to the onset of magmatism and to consider possible temporal and spatial links between the igneous products.

2.a. Tectonic settings

Following the closure of the Iapetus Ocean and the collapse of the Caledonian Orogen in Silurian–Devonian times (Roberts, 2003), the proto-North

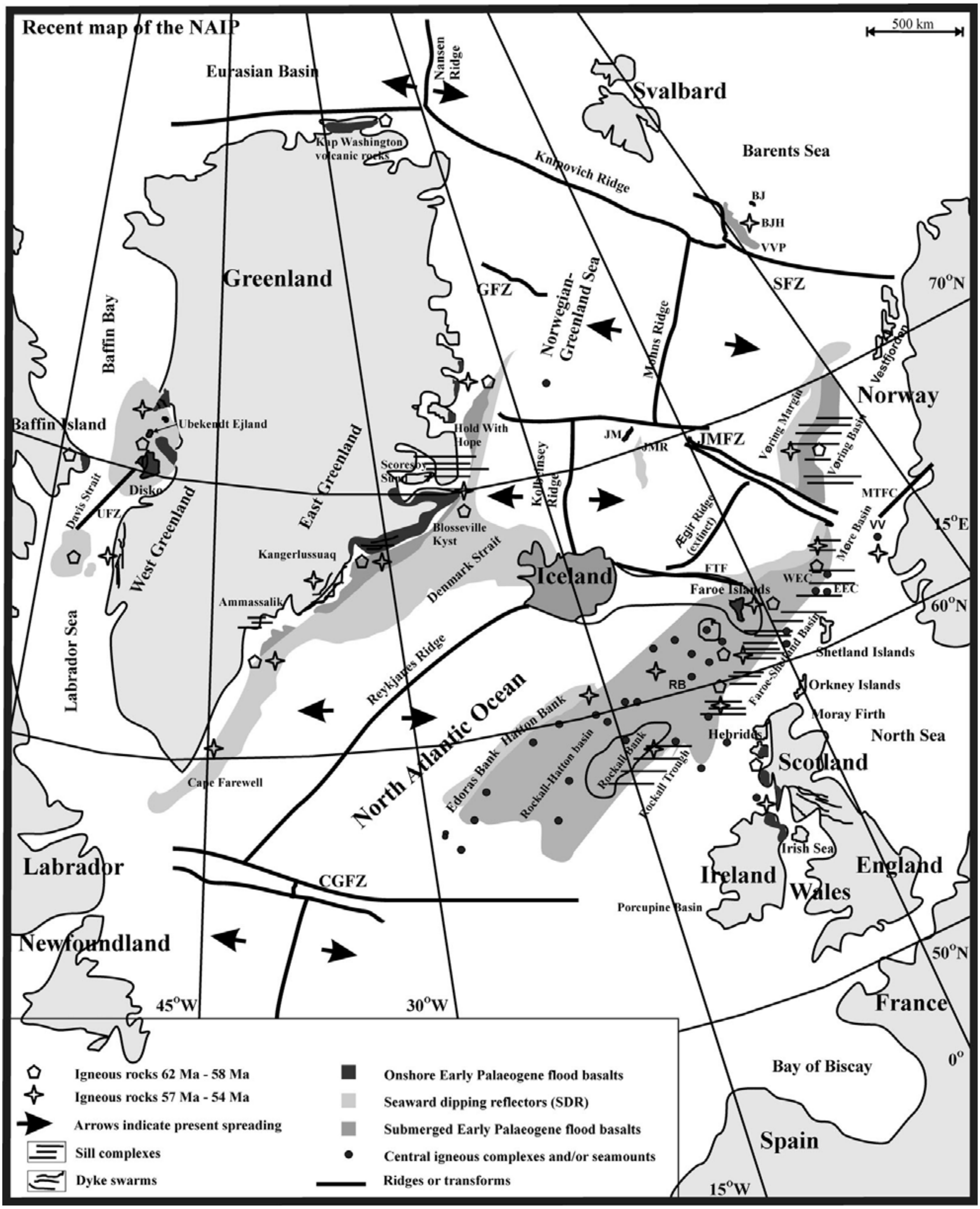

Figure 1. Simplified geological map of the North Atlantic Igneous Province and surrounding areas modified from Saunders *et al.* (1997); Nielsen, Larsen & Hopper (2002) and Nielsen, Stephenson & Thomson (2007). The ages are from the references in Table 1. The Early Palaeogene transient regional uplifts are from references in Table 2. The central igneous complexes and/or seamounts are modified from Bull & Masson (1996); Ritchie, Hitchen & Edwards (1997); Naylor *et al.* (1999); Edwards (2002); Hitchen (2004); Archer *et al.* (2005). Abbreviations: BJ – Bjørnøya; BJH – Bjørnøya High; CGFZ – Charlie Gibbs Fracture Zone; EEC – East Erlend Complex; FTF – Faroe Transform Fault; GFZ – Greenland Fracture Zone; JM – Jan Mayen; JMFZ – Jan Mayen Fracture Zone; JMR – Jan Mayen Ridge; MTFC – Møre–Trøndelag Fault Complex; RB – Rosemary Bank; SFZ – Senja Fracture Zone; UFZ – Ungava Fracture Zone; VV – Vestbrona Volcanic rocks; VVP – Vestbakken Volcanic Province; WEC – West Erlend Complex.

Atlantic area to the south of the Caledonian front (Figs 2, 3) was underlain by a patchwork of Archaean and Proterozoic terranes (Dickin, 1992).

Permian and Triassic broadly E–W-directed extension between Eurasia and Greenland resulted in the formation of numerous large half-graben basins widely distributed at the margins (Ziegler, 1989; Brekke *et al.* 1999; Doré *et al.* 1999; Surlyk, 1990). Jurassic E–W extension between Eurasia and North America–Greenland gave way to a dominantly NW–SE-directed extension in Early to Middle Cretaceous times (Doré *et al.* 1999). The Middle Cretaceous extension resulted in northwards-narrowing sea-floor spreading from the Rockall Trough to the Vøring Basin off W Norway (Price & Rattey, 1984). Renewed NW–SE-directed extension occurred in the proto-NAIP area from the Late Cretaceous to the Early Palaeogene (Doré *et al.* 1999). This event led to the initiation of sea-floor spreading in the Labrador Sea in the Early Paleocene (Chalmers & Laursen, 1995) and the initiation and northwards propagation of sea-floor spreading at the conjugate NW European–E Greenland margins in Early Eocene times (Ziegler, 1989, 1992; Doré *et al.* 1999). At around the same time, the Eurasian Basin began to open (Ziegler, 1989). Early Palaeogene exploitation/reactivation of Precambrian and Caledonian fault zones are inferred for the early phases of continental rifting and NAIP formation (Doré *et al.* 1997, 1999).

Regional vertical movements and the formation of transient domal uplifts preceded the main phases of Early Palaeogene igneous activities in many parts of the NAIP (e.g. Maclennan & Jones, 2006; Meyer, Van Wijk & Gernigon, 2007; Saunders *et al.* 2007). Published examples of some regional domal uplifts are listed in Table 2 (Fig. 2). Without constraining the depth of origin, Saunders *et al.* (2007) suggested that the ascent of narrow hot mantle jets and broadly contemporaneous rifting in areas of uplifts generated doming.

2.b. Igneous settings

While the igneous rocks of the NAIP cover a compositional spectrum from picrites to silicic rocks (Table 1), most of the rocks encountered in the province today are of basaltic composition (e.g. Saunders *et al.* 1997). Crustally contaminated rocks occur at or close to the base of volcanic successions in many parts of the basaltic sequences of the province (Gibson, 2002). The igneous products include both fissure or point-source fed lava-flows (Peate, Larsen & Lesher, 2003; Single & Jerram, 2004; Passey & Bell, 2007), water-influenced and water-lain volcanic successions (e.g. Peate, Larsen & Lesher, 2003; Jerram *et al.* 2009, this issue) and ignimbrites as well as plutonic or sheet intrusions (sills and/or dykes) (Table 1; Fig. 1), each reflecting the processes and crustal environment that prevailed in that particular area during melt emplacement. Most of the igneous activity of the NAIP occurred in the time span from *c.* 62 to *c.* 53 Ma. Two main periods of melt emplacement have been inferred for the NAIP, with ages of *c.* 62 to 58 Ma and *c.* 57 to 53 Ma, and detectable peaks at *c.* 60 Ma and at *c.* 55 Ma, respectively (Saunders *et al.* 1997; Torsvik, Mosar & Eide, 2001; Jerram & Widdowson, 2005; Meyer, Van Wijk & Gernigon, 2007) (Table 1; Fig. 1). Smaller-scale igneous activity preceded these main periods in, for example, the N Rockall Trough (Morton *et al.* 1995; O'Connor *et al.* 2000), continued subsequently in parts of the NAIP area for tens of millions of years (e.g. Tegner & Duncan, 1999; O'Connor *et al.* 2000; Tegner *et al.* 2008), and is continuing on Iceland and on the island of Jan Mayen (e.g. Trønnes *et al.* 1999) (Table 1; Fig. 1).

3. The spatial distribution of known and inferred magmatic centres of the NAIP

It is noticeable that many of the inferred earliest igneous activities in the NAIP coincide well with some of the transient uplifts recorded for this period (Figs 1, 2; Tables 1, 2). Furthermore, it appears that a number of the uplifted regions and the parts of the NAIP with the most voluminous igneous production for this period, namely in the NW British Isles, the Faroe Islands, (central-east) CE Greenland and the Disko region in W Greenland (Upton, 1988; Saunders *et al.* 1997; Meyer, Van Wijk & Gernigon, 2007), were emplaced in the vicinity of old orogenic sutures and/or fronts from the Palaeozoic Caledonian Orogen, at suture zones between Archaean–Proterozoic terranes at the conjugate East Greenland–NW European margins and at the suture zone between the Archaean Nagssugtoqidian–Rinkian Orogen in the Disko–Baffin Island area (Figs 1, 2, 3).

In a reconstructed map of the NAIP region intended to show the spatial distribution of the igneous activities for the Middle Paleocene (Fig. 2; Table 1), the magmatic regions and/or centres at the conjugate E Greenland–NW European margins seem to form conspicuous double zigzag and roughly NNE–SSW-directed trends, from just to the north of Hold With Hope and southwards to the Ammassalik area along the E Greenland margin and from the Vøring area and southwards to the NW British Isles area at the NW European margin, converging at the CE Greenland–Faroe Islands area. According to current published data the igneous activities in N and W Greenland were spatially isolated from these events.

The suggested trends of igneous activities at the conjugate E Greenland–NW European margin from the Middle Paleocene seem to be more or less repeated in the Early Eocene (Fig. 3; Table 1), apart from the westward relocation of magmatism at the Vøring margin, the eastward relocation of magmatism at the Blosseville Kyst and the establishment of volcanism in the W Barents Sea. Final sea-floor spreading at the

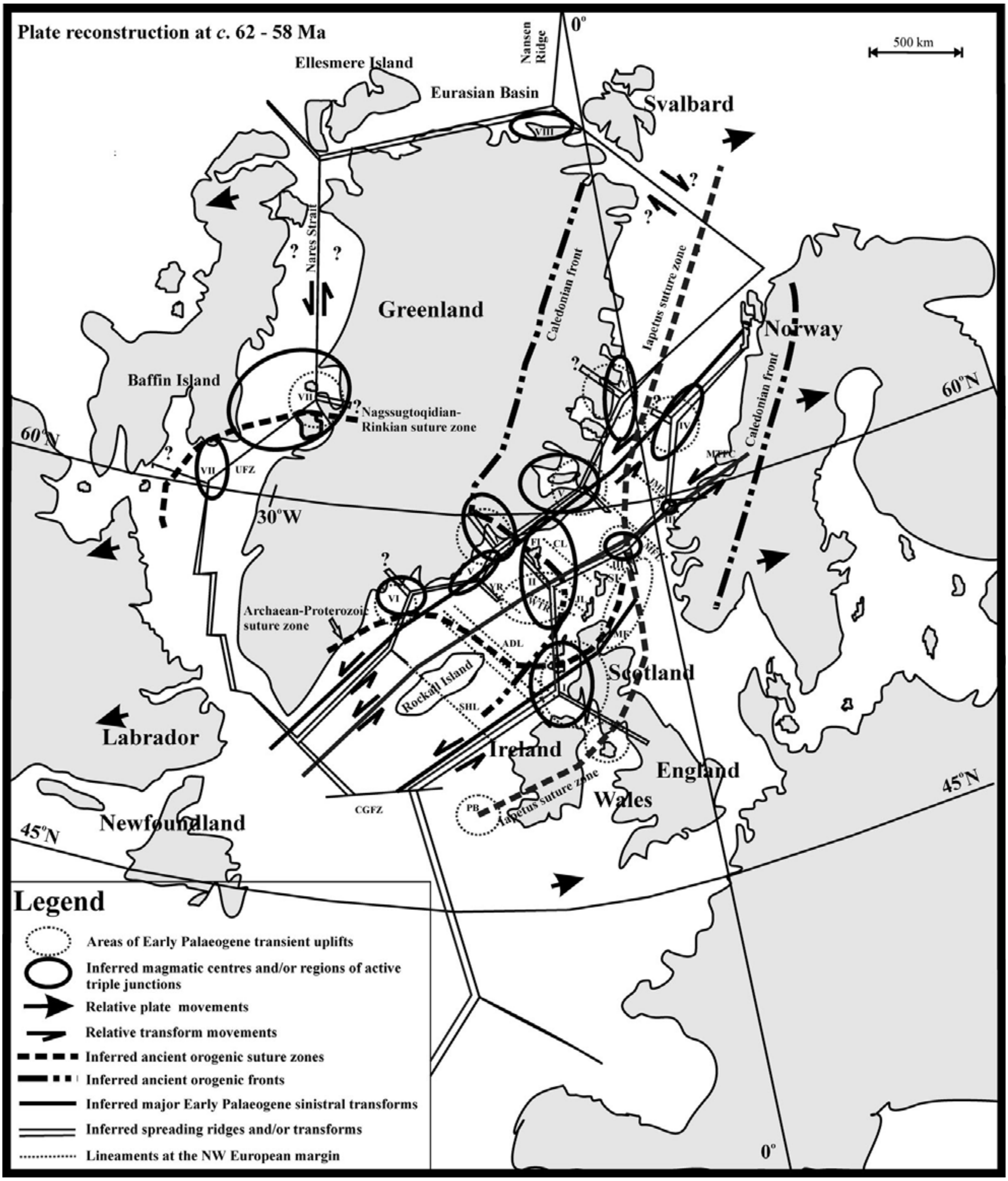

Figure 2. Simplified map of the NAIP at around 62 to 58 Ma modified from Torsvik *et al.* (2001) and Torsvik, Mosar & Eide (2001). The inferred locations of the Caledonian fronts and the Iapetus suture zone are from: Bott (1987); Soper *et al.* (1992); Ziegler (1992); Masson, Hauser & Jacob (1999); Skogseid *et al.* (2000); Hansen & Brooks (2002); Roberts (2003); Foulger, Natland & Anderson (2005*a*,*b*); Cocks (2005). The inferred Archaean–Proterozoic suture zone in the Rockall–Hatton–NW Britain area is modified from Dickin (1992). The inferred Nagssuqtocidian–Rinkian suture zone in the Disko region is modified from Krawiec (A. Krawiec, unpub. M.S. thesis, Univ. Texas Austin, 2003) and Connelly *et al.* (2006). The three major sinistral transforms are modified from Nielsen, Stephenson & Thomsen (2007). Broadly NW-trending lineaments at the NW European margin are modified from Kimbell *et al.* (2005). General spreading directions are from Harrison *et al.* (1999) and Nielsen, Stephenson & Thomsen (2007). Abbreviations: ADL – Anton Dohrn Lineament; CGFZ – Charlie Gibbs Fracture Zone; CL – Claire Lineament; JL – Judd Lineament; JML – Jan Mayen Lineament; FI – Faroe Islands; MF – Moray Firth; MFL – Marflo Lineament; MTFC – Møre–Trøndelag Fault Complex; PB – Porcupine Basin; SHL – South Hatton Lineament; SI – Shetland Islands; UFZ – Ungave Fault Zone; WTR – Wyville-Thomson Ridge; YR – Ymir Ridge. See text for further explanation.

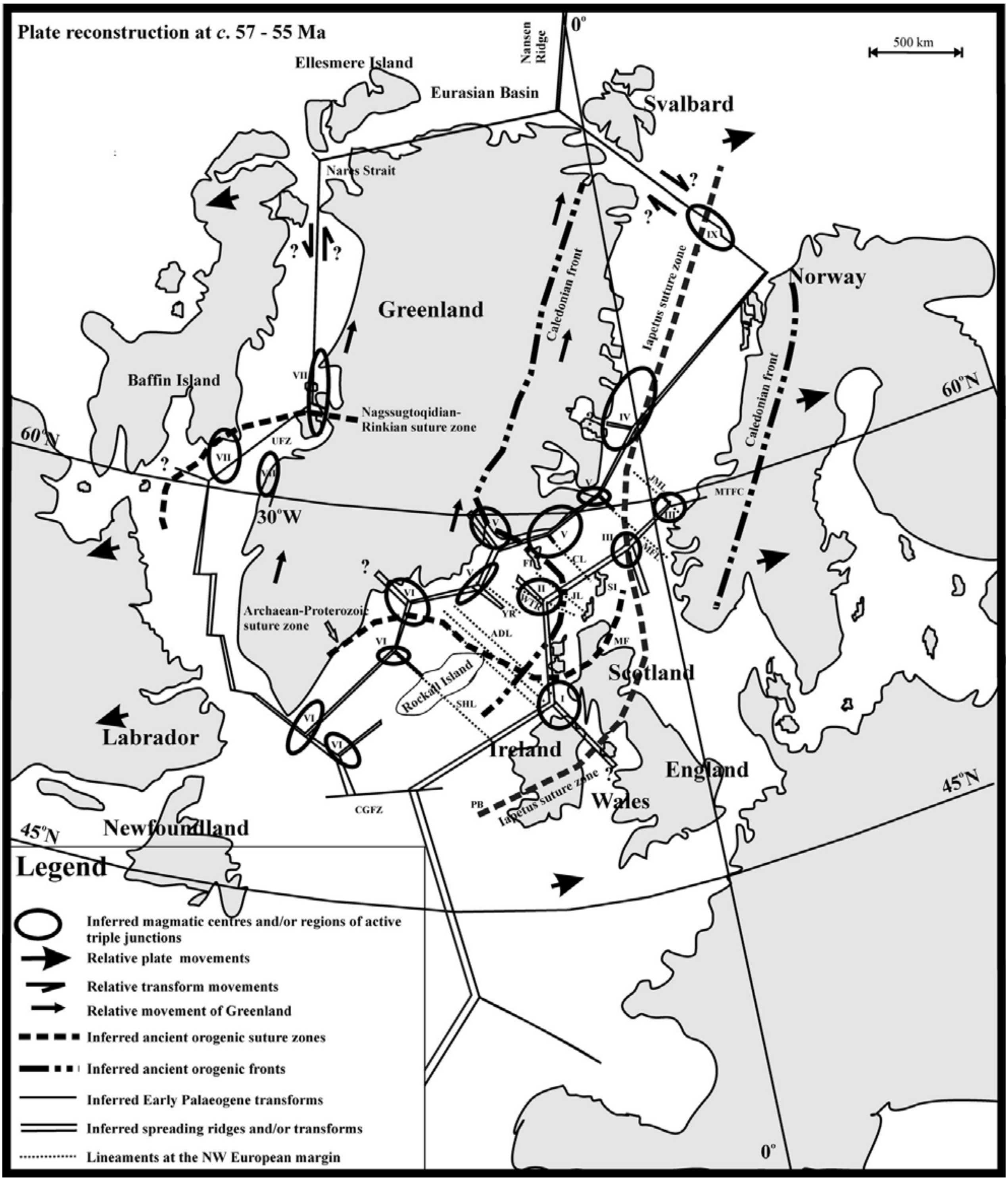

Figure 3. Simplified map of the NAIP at around 57 to 55 Ma modified from Torsvik *et al.* (2001) and Torsvik, Mosar & Eide (2001). Explanation and abbreviations as in Figure 2. See text for further explanation.

Blosseville Kyst latitude occurred further to the east at *c.* 54 Ma (Bott, 1985).

Each part of the double zigzag geometry for the inferred Early Palaeogene magmatic trends of the NAIP in the NE Atlantic area (Figs 2, 3) seems to resemble the classic rifting trends associated with the embryonic stages of continental rifting where the surface expression of the rift processes appears as interconnected triple junctions at various stages of development (Burke & Dewey, 1973; Ziegler, 1989; Park, 1995; Sears, George & Winne, 2005).

3.a. **The NW British Isles** (Fig. 1; 'I' in Figs 2, 3)

A magmatic centre at an Early Palaeogene triple junction in the Hebrides–Ireland area has been inferred to have caused the contemporaneous magmatism in the NW British Isles (Burke & Dewey, 1973; Geoffroy,

Table 1. Summary of Early Palaeogene ages for the key regions of the North Atlantic Igneous Province (most studies are overlapping and fall within the time frames from *c.* 62 Ma to *c.* 53 Ma)

Regions: average emplacement ages	Rock compositions: modes of emplacements	Published examples
British Isles: *c.* 61 to *c.* 55 Ma	Ultramafic, mafic, silicic: volcanic, plutons, sills, dykes	Gamble, Wysoczanski & Meigham (1999); Chambers, Pringle & Parrish (2005); Storey, Duncan & Tegner (2007)
Rockall-Hatton margin: *c.* 58 to *c.* 53 Ma	Mafic, silicic: volcanic, plutons, sills, dykes	Sinton & Duncan (1998); Hitchen (2004)
Rockall Trough: *c.* 70 to *c.* 54 Ma	Mafic, silicic: volcanic, sills	Hitchen & Ritchie (1993); Morton *et al.* (1995); Sinton, Hitchen & Duncan (1998); O'Connor *et al.* (2000); Archer *et al.* (2005)
Faroe-Shetland Basin: *c.* 61 to *c.* 55 Ma	Mafic, silicic: volcanic, sills, dykes	Hitchen & Ritchie (1993); Trude *et al.* (2003)
Vøring margin: *c.* 61 to *c.* 55 Ma	Mafic, silicic: volcanic, sills, dykes	Skogseid *et al.* (1992); Sinton, Hitchen & Duncan (1998); Planke *et al.* (2005)
Møre Margin: *c.* 56 to *c.* 55 Ma	Mafic: sills	Planke *et al.* (2005)
Faroe Islands: *c.* 61 to *c.* 55 Ma	Ultramafic, mafic: volcanic, sills, dykes	Waagstein, Guise & Rex (2002); Storey, Duncan & Tegner (2007)
NE Greenland: *c.* 59 Ma to *c.* 53 Ma	Ultramafic, mafic: volcanic, sills, dykes	Upton *et al.* (1995); Price *et al.* (1997)
CE Greenland: *c.* 61 to *c.* 53 Ma	Ultramafic, mafic, silicic: volcanic, plutons, sills, dykes	Karson *et al.* (1998); Tegner *et al.* (1998); Hald & Tegner (2000); Lenoir, Féraud & Geoffroy (2003); Peate *et al.* (2003); Storey, Duncan & Tegner (2007)
SE Greenland: *c.* 62 Ma to *c.* 55 Ma	Ultramafic, mafic, silicic: volcanic, sills, dykes	Sinton & Duncan (1998); Sinton, Hitchen & Duncan (1998); Tegner & Duncan (1999); Storey, Duncan & Tegner (2007)
W Greenland: *c.* 61 Ma to *c.* 54 Ma	Ultramafic, mafic, silicic: volcanic, dykes	Storey *et al.* (1998); Larsen *et al.* (1999a); Geoffroy *et al.* (2001)
N Greenland: *c.* 64 Ma	Mafic, silicic: volcanic, dykes	Estrada, Höhndorf & Henjes-Kunst (2001)
Bjørnøya Marginal High: *c.* 54 Ma	Mafic: volcanic	Tsikalas, Eldholm & Faleide (2002)
Vestbrona, off SW Norway: *c.* 55 Ma	Mafic: volcanic	Bugge, Prestvik & Rokoengen (1980)

The ages presented in this table reflect only the initial main phases of NAIP magmatism. Subsequent magmatism occurred in many of the same regions as those presented in this table. For further information see e.g. Tegner *et al.* (2008), Morton *et al*. 1995 and O'Connor *et al.* (2000) and references in these papers.

Table 2. Early Palaeogene transient uplifts reported for regions within the North Atlantic Igneous Province

Regional locations	Cited example
Disko area, W Greenland	Japsen, Green & Chalmers (2005)
Ammassalik area, SE Greenland	Clift, Turner & ODP Leg 152 Scientific Party (1995); Larsen & Saunders (1998)
Kangerlussuaq area, CE Greenland	Peate, Larsen & Lesher (2003)
Scoresby Sund area, CE Greenland	Mathiesen, Bidstrup & Christiansen (2000)
Hold With Hope, NE Greenland	Thomson *et al*. (1999)
Vøring margin, off Norway	Ren *et al*. (2003)
Møre margin, off Norway	Brekke *et al.* (1999)
North N Sea Basin	Nadin, Kusznir & Cheadle (1997)
Faroe-Shetland Basin	Nadin, Kusznir & Cheadle (1997); Rudge *et al.* (2008)
North Rockall Trough	Archer *et al*. (2005)
Moray Firth to Shetland	Mackay *et al.* (2005); Rudge *et al.* (2008)
NW British Isles (Scotland)	Green *et al*. (1993); Mudge & Jones (2004)
Irish Sea	Cope (1994)
Porcupine Basin	Jones, White & Lovell (2001)

Bergerat & Angelier, 1996). In accepting the presence of a junction in this region, a broadly SE-trending failed rift arm or leaky transform with NE–SW to ENE–WSW-directed extension fits roughly with the observed orientation of dykes (NW–SE to NNW–SSE-directed) emplaced in NW Britain during this period (Speight *et al.* 1982; England, 1988; Geoffroy, Bergerat & Angelier, 1996). The later Eocene extension in NW Britain has been interpreted to result from broadly NW–SE-directed crustal extension associated with the opening of the North Atlantic (Geoffroy, Bergerat & Angelier, 1996). The Early Palaeogene magmatism in NW Britain has been associated with melting of the 'Iceland Plume' (Kent & Fitton, 2000; Upton *et al.* 2002), although Nadin, Kusznir & Cheadle (1997) tentatively suggested that a separate distinct mantle plume may have been active in the NW Britain area during this period. Tectonic activity has also been invoked by some authors to have facilitated melt generation in the area (Upton *et al.* 2002; Chambers, Pringle & Parrish, 2005).

3.b. The Faroe Islands–N Rockall Trough (Fig. 1; 'II' in Figs 2, 3)

Geoffroy, Bergerat & Angelier (1994) suggested that an Early Palaeogene triple junction was more or less centred on the Faroe Islands, while Burke & Dewey (1973) proposed a contemporaneous triple junction in the Faroes–N Rockall Trough area with magmatic centres in the N Rockall Trough and to the SSW and/or SW off the Faroe Islands. This accords with the inferences by Waagstein (1988) regarding the depocentre of the Faroe Islands Beinisvørð Formation (formerly lower basalt series: e.g. Passey & Bell, 2007) being located in the southern or central part of the Faroe Islands area. A NW-trending failed rift arm or leaky transform from this inferred junction(s) or from a junction that migrated within this region during Paleocene and Eocene times with relative extension directed towards the NE–SW and another rift arm or leaky transform with extension towards the NNW–SSE may explain the NW–SE and ENE–WSW sub-parallel igneous emplacement trends of contemporaneous central igneous complexes in the SW parts of the area (e.g. Archer *et al.* 2005), as well as NW-trending lineaments reported for this region (e.g. Johnson *et al.* 2005; Kimbell *et al.* 2005). A hypothetical connection between a Faroese and a NW British triple junction (Figs 2, 3) would presumably have been sub-parallel to the N–S-trending contemporaneous dykes in mainland Scotland to the E and S of Skye (e.g. Speight *et al.* 1982). Morton *et al.* (1995) tentatively suggested that volcanism at the Rosemary Bank (Fig. 1) in the N Rockall Trough was due to a separate underlying source, and Hitchen *et al.* (1997) likewise suggested a local source for the Early Palaeogene rocks in the area. Other authors have associated the Early Palaeogene magmatism in this area with the 'Iceland plume' (Holm, Hald & Waagstein, 2001; Archer *et al.* 2005).

3.c. The NE Faroe–Shetland Basin; N North Sea; offshore W Norway (Fig. 1; 'III' in Figs 2, 3)

An Early Palaeogene triple junction to the NNE off Shetland has been suggested by Burke & Dewey (1973), and an additional contemporaneous magmatic centre was active further to the NNE off the SW Norwegian coast. Based on reported Early Palaeogene uplifts and igneous activity in the area, Mudge & Jones (2004) and Rudge *et al.* (2008) suggested that the 'Iceland Plume' could be responsible for contemporaneous uplifts recorded in the northern North Sea and the NE Faroe–Shetland Basin area. Kanaris-Sotiriou, Morton & Taylor (1993) interpreted the Early Palaeogene basaltic and associated intermediate volcanic rocks of the Erlend Complex in the northern North Sea to be a result of extensional volcanism in the area. The Møre–Trøndelag Fault Complex, which extends offshore from the SW Norwegian coast, trends towards the area of this inferred junction and is thought to have been active in Early Palaeogene times (Doré *et al.* 1997; Redfield *et al.* 2004) and could have been linked to the contemporaneous igneous activity in the area. Torske & Prestvik (1991) tentatively suggested that the igneous products recorded off W Norway were related to an Early Palaeogene precursor to the subsequent Jan Mayen Fracture Zone (Fig. 1).

3.d. The Vøring margin; NE Greenland (Fig. 1; 'IV' in Figs 2, 3)

The inferred magmatic activity at the Vøring margin in Early Palaeogene times occurred at some distance from the future break-up zone in the region, but moved westwards with time (Eldholm, Thiede & Taylor, 1989). Early Eocene magmatism in NE Greenland and at the Vøring margin had a close spatial relationship (Viereck *et al.* 1988; Upton *et al.* 1995) and recent studies reveal a continuous Early Eocene igneous complex that directly linked these two regions together in the early stages of sea-floor spreading (Olesen *et al.* 2007). The igneous activities (volume and rock types) associated with these centres resemble those found in some places in the Rockall Trough (Upton, 1988) and on the NW British Isles (Viereck *et al.* 1988 and references therein). Volumes of the Paleocene to Early Eocene volcanism decreased from the central Vøring margin towards the south and north, respectively (Berndt *et al.* 2001), indicating melt supplies from a relatively confined magmatic source. An 'Iceland Plume' origin has been inferred for the NE Greenland magmatism (e.g. Upton *et al.* 1995) and for the igneous products at the Vøring margin by some authors (Skogseid *et al.* 1992). Conversely, Eldholm, Thiede & Taylor (1989) and Van Wijk *et al.* (2001) suggested that decompression melting triggered by rifting caused the magma generation at the Vøring margin. Recent re-interpretations of available magnetic, bathymetric, gravity and seismic data from the Vøring margin strongly suggest local Eocene magmatism related to an Azores-type triple junction linked to the embryonic stages of sea-floor spreading in the Norwegian–Greenland Sea (Gernigon *et al.* 2008).

3.e. The (central-east) CE Greenland (Fig. 1; 'V' in Figs 2, 3)

The voluminous and widespread igneous products in this region were probably the result of several contemporaneous magmatic centres (e.g. Callot, Geoffroy & Brun, 2002). The locations of hypothetical triple junctions at the CE Greenland margin have been estimated from Early Palaeogene magmatism and uplifts in the area (Larsen & Watt, 1985; Nielsen, 1987; Mathiesen, Bidstrup & Christiansen, 2000; Callot, Geoffroy & Brun, 2002; Peate, Larsen & Lesher, 2003) and from triple junction localities as suggested by Burke & Dewey (1973); Karson & Brooks (1999) and Tegner *et al.* (2008). This vast area was characterized by Early Palaeogene episodic igneous activity and frequent migration of magmatic centres (Larsen & Watt, 1985; Peate, Larsen & Lesher, 2003), and at least three separate rifting events have been recorded for this region, some of which occurred far inland (Nielsen, 1987; Olesen *et al.* 2007). The rifting associated with the bulk of the magmatism in CE Greenland and the Faroe Islands approximately at anomaly 24 (*c.* 55 Ma) occurred close to the Blosseville Kyst (Larsen & Watt, 1985; Nielsen, 1987; Larsen *et al.* 1999*b*). This is in accordance with inferences that the magmas of the younger basalt formations of the then neighbouring Faroe Islands were supplied from the north during this period (Waagstein, 1988; Larsen *et al.* 1999*b*). The onset of final sea-floor spreading at the Blosseville Kyst latitude occurred further to the east along the now extinct Ægir Ridge at *c.* 54 Ma (Bott, 1985). On the one hand, Larsen & Marcussen (1992) and Hanghøj, Storey & Stecher (2003) considered the magmatism in CE Greenland to be related to extension in the area; on the other hand, authors such as Tegner *et al.* (2008 and references therein) suggested that the CE Greenland igneous products resulted from actions of the 'Iceland Plume'.

3.f. The Hatton–Edoras margin; SE Greenland (Fig. 1; 'VI' in Figs 2, 3)

Only parts of this extensive area have been investigated in detail, but the close proximity in the Early Palaeogene suggest that these two margins perhaps shared some magmatic centres prior to the sea-floor spreading in the region (Figs 2, 3). Locations for some possible triple junctions in this region in Early Palaeogene times have been implied previously by Burke & Dewey (1973), Bull & Masson (1996), Karson & Brooks (1999), Nielsen, Larsen & Hopper (2002) and Nielsen, Stephenson & Thomsen (2007), and locations of some separate large magmatic centres and domal uplifts have been recorded by Morgan & Barton (1990), Barton & White (1997), Larsen & Saunders (1998) and Elliot & Parson (2008). A hypothetical SE-trending failed rift arm or transform from a triple junction in the southern parts of the Hatton Bank (Figs 2, 3) would be sub-parallel to the South Hatton Lineament (Johnson *et al.* 2005; Kimbell *et al.* 2005). Another major lineament intersecting the Hatton margin is the Anton Dohrn Lineament, which in part has been interpreted by Dickin (1992) to include an ancient orogenic suture zone (Figs 2, 3). Morgan & Barton (1990) detected a large separate Early Palaeogene magmatic centre on the NW Hatton Bank, and recent work by Elliot & Parson (2008) revealed that the Hatton rifted margin could be divided into three separate segments, each with a distinctive magmatic evolution. They tentatively suggested that the northern parts of the Hatton margin only experienced diffuse spreading in the Early Palaeogene prior to Chron 21 (*c.* 50 Ma) when regular coherent spreading was established. The phenomenon of diffuse sea-floor spreading has been inferred to reflect low obliquity rifting in a magmatically starved environment (e.g. Corti *et al.* 2001). In the southernmost parts of this margin, Elliot & Parson (2008) recorded relatively concentrated syn- to post-break-up volcanism. Most authors infer the 'Iceland Plume' to be the main source for the magmatism in these two margins (Barton & White, 1997; Fitton *et al.* 2000), but Edwards (2002) considered any 'Iceland Plume'-dominated processes further eastwards toward the Rockall–Hatton Basin to be problematic, and Barton & White (1997) suggested that there was no major long-distance lateral migration of the melts supplying the magmatism at the Edoras Bank.

3.g. The West Greenland–Baffin Island area (Fig. 1; 'VII' in Figs 2, 3)

Based on reported locations for large concentrations of Early Palaeogene igneous products (e.g. Chalmers, Larsen & Pedersen, 1995; Skaarup, Jackson & Oakey, 2006), large contemporaneous igneous centres (Callot, Geoffroy & Brun, 2002), doming (Japsen, Green & Chalmers (2005) and the trends of major faults thought to have been active in the same period (Chalmers, Larsen & Pedersen, 1995; Geoffroy *et al.* 2001; Callot, Geoffroy, Brun, 2002; Skaarup, Jackson & Oakey, 2006), the location of a hypothetical triple junction at the southern tip of the Ungava Fault System and another at Ubekendt Ejland around 100 km north of Disko seems to be reasonable. Another triple junction or kink between major faults further to the north between Baffin Island, Ellesmere Island and W Greenland reconstructed back at *c.* 60 Ma has been interpreted to have been active during the same period (Burke & Dewey, 1973; Torsvik *et al.* 2001; Nielsen, Stephenson & Thomsen, 2007). Gill, Holm & Nielsen (1995) associated a presumed high-temperature melting required for the generation of Early Palaeogene picrites in this region with a separate 'Baffin Bay Plume' rather than with a distant asymmetrical/irregular 'Iceland Plume' as suggested by Chalmers (1997) and Storey *et al.* (1998), among others. The generation of Eocene dykes in SW Greenland and the volcanism along the Ungava Fault System are supposed to have been facilitated by plate reorganizations in the area during that period (Storey *et al.* 1998; Larsen *et al.* 1999*a*; Skaarup & Pulvertaft, 2007 and references therein).

3.h. N Greenland (Fig. 1; 'VIII' in Fig. 2)

The Early Paleocene Kap Washington Group is thought to have been generated in response to continental rifting related to the break-up of the Laurasian plate (Estrada, Höhndorf & Henjes-Kunst, 2001). A contemporaneous triple junction off Kap Washington is in accordance with the study of Torsvik *et al.* (2001); Torsvik, Mosar & Eide (2001) and Nielsen, Stephenson & Thomsen (2007).

3.i. The W Barents region (Fig. 1; 'IX' in Fig. 3)

Volcanic rocks in the W Barents Sea (Vestbakken Volcanic Province) located at the inferred trace of the Caledonian suture zone are interpreted to have formed in response to Early Eocene transtension associated with plate reorganizations in the area (Tsikalas, Eldholm & Faleide, 2002).

4. Discussion

4.a. Competing theories on the NAIP petrogenesis

A number of theories and geodynamic models (including mantle processes such as delamination, orogenic collapse, small-scale edge-driven convection, melting of fertile mantle, and melting of an individual large mantle plume) have previously been proposed to have caused the Early Palaeogene magmatism of the NAIP (e.g. Meyer, Van Wijk & Gernigon, 2007 and references therein). Other mantle processes sometimes thought to result in voluminous magmatism in general include decompression melting in response to global-scale extension (Ziegler, 1992), and melting resulting from spontaneous upwellings of near-solidus buoyant mantle material (Raddick, Parmentier & Scheirer, 2002). Other models applied to lithospheric processes, sometimes suggested to have influenced the NAIP genesis, include: (1) the 'soft-point model', where the lithosphere is pre-weakened locally by igneous activity and their sources at depth, thereby localizing extensional stresses, which in turn may control the rift propagation and geometry (Corti *et al.* 2001; Callot, Geoffroy & Brun, 2002; Geoffroy, 2005); (2) lithospheric extension due to relaxation of intra-plate tensional stress regimes, which in turn generates numerous centres of extension dispersed over plate-wide areas, perhaps ultimately facilitating rifting (Nielsen, Stephenson & Thomsen, 2007).

4.b. Exploring potential source regions for the NAIP magmas

Key issues for theories regarding the NAIP petrogenesis include the high temperatures necessary to explain the common occurrence of picrites and the nature of source rocks necessary to explain the heterogeneous compositions of many of the encountered basalts (Meyer, Van Wijk & Gernigon, 2007). Melting of peridotites, contaminated with various amounts of recycled oceanic crustal material, is frequently invoked to explain the geochemical variations in flood basalt provinces (Kogiso, Hirose & Takahashi, 1998; Yaxley, 2000; Green & Falloon, 2005). However, as subducted oceanic crustal material is thought to reside in the lower mantle (Zhao, 2004), in the middle mantle (Courtillot *et al.* 2003, Zhao, 2004) and in the upper mantle (Green *et al.* 2001; Donnelly *et al.* 2004), geochemical signatures do not necessarily constrain a certain level of the mantle as the source of origin. Picrites have been interpreted to form at $\sim 1440\,^{\circ}$C and ~ 2 GPa (Green *et al.* 2001; Green & Falloon, 2005), and mid-ocean ridge basalts (MORB) are thought to form at temperatures above $\sim 1240\,^{\circ}$C but below $\sim 1400\,^{\circ}$C and at depths ranging from ~ 30 km to ~ 45 km (Hirose & Kawamoto, 1995; Presnall, Gudfinnsson & Walter, 2002). Presnall, Gudfinnsson & Walter (2002) showed that a temperature increase of only $\sim 20\,^{\circ}$C was required to increase melt produtivity from 0 to 24 % in a homogeneous peridotitic mantle at near-solidus temperatures. The presence of small amounts of recycled oceanic crust and/or water in peridotitic source rocks is inferred to increase the degree of melting at fixed temperatures (Kogiso, Hirose & Takahashi, 1998; Yaxley, 2000) and to lower the solidus temperature (Hirose & Kawamoto, 1995; Yaxley, 2000; Presnall, Gudfinnsson & Walter, 2002; Green & Falloon, 2005).

At average geothermal gradients for the upper mantle in an ocean ridge environment (e.g. Blatt & Tracy, 1995), adiabatic ascent of uncontaminated potential peridotitic source rocks from depths of > 400 km is required in order to produce picrites at $\sim 1440\,^{\circ}$C and ~ 2 GPa (Fig. 4a). Substantially shallower depths may be required for picrite genesis from hypothetical assemblages of contaminated and/or hydrated source rocks (Fig. 4b, c). For flood basalts comparable in composition to oceanic island basalts (OIB), melting of enriched/hydrated source rocks would be expected to commence a few tens of kilometres deeper than similar melting of a pure peridotitic counterpart to produce MORB (Yaxley, 2000) (Fig. 4d, e). In summary, the adiabatic ascent of source material from depths of a few hundred kilometres is probably required in order to provide temperatures realistically needed to produce picrites.

4.c. The NAIP in the context of rift geometry and triple junctions

The geometry of the NAIP (Figs 2, 3) and the longevity of the igneous activity, together with the involvement of the Rockall–Faroe Islands microcontinent (Roberts & Searle, 1979; Edwards, 2002) and the Jan Mayen microcontinent (Kodaira *et al.* 1998; Mjelde *et al.* 2008) in the rift processes, suggest a complex and discontinuous break-up history. A comparable complex rifting evolution has been reported for the Afar Volcanic Province with migrating triple junctions and magmatism (Tesfaye, Harding & Kusky, 2003; Wolfenden *et al.* 2004) and where microcontinents (Danakil and Aisha) were involved in the rifting/igneous processes and commonly defined their own secondary triple junctions and associated magmatism (Garfunkel & Beyth, 2006). Individual large mantle plumes have commonly been linked to magmatism, rifting and triple junction formation in flood basalt provinces like the Afar Volcanic Province (Garfunkel & Beyth, 2006) and the NAIP (Section 3), but other authors have argued that the East African rift system in general developed in response to global plate reorganizations (e.g. Wolfenden *et al.* 2004). The common occurrence of dissimilar geochemical and isotopic signatures in rift-related basalts, within confined areas from, for example, the East African rift system (Barrat *et al.* 1998; Orihashi, Al-Jailani & Nagao, 1998; Rogers *et al.* 2000; George & Rogers, 2002; Keranen & Klemperer,

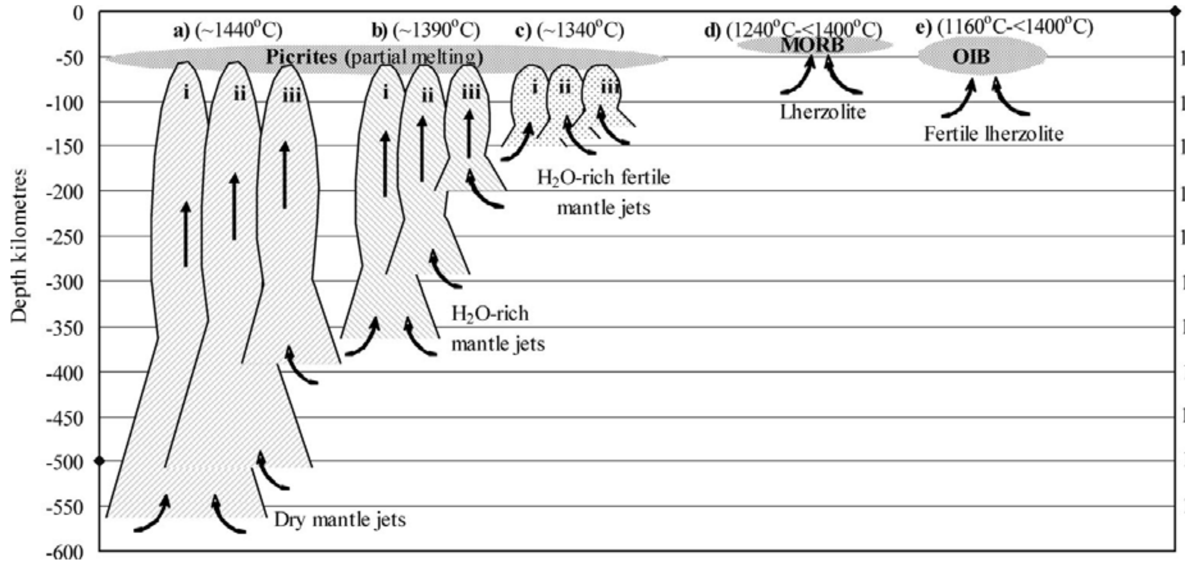

Figure 4. Simplified diagram showing depths versus Mid-Ocean Ridge mantle geotherms (right y axis) from (Blatt & Tracy, 1995). (a) Required depths of adiabatic ascent and melting of dry peridotitic source rocks to generate picrites at ~ 2.0 GPa (around 60 km depth) and at ~ 1440 °C have been calculated/estimated. Adiabatic gradients of (i) 0.60 °C km^{-1} (McKenzie & Bickle, 1988), (ii) 0.54 °C km^{-1} (McKenzie, Jackson & Priestley, 2005) and (iii) 0.42 °C km^{-1} (Ichiki *et al.* 2006) have been applied in the calculations/estimations. In assuming lowering of solidus temperatures of ~ 50 °C for source material containing H_2O (Green & Falloon, 2005) and a further decrease of solidus of ~ 50 °C for fertile source material (Yaxley, 2000) calculations/estimations are carried out for (b) wet and (c) wet + fertile source rocks. However, the scenarios in (b) and (c) may produce normal basalts unless melting starts at deeper levels (e.g. Yaxley, 2000). (d) MORB generation from partial melting at ~ 30 to ~ 45 km depth. (e) Increased melting column for the generation of OIB (oceanic island basalts). See text for further explanation.

2008), from Iceland (Kitagawa *et al.* 2008) and from the Azores (Beier *et al.* 2008), suggests melting from distinct mantle reservoirs.

The association between enhanced magmatism and rift geometry, that is, triple junctions (Sears, George & Winne, 2005) or kinks in rifting trends (Abdel-Rahman & Nassar, 2004; Wolfenden *et al.* 2004), is well known. In this context the evolution of the proto-Iceland region may be of relevance for the Early Palaeogene NAIP magmatism, as the great increase in the volume of magma production in that area in Middle Palaeogene times (Foulger & Anderson, 2005) coincided with the establishment of the ridge–ridge–transform triple junction (Reykjanes ridge–Kolbeinsey ridge–Faroe transform fault) recorded by Bott (1985).

4.d. NAIP in the context of plate tectonic processes in adjacent areas

In the context of Early Palaeogene global plate-tectonic processes, it is noteworthy that the relative convergence and associated compression of Africa and Iberia with respect to W Europe came to a standstill from the earliest Paleocene to the Early Eocene (Rosenbaum, Lister & Duboz, 2002), that is, in the same time interval as the occurrence of the majority of Early Palaeogene NAIP magmatism and the initiation of the continental break-up of the proto-North Atlantic area (Table 1; Figs 1, 2, 3). The causal mechanism for this standstill of relative plate convergence has been tentatively interpreted to result from a contemporaneous continental collision in the Alps between the African and European plates at around 65 Ma (Jolivet & Faccenna, 2000; Rosenbaum, Lister & Duboz, 2002). A recent complementary tectonic model inferred to have terminated compression and perhaps facilitated extension in the NW Atlantic area in the Early Palaeogene involves major left-lateral displacements between Greenland and Europe and within the NW parts of Europe (Fig. 2) that ultimately resulted in narrowing (contraction) and retreat of the European plate relative to the African plate (Nielsen, Stephenson & Thomsen, 2007).

In a rifting perspective, Lundin & Doré (2005) argued that the Early Palaeogene igneous–tectonic activities in the proto-North Atlantic area that generated the NAIP were merely a result/expression of the final phases of the ongoing break-up of Pangaea, spatially and temporally linking the Early Paleocene central Atlantic rifting (e.g. Ziegler, 1989, 1992) in the south with the Early Eocene rifting in the Eurasian Basin to the north (e.g. Srivastava, 1985; Brown, Parsons & Becker, 1987).

4.e. Lithospheric strength

An important issue to be addressed in complex large igneous provinces like the NAIP is: what caused the magmatism to be so widespread until a relatively narrow sea-floor-spreading zone was finally established? Clearly, the strength of certain parts of the lithosphere and its relative capability to resist stretching, rupture and/or intrusion of magmas must have played a major role. Studies on lithospheric strength in a laterally homogeneous undeformed lithosphere have been dealt with in a number of studies (e.g. Kohlstedt, Evans & Mackwell, 1995; Hirth & Kohlstedt, 1996; Kusznir & Park, 2002; Van Wijk & Cloetingh, 2002; Jackson *et al.* 2008). In brief, these authors concluded that increased heat flow and high rates of spreading generally resulted in a net weakening of the lithosphere and conversely, very slow spreading rates and low heat flows could result in a net strengthening. Increased fluid pressure further weakens all affected rock assemblages in the lithosphere (Hirth & Kohlstedt, 1996; Jackson *et al.* 2008). Upper mantle heterogeneity and the presence of old shear zones in the lithosphere may play a prominent role in incipient rifting both by enhancing partial melting and by reactivation of old shear zones (Holdsworth, Butler & Roberts, 1997; Ryan & Dewey, 1997; Kohlstedt, Evans & Mackwell, 1995).

5. Conclusions and closing remarks

In this contribution we have reviewed some key magmatic centres of the NAIP in a geodynamic framework, focusing on their interrelationships and the tectonic developments during the onset and development of the NAIP. The specific conditions directly prior to the onset of the NAIP and the continued development of the region during the Palaeogene, based on the findings of the present study, are highlighted as follows:

(1) The onset of the rifting and igneous activity of the NAIP area was a temporal and spatial continuation of the rifting in the adjacent central Atlantic Ocean to the south and a precursor for the rifting in the Eurasian Basin to the north. The main igneous and tectonic activities in the NAIP in Early Palaeogene times coincide with contemporaneous changes in the relative motion between the European and African plates, which possibly halted the previous compressional regimes in the NW Atlantic during this time span.

(2) Taken all together, the apparent geometry of the main igneous regions of the NAIP at the conjugate E Greenland–NW European margins in particular shows similarities with trends of the embryonic stages of classic continental rifting regimes consisting of numerous more or less interconnected triple junctions. However, the locations of numerous smaller central igneous complexes and/or seamounts at the NW European margin (Fig. 1) do not seem to fit with such a simple rifting model if they all formed contemporaneously with the larger igneous NAIP regions.

(3) An aiding factor to NAIP rifting could have been Early Palaeogene oblique extension and active sinistral transforms (reactivation?) at the conjugate E Greenland–NW European margins (Nielsen, Stephenson & Thomsen, 2007) (Fig. 2).

(4) While partial melting in the upper mantle to produce the bulk of the (normal) basaltic rocks of the NAIP is not necessarily dependent on deep mantle convection, some ascent of hot mantle jets seems to be required in order to generate the NAIP picrites (Fig. 4).

(5) Whether global plate reorganizations or a single large mantle plume was the driving force for the NAIP evolution, the close proximity of many parts of the NAIP magmatism and transient uplifts to ancient orogenic sutures and/or fronts (Figs 2, 3) suggests that lithospheric control was an important factor in the embryonic stages of magmatism and rifting.

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