Breakup volcanism and consequences for climate change

- MagellanPlus Workshop report

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Abstract

The north-east Atlantic is an archetypal example of volcanic rifted margins. Drilling this margin will allow us to address major questions within four key themes: 1) The early rift history of the north-eastern Atlantic; 2) The role of North Atlantic volcanism in the Paleocene-Eocene Thermal Maximum (PETM) climate event, 3) The long-term paleoceanography of the Nordic Atlantic-Arctic Gateway; and, 4) the hydrological implications of large-scale magmatic crustal thickening. Tackling these questions with new drilling in the eastern North Atlantic region will advance our understanding of the long-term interactions between tectonics, volcanism, oceanography, and climate, and the functioning of subpolar northern ecosystems and climate during intervals of extreme warmth.

1. Introduction

The formation of continental margins is accompanied by a broad spectrum of magmatic activity ranging from basically no significant volcanism to the emplacement of a large igneous province (LIP) (Figure 1). The reasons for this variability in magmatism are still poorly understood although it is of large societal and economic importance. DSDP legs 38 and 81 investigated the nature of the continental margins around the NE Atlantic. ODP legs 104, 152 and 163 in 1985, 1993, and 1995 established that volcanism plays a major role in the formation of passive margins, and instituting the concept of volcanic passive margins (Coffin and Eldholm, 1992; Eldholm et al., 2000). Break-up volcanism has since been identified as a major short-term climate driver that has potentially caused several mass extinctions (Eldholm and Thomas, 1993; Svensen et al., 2007). Magmatic intrusions seem to be of particular importance as they can release large amounts of greenhouse gas in a very short time (Berndt et al., 2016) and it seems likely that the magmatism associated with the break-up of the North Atlantic has triggered the Paleocene Eocene Thermal Maximum (PETM) (Minshull et al., 2016; Svensen et al., 2004). The subsequent tectonic evolution of the north Eastern Atlantic through the Paleogene and Neogene created an ocean gateway linking the Arctic Ocean that is likely to have played a significant role in causing, or amplifying, environmental changes through its influence on water mass circulation (Laughton, 1975; Miller and Tucholke, 1983; Jakobsson et al., 2007; Coxall et al., 2018).

Despite the importance of break-up magmatism as a driver in climate change the underlying deep Earth processes remain elusive. A break-through was the development of the concept of seismic volcano stratigraphy in 2000 that was based on ODP Legs 104 and 152 and large amounts of seismic data (Planke et al., 2000). It allows us to predict the distribution of different types of volcanic emplacement environments which can be used to determine the duration of volcanism and emplacement rate changes as well as the subsidence history of volcanic margins. Since 1996 there was no dedicated scientific drilling leg to test the predictions deriving from the concept of seismic volcano stratigraphy, and thus the primary hypothesis, i.e. that the break-up volcanism was short-lived enough to be a viable driver for climate change during the PETM, still has to be tested.

In May 2018 we convened a MagellanPlus IODP/ICDP drilling workshop at GEOMAR, Germany to develop new drilling proposal(s) that would shed new light on the nature of break-up volcanism and evolving Atlantic-Arctic gateways. This includes the question whether the Paleocene Eocene Thermal Maximum was caused by hydrothermal venting of greenhouse gas during the intrusion of magma into the sedimentary basins around the NE Atlantic. This would involve dating the intrusions and the hydrothermal vent structures as well as constraining the extent of break-up-related volcanic successions and environments in which they were emplaced. It also includes an improved understanding of the nature of volcanic seismic facies units and whether they represent specific environmental conditions during the emplacement of the break-up volcanic extrusive successions and can be used to decipher the interaction of magmatic processes and relative sea level change. The early Nordic basins were initially restricted by igneous sills with at best only shallow surface exchange with the Arctic Ocean and North Sea until the Miocene, after which the Greenland Scotland Ridge and Fram Strait had deepened to allow exit of cold dense waters important for Atlantic overturning circulation. Testing this hypothesis would require piston coring of Eocene-Neogene sediments overlying volcanic basement to produce a chronologic and paleoenvironmental framework that constrains deep and surface water properties, including basin ventilation state and surface salinities.

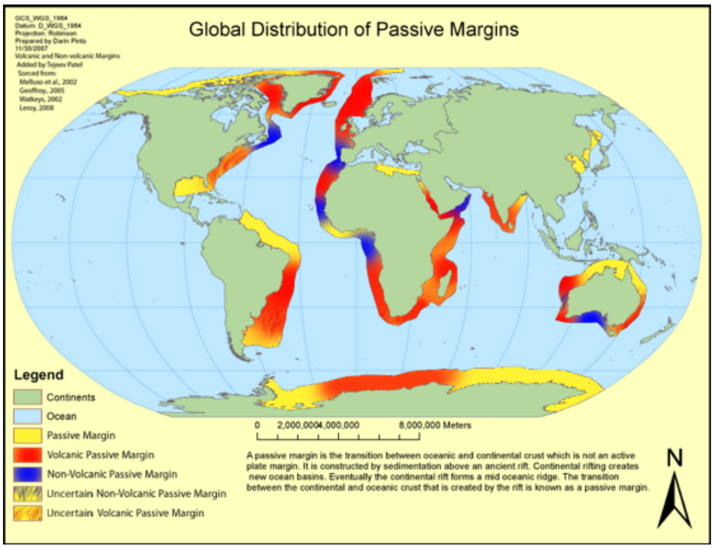

Figure 1: Distribution of the different types of passive margins around the world. The North Atlantic rifted margins are the type example of volcanic rifted margins.

Since the mid-90s, major advances in seismic imaging, e.g. the ascent of three-dimensional seismic techniques, and their application to these volcanic provinces by industry delineated the youngest, best imaged and most accessible sub-surface structures. As a result, a number of suitable IODP/ICDP drilling targets offshore in the Northeast and Northwest Atlantic and onshore in northern Denmark have been identified. Drilling these targets would allow us to better establish the sequence of events leading to the emplacement of the break-up volcanic rocks. Furthermore, drilling of individual seismic facies units would ground truth the predictions of seismic volcano stratigraphy. Together this information will constitute a step increase in our understanding of the underlying geodynamic processes of continental break up, break-up related volcanism and the consequences of these processes on global climate.

2. Globally relevant aspects of studying break-up volcanism

2.1. Fundamental tectono-magmatic processes controlling break-up volcanism

Despite the unsurpassed constraints that we have on conjugate crustal structure between the Norwegian-Jan Mayen-Greenland rifted margins in the NE Atlantic, the mechanism responsible for rift-related anomalous excess magmatic productivity is still debated (e.g. Lundin and Doré, 2005). The controversy centres on three competing hypotheses: 1) excess magmatism resulted from elevated mantle potential temperatures resulting from mantle plume processes, 2) small-scale convection at the base of the lithosphere enhanced the flux of material through the melt window during rifting and mid-oceanic ridge spreading, 3) depth-dependent extension with wide margins promoted excess magmatic accretion. In addition to these geodynamic end-members for the formation of excess magmatism an alternative based on mantle heterogeneities has been proposed (Bonatti, 1990). Whereas the mantle plume mechanism requires anomalous high temperatures resulting in high degrees of melting during asthenosphere upwelling, small-scale convection operates without elevated potential temperatures. In contrast small-scale convective instabilities at the base of the lithosphere are inherently connected to and produced by the rifting process (Keen & Boutilier, 2000).

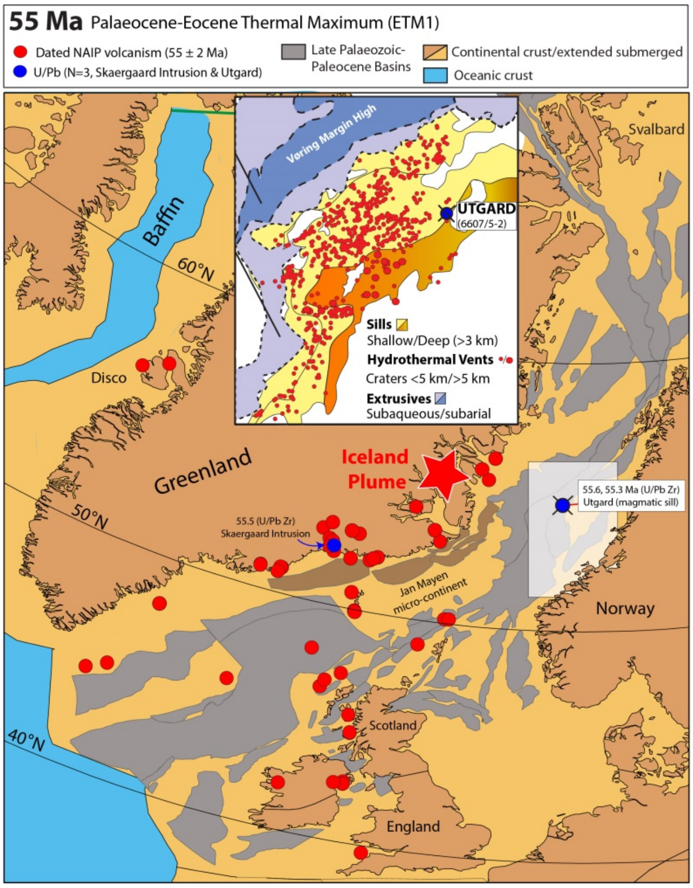

Figure 2 Reconstruction of the North Atlantic at 55 Ma with the distribution of dated (57-53 Ma) onshore and offshore sample locations (red filled circles) for the North Atlantic Igneous Province, the location of the Iceland plume with respect to Greenland (Torsvik et al., 2015), and rift basins developed from the Late Palaeozoic to the Palaeocene (Faleide et al., 2010). The inset map demonstrates the extensive sill and hydrothermal vent complexes in the Vøring Basin offshore Norway (see white box in main map), and location of the 6607/5-2 Utgard borehole where magmatic sills intruding organic-rich sediments are dated to 55.6 and 55.3 Ma (U/Pb Zircon; Svensen et al., 2009). From a database of many hundred dated volcanics and intrusions there are only six U/Pb ages, ranging from 62.6 ± 0.6 Ma (Antrim lower basalt in Ireland) to 55.5 ± 0.1 Ma (Skaergaard Intrusion in East Greenland).

Continental breakup may be associated with extensive volcanism over large distances along strike of the rifted margins as exemplified in the NE Atlantic (Figure 2). The causes for the anomalous magmatic activity and the implications on the paleoenvironment are, however, still debated. Magmatic products (Figure 3) emplaced along these volcanic rifted margins have four major characteristics: 1) wedges of seaward dipping reflectors (SDR's) and associated volcanic seismic facies units interpreted as massif sub-aerial and sub-marine lava flows and volcanoclastic sediments are found on both sides of the ocean continent boundary, 2) extensive sill and hydrothermal vent complexes emplaced in organic-rich sedimentary basins along the incipient breakup axis, 3) thick high-velocity bodies in the lower crust

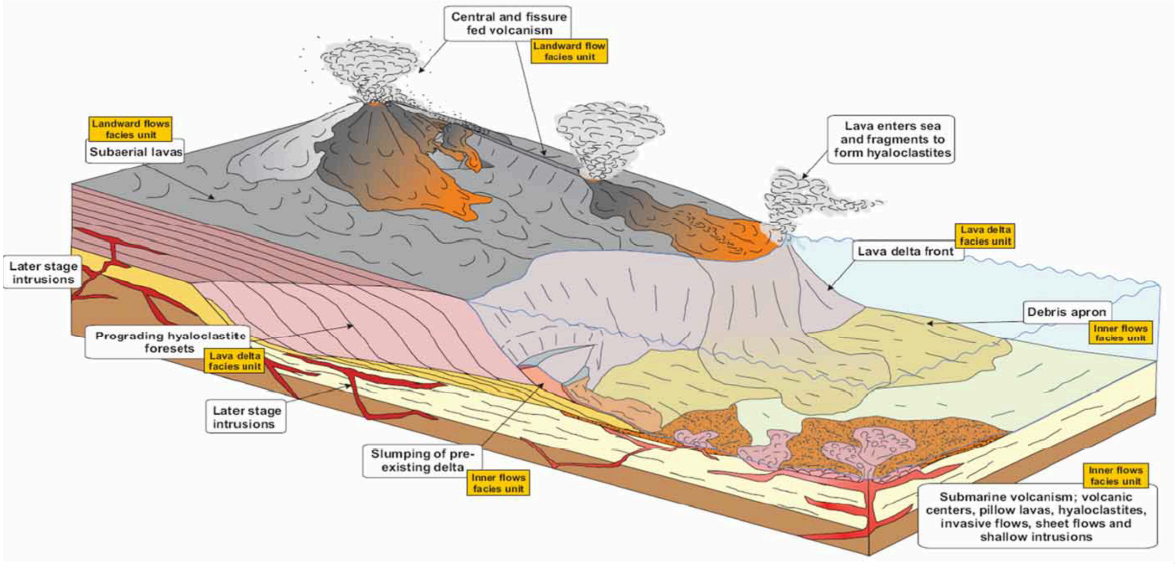

Figure 3: Break-up volcanism in the North Atlantic resulted in extrusion (pink and orange colours) and intrusions (red) of magmas into the sediments basins and led to the development of lower crustal bodies with particularly high seismic velocities called underplating (not shown).

along the ocean-continent boundary commonly interpreted as magmatic underplated material, and 4) the magmatic crust at these margins often exceeds 20 km, more than three times as thick as normal oceanic crust produced by passive upwelling of normal potential temperature mantle. It appears that volcanic rifted margins require mantle that is either 1) anomalously hot, 2) anomalously fertile, or 3) actively upwelling at rates higher than the plate half-spreading rate, or some combination of these factors. For the IODP drilling campaign we propose to test the following hypotheses:

Hypothesis I: Mantle plume involvement produces excess magmatism

Discussion of the causes for the excess magmatic productivity have been strongly influenced by the association of the North Atlantic volcanic rifted margins with the Iceland hotspot (e.g. Bijwaard and Spakman, 1999; Ritsema et al., 1999; Foulger et al., 2001; Montelli et al., 2004) and have led to the hypothesis that excessive magmatic productivity resulted from high mantle temperatures was caused by a mantle plume (Brown and Lesher, 2014; McKenzie and Bickle, 1988; White and McKenzie, 1989). Various plume structures have been suggested including 1) a plume head impinging on the base of the lithosphere, and 2) rising vertical plume sheets. Numerical models predict that a plume, with a potential temperature possibly 50-300°C in excess of the surrounding mantle, can produce large quantities of melt (White and McKenzie, 1995; Hole and Millett, 2016; McKenzie and Bickle, 1988). Larsen and Saunders (1998) proposed that the opening of the northeast Atlantic rift allowed a sheet of hot plume material to spread along the rift for as much as 2700 km from south of Greenland to the Barents Sea. Recent seismic tomography confirms that the Iceland anomaly extends to the lower mantle (e.g., French and Romanovitch, 2015; Jenkins et al., 2016).

Hypothesis II: Active upwelling without a thermal anomaly

Active mantle upwelling without a thermal anomaly provides an alternative mechanism for excess magmatism at volcanic rifted margins involves. Active upwelling defined as upwelling of mantle at a rate higher than the half spreading rate of the rift zone (Holbrook and Kelemen, 1993). Mutter et al. (1988) first suggested that small-scale convection induced by lateral temperature gradients may provide an enhanced flux of material into the region of partial melting, thereby increasing magmatic activity in the absence of mantle potential temperatures elevated by an external influence (e.g. Fig. 8). While this hypothesis has attracted considerable attention (Mutter et al. 1988; Boutilier and Keen, 1999; Keen and Boutilier, 2000; Nielsen and Hopper, 2004), the relative importance of active upwelling in the evolution of rifted volcanic margins is still debated (Holbrook et al., 2001, Korenaga et al., 2000, 2002).

Hypothesis III: Excess magmatism owing to an enriched mantle source

Major element source heterogeneity may also contribute to anomalously high melt production during continental breakup (Davies, 1983; 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). The mantle is characterized by significant chemical and isotopic heterogeneity and appears to be a heterogeneous assemblage of depleted and enriched peridotite, as well as recycled subducted oceanic crust, lithosphere, and sediments. Inherited enriched domains in the sub-lithospheric mantle with anomalously low melt temperatures may therefore deliver more melt during their ascent beneath extending lithosphere and at the ridge axis.

These end member processes have distinct characteristics and diagnostic features that may be used to differentiate their relative roles during volcanic margin formation. **1**) Plume related anomalous high mantle temperatures result in high melt fractions, high pressure melting, and distinct geochemical characteristics (e.g. He, Sr-Nd isotope anomalies). **2**) Active upwelling (small-scale convection), conversely, without a thermal anomaly will result in low average pressure of melting (Holbrook et al., 2001; Korenaga et al., 2002), low degrees of melting, and geochemical signatures closer to MORB. Furthermore, the plume mechanism predicts the largest excess magmatic productivity to occur close to the plume centre in addition to local structural control on melting. Active upwelling caused by small-scale convection on the contrary is completely controlled by the local geometry of rifting, its consequences for local perturbations in thermal structure, and the local viscosity and density structure of the mantle lithosphere and sub-lithospheric mantle. **3**) A fertile source should result in high average pressure of melting and distinct isotope geochemistry of the melts indicating an enriched source. Information on the temporal and spatial variations of mantle potential temperature and active upwelling can be used to constrain models of rift dynamics, rift related convection, and plume-rift interaction (Brown and Lesher, 2014).

While the existence of the Iceland mantle plume is indisputable and demonstrated, the degree to which it has controlled excess magmatism in the NE Atlantic is debated and unresolved. The thermal anomaly associated with the plume is not well resolved with estimates ranging from 50 to 300°C excess mantle potential temperature. In the addition, the relative roles of plume versus the non-plume processes is not understood and vigorously debated. The three key questions with regard to these hypotheses are: **1**) what was the magnitude of the thermal anomaly resulting from the Iceland plume during continental breakup and how did it vary in time and space, **2**) did active mantle upwelling contribute to excess melting, and **3**) was there any heterogeneity in the source for melt production?

In addition to the fundamental reasons of break-up magmatism we concluded during the workshop that it is important to test a further hypothesis that will deal with the consequences of break-up magmatism.

Hypothesis IV: Voluminous emplacement of magma in organic-rich sedimentary basins and basaltic eruptions may trigger global warming

The magma volume, eruption duration, and emplacement environment are critical parameters for the paleoenvironmental implications of LIPs. Svensen et al. (2004) proposed a new hypothesis to explain how LIPs could trigger global environmental disasters. The basic feature of this hypothesis is that magma emplaced into organic-rich sedimentary sequences leads to heating of the host rock and generation of large volumes of greenhouse gases (CH_4, CO_2) (Aarnes et al. 2010; 2011). The gas generation may cause overpressure build-up and formation of so-called hydrothermal vent complexes (Svensen et al., 2004; Reynolds et al., 2017), transporting fluids and sediments to the hydrosphere and atmosphere (Aarnes et al., 2015). This hypothesis may be tested by collecting climate proxy data and sampling proximal deposits across the Paleocene-Eocene boundary in the Vøring Basin (e.g. Svensen et al. 2004, Frieling et al. 2016). The proximal nature of the Vøring Basin to the volcanic and magmatic sequences of the NAIP could allow for the differentiation between volcanic and thermogenic origins of gases, as differences between subaerial and subaqueous emissions of key magmatic tracers such as tephra and mercury have a primary control on their subsequent dispersal. Comparisons of this proximal dataset with distal sedimentary systems would then offer insights into the relative timing of extrusive and intrusive magmatic activity, and its temporal relationship to climate change events. The sedimentary record may also provide insight into the long-term paleoclimate variation in the Paleocene in a proximal setting during the early phase of the NAIP, and potential paleoclimate links to basaltic explosive and effusive eruptions.

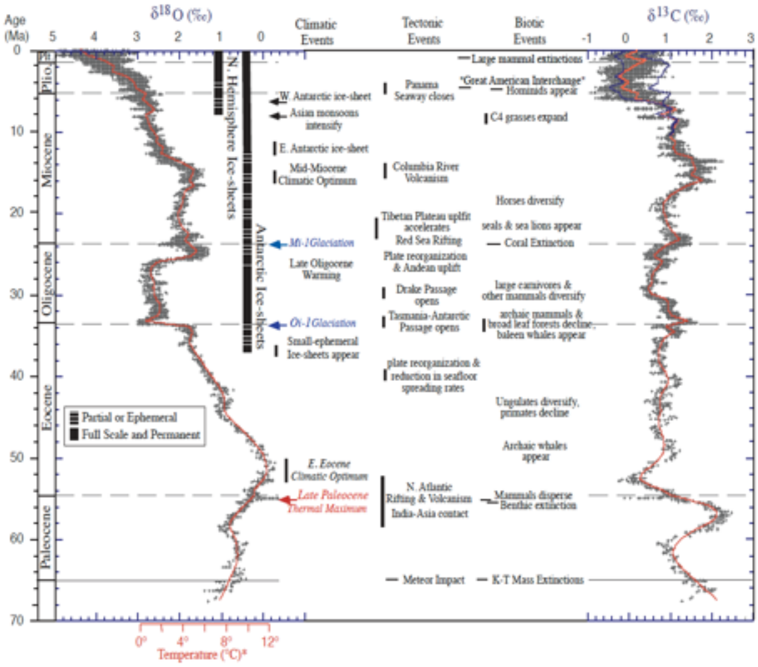

Figure 4: Global δ18O isotope ratio as a proxy for temperature and δ13C ratio as an indication of the type of injected carbon (after Zachos et al., 2001). Note the Late Paleocene Thermal Maximum at about 55 Ma at which global temperatures increased by about 5 degrees due to injection of light carbon.

2.2. Effects of volcanism on climate change

Volcanoes play a key role in the global fluxes of elements, helping to replenish and regulate atmospheric and oceanic chemistry over time. However, volcanism is episodic and stochastic in nature, and elevated periods of activity in Earth history will impact climate-sensitive processes such as the carbon cycle (Jones et al., 2016). Periods of elevated volcanism such as the emplacement of the North Atlantic Igneous Province (NAIP) often coincide with considerable environmental perturbations such as the Palaeocene-Eocene Thermal Maximum (PETM, Figure 4), suggesting a possible causal relationship (Bond and Wignall, 2014). The total volume of magma emplaced during the Palaeogene is estimated to 6-10 x 106 km^3 (Saunders et al., 2007). NAIP activity is interpreted as occurring in two main pulses of activity:

1) A pre-break up phase of continental flood basalt volcanism that were largely erupted through and onto continental crust.
2) The main, more voluminous phase of thick lava flows and widespread intrusions that is closely associated with the break-up of the Northeast Atlantic Ocean (Saunders et al., 2007; Storey et al., 2007b; White and McKenzie, 1995).

The formation of the NAIP delivered considerable volumes of greenhouse gases to the atmosphere, both in the form of direct volcanic degassing and explosive discharge of thermogenic gases generated by contact metamorphism around magma intrusions into sedimentary basins (Svensen et al., 2004). Therefore, the NAIP is one of the primary contenders for causing the steady warming and numerous hyperthermal events in the Palaeogene, either by direct forcing and/or as an instigator of positive climate feedbacks such as methane hydrate melting.

The relationship between the NAIP and Palaeogene climate perturbations remain a topic of intense debate. The extreme greenhouse conditions of the PETM occurred at ca. 55.8 Ma (Charles et al., 2011), which coincides with the 2nd major pulse of activity from the NAIP (Storey et al., 2007a). However, there are significant gaps in our understanding of the timing and volumes of greenhouse gas fluxes from both volcanic and intrusive NAIP activity. A robust geochronology of NAIP activity is currently hindered by the limited number of accurate radiometric ages. At present, the available modern geochronological data are restricted to 40Ar/39Ar mineral ages and a few U-Pb ages for subvolcanic intrusions (Larsen et al., 2016; Storey et al., 1998; Storey et al., 2007b; Svensen et al., 2010; Wilkinson et al., 2016). Significant hiatuses can be observed in between the two phases of magmatism in the late Palaeocene (Larsen et al., 1999; Storey et al., 2007b), although the apparent timing of these repose periods seems to vary across the NAIP. In East Greenland there is corroborating evidence that voluminous volcanism occurred in the late Palaeocene and early Eocene. The initial emplacement of Skaergaard intrusion occurred at 56.02 Ma (Wotzlaw et al., 2012), and a geobarometer study using amphiboles suggests that the intrusion was buried by 5.3-6.3 ±2.7 km of flood basalts as it crystallized (Larsen and Tegner, 2006). This estimate equates to around 100-300 kyr, representing a huge outpouring of lava that began ~200 kyr before the PETM (Charles et al., 2011). Moreover, a distinctive tephra layer in the uppermost part of the East Greenland flood basalts (Heister et al., 2001) is indistinguishable in both chemistry and age to a prominent tephra horizon found in the North Sea and in Danish strata (Storey et al., 2007a). The corrected Ar/Ar radiometric age is ~55.6 Ma for this tephra, indicating a 400 kyr time interval for the East Greenland flood basalts that encompasses the PETM.

There is also mounting evidence for considerable magmatic intrusions during this time interval. Vent structures form at the edges of sill intrusions due to overpressure generated by pore fluid boiling and/or gas generation from contact metamorphism (Aarnes et al., 2015). The resulting explosions are capable of ejecting gases into the atmosphere, even from submarine vents (Svensen et al., 2004). Thousands of submarine hydrothermal vent complexes have been identified in the Norwegian Sea (Svensen et al., 2004), in the Faroe-Shetland basin (Hansen, 2006), and on the northeast Greenland margin (Reynolds et al., 2017), which suggests that these features were widespread along the proto-northeast Atlantic margins. The majority (~95%) of the vent complexes in the Vøring and Møre basins terminate at the horizon between Paleocene and Eocene strata, with the remainder terminating within the Paleocene sequence (Planke et al., 2005). The only drilled vent complex is dated to within the PETM (Frieling et al., 2016), and the only zircon U-Pb age from a sill in the Vøring basin was dated to 55.6 Ma (Svensen et al., 2010). It therefore appears likely that the emplacement of sills led to considerable hydrothermal venting of gases around the time of the PETM.

While both volcanism and contact metamorphism degassing appear to coincide with the global warming events on the late Palaeocene and Early Eocene, there remain considerable unknowns in terms of temporal development and potential gas fluxes from these sources. Moreover, it is currently difficult to separate the effects of volcanism and contact metamorphism in order to assess their relative forcing on the climate system. There are a number of possible ways to improve the geochronology and relative importance of each flux in the Palaeogene. The acquisition of a core through continuous strata in close proximity to the NAIP would be an invaluable asset in deciphering the relative importance of these two processes. While both volcanism and contact metamorphism release greenhouse gases, the latter is likely to be rich in organic material and therefore have lower δ13C values. The eruptions from hydrothermal vent complexes are also more likely to transfer co-erupted metals such as mercury to the overlying water column, so large variations in metal concentrations in sediments proximal to vent complexes would suggest periods of elevated degassing driven by sill intrusions (Jones et al., in review).

3. North Atlantic Volcanic Province

While many continental margins may be considered volcanic rifted margins (e.g. South Atlantic, Arabian Sea, Northwest Australia) the North East Atlantic is by far the most intensely studied volcanic rifted margin. Being an early frontier for hydrocarbon exploration, also focused scientific attention to this part of the ocean and for the past seven decades an enormous amount of geophysical and drilling data were collected culminating in five DSDP and ODP legs: ***Leg 38*** (1974) – **Vøring** – Talwani et al., 1976; ***Leg 81*** (1981) – **Rockall** – Roberts et al., 1984; ***Leg 104*** (1985) – **Vøring** – Eldholm et al., 1987; 1989; ***Leg 152*** (1993) – **SE Greenland** – Larsen et al., 1994; 1998; ***Leg 163*** (1995) – **SE Greenland** – Larsen et al., 1996; 1999. Apart from the enormous amount of available data and a priori information the North Atlantic Volcanic province also lends itself to the study of break-up volcanic processes because both conjugate margins can still be studied and because rifting occurred over a wide area trapping terrestrial sediments. This results in a situation in which the break-up volcanic successions are nearer to the seafloor than on other volcanic margins which makes it easier to study them by geophysical methods and drilling.

The NE Atlantic rift system developed as a result of a series of rift episodes succeeding the Caledonian orogeny that ultimately led to continental breakup and passive margin formation in the Paleocene-Eocene (e.g. Talwani and Eldholm, 1977; Eldholm et al., 1989; White and McKenzie, 1989; Skogseid et al., 2000). The conjugate Norwegian-Jan Mayen-Greenland margins are now very well covered by 2D and 3D reflection and refraction seismic surveys, by potential field and heatflow data, and by borehole data that allow a refined structural and stratigraphic framework (Figs. 1, 2 and 3) (e.g. Gudlagusson et al., 1988; Lundin and Doré, 1997; Brekke, 2000; Raum, 2000; Tsikalas et al., 2001; Osmundsen et al., 2002; Gernigon et al., 2003; Ren et al., 2003; Hamann et al., 2005; Mjelde et al., 2005; Tsikalas et al., 2005; Breivik et al., 2006).

The Norwegian margin is segmented along strike by the NW-trending Jan Mayen Fracture Zone and the Bivrost Lineament, which separate from south to north the Møre, Vøring, Lofoten-Vesterålen, and Barents Sea margin segments on the Norwegian side and their conjugates at the Jan Mayen microcontinent and off NE Greenland (Figs. 1 and 2). Margin segments are characterized by strongly different tectono-magmatic style and sediment distribution (Fig. 4) (Doré et al., 1999; Berndt et al., 2001; Eldholm et al., 2002). The largest magmatic accumulation is observed in the Vøring segment with decreased volumes to the south and north. In the southern segment, passive margin formation and oceanic spreading was accommodated by the Aegir Ridge between the Møre and Jan Mayen (at the time still connected to Greenland) conjugate margins in the Paleocene-Eocene. The Aegir Ridge was abandoned in the Late Oligocene and the Jan Mayen micro-continent separated from Greenland during the development of the Kolbeinsey Ridge (Talwani and Eldholm, 1977; Nunns, 1982; Skogseid et al., 2000; Müller et al., 2001).

Rifting and passive margin formation in the NE Atlantic was accompanied by strong volcanic activity (White and McKenzie, 1989; Eldholm et al., 1989; Eldholm and Grue, 1994; Larsen and Saunders, 1998). Along the NE Atlantic rifted margins, evidence for extensive magmatism is provided by seaward dipping reflector sequences (SDRs), magmatic intrusives, and high velocity bodies at the base of the continental crust underlying the ocean-continent boundary which in the distal margin are unequivocally interpreted as magmatic underplate (Talwani, et al., 1976; Roberts et al., 1984; Eldholm et al., 1989; Larsen and Saunders, 1998; Berndt et al., 2001; Mjelde et al., 2005; Planke et al., 2005).

ODP drilling of the Vøring Margin (Leg 104) and off SE Greenland (Legs 152 and 163) recovered volcanic rock successions erupted during the initial stages of opening of the NE Atlantic (Fig. 5). The drilled rocks (Legs 152, 163) range from pre-break-up continental tholeiitic flood basalt, through syn-break-up picrite, to oceanic-type basalt that form the main part of the SDRs (Fitton et al. 2000). The oceanic-type lavas show increasing degree of melting and contribution from asthenospheric mantle sources with time (Fram et al., 1998; Fitton et al., 1998). The thickness of igneous crust accreted at the SE Greenland continent-ocean boundary increases from about 18 km in the south to about 30 km near the Greenland-Iceland Rise (Fig. 6) (Holbrook et al., 2001). Similarly, geochemical enrichment of volcanics of the East Greenland Margin (e.g. chondrite-normalized $(Ce/Y)_N$ and isotopes; Fram et al., 1998; Fitton et al., 1998; Tegner et al., 1998; Brown and Lesher, 2014), increases from south to north. The correlation of crustal thickness and compositional enrichment suggests a combination of changes in source composition, source temperature, and/or melting dynamics (Fig. 6). It is not known if a similar correlation of crustal thicknesses and magma compositions exists along the Norwegian margin, and to establish the relationship between chemistry of the volcanics and crustal configuration is a milestone of the proposed investigations. Geochemical data (Fig. 5) show strong chemical and isotopic similarities between the “Upper Series” from the Vøring Plateau and SE Greenland. In contrast, the “Lower Series” from both areas are fundamentally different from each other in many aspects. These differences point to substantial differences in either the pre-breakup lithosphere composition at the two localities, or to different styles of mantle-crust interaction.

Periods of elevated magmatism such as the emplacement of the North Atlantic Igneous Province (NAIP) often coincide with considerable environmental perturbations such as the Palaeocene-Eocene Thermal Maximum (PETM; 56 Million years ago(Ma)) and/or long-term climate warming (e.g. the early Eocene Climate Optimum (EECO; ~50-53 Ma) suggesting a possible causal relationship (Bond and Wignall, 2014; Eldholm & Thomas, 1993). The total volume of magma emplaced during the Paleogene is estimated to be 6-10 x 10^6 km^3; Saunders et al., 2007; Horni et al., 2017), with the most voluminous activity roughly coinciding with the Paleocene-Eocene boundary (Storey et al., 2007b), although the full emplacement spans several Myr (e.g. Wilkinson et al. 2016). Greenhouse gas emissions are likely to have been generated by magmatic degassing (Storey et al. 2007, Gutjahr et al. 2017) and by explosive discharge of thermogenic gases generated by contact metamorphism (Svensen et al., 2004, Frieling et al. 2016, Aarnes et al. 2010). Therefore, the emplacement of the NAIP is one of the primary contenders for instigating numerous hyperthermal events and long-term warming in the Paleogene, either as a direct forcing and/or as an instigator of positive climate feedbacks such as methane hydrate melting.

While both volcanism and contact metamorphism degassing may appear to coincide with the global warming events in the early Paleogene, considerable unknowns in terms of temporal volcanic development and potential gas fluxes from these sources remain. Moreover, with the presently available material it is difficult to separate the effects of volcanism and contact metamorphism in order to assess their relative forcing on the climate system. The acquisition of a core through continuous strata in close proximity to the NAIP would be an invaluable asset in deciphering the absolute and relative importance of these two processes. Both volcanism and contact metamorphism release greenhouse gases (CO_2, CH_4), the latter is likely to be rich in organic material and therefore has a different stable carbon isotope signature ($\delta^{13}C$) to mantle-derived carbon. The eruptions from hydrothermal vent complexes are also more likely to transfer co-erupted metals such as mercury to the overlying water column (Scaife et al., 2017), so that large variations in metal concentrations in sediments proximal to vent complexes could suggest periods of elevated degassing driven by sill intrusions. There may also be a systematic temporal evolution in the magmatic system e.g. from eruptive to intrusive as has been proposed elsewhere (Burgess et al. 2017).

4. Drilling strategy and potential Sites

During the workshop discussions focused on a potential drilling strategy to maximize knowledge gain from a new drilling campaign to the North Atlantic Volcanic processes. The most promising approach would involve drilling one along-strike and one cross-strike margin transects, and two high-resolution Paleogene sedimentary sites. There are three main reasons for the proposed strategy:

(1) Temporal and spatial sampling of volcanic rocks is important to constrain melting conditions and plume influence on magmatism. The holes should provide samples of the main volcanic terrains and ages (61-50 Ma). Geochemical data (example) can provide proxy data for the melting temperature and dynamics in space and time. Furthermore, the data can be used to asses mantle heterogeneities, lithospheric structures (e.g., transform margins), and lithospheric contamination. Geochronological data (example) combined with geophysical data (example) are essential to provide constraints on how magma fluxes vary along strike and across the margin. These are all crucial parameters required to model melting processes.

(2) Determine the nature of volcanic seismic facies units. Seismic volcano-stratigraphic interpretation suggests that the emplacement environment can be determined from the seismic data (Planke et al. 2000; Berndt et al., 2001). Previous drilling on the Vøring Margin (Hole 642E) has documented that the Inner SDR and Landward Flows represent sub-aerially emplaced lava flows. However, no SDR reflections have been drilled to date. Furthermore, the nature of the Inner Flows, Lava Delta, Outer High, and Outer SDR has not been documented by sampling. In the model of Planke et al. (2000) the Outer SDR are emplaced in a deep marine environment, the Outer High in a shallow marine environment, the Lava Delta in a coastal environment, and the Inner Flows in a deep marine environment. The documentation of the emplacement environment of the different facies units will provide important control on the vertical motions of the volcanic eruption centres in space and time, which are important parameters for modelling margin dynamics.

(3) The acquired drill cores will allow high-resolution sampling of Paleogene sediments to determine the relationship between the evolution of magmatism and paleoenvironment. This would include radiometric dating of tephra layers, coupled use of volcanic proxies such as metal enrichments, evidence of hydrothermal vent complex ejecta, palynology and organic molecular proxies to reconstruct paleo-temperatures.

The across-strike margin transect is proposed for the northern Vøring Margin segment, and could consist of four sites. This transect is located in a typical volcanic rifted margin setting and will cover the entire age range of breakup volcanics to understand syn- and post-breakup volcanism, melting, and margin dynamics. The inner two sites are located on modern 3D seismic profiles, whereas the outer two sites are located on 2D seismic profiles. The holes are complimentary to the previous DSDP and ODP holes in the region.

The aim of the along-strike transect is to sample volcanic rocks in the northern part of the Møre Margin, the Kolga High. This structure has recently been covered by high-resolution 3D industry seismic data, and reveals very thin basalt above a non-reflective structural high. The two sites aim at sampling the sub-basalt and initial basalt deposits on this margin segment. The along-strike profile will include the existing deep ODP 642 Site on the southern Vøring Margin, DSDP Sites, and the two proposed site on the Vøring Marginal High.

Two high-resolution Paleogene sediment sites are proposed along the Vøring Transform Margin. The Paleogene is within the 200 mbsf limit in two places, the northern Kolga High, and the Mimir High. Two holes are proposed on the northern Kolga High to ensure relatively complete coverage of the sequence. Four slightly offset holes are proposed on the Mimir High. Here, the Paleocene and lower Eocene sediments are dipping gently northwards and offset drilling may provide a more complete sampling of the succession.

5. Secondary Objectives

5.1. The role of oceanographic gateways on the onset of MOC

A significant consequence of the tectonic opening of the north-eastern North Atlantic during the Paleogene and Neogene is the creation of ocean gateways linking the Arctic Ocean to the Atlantic through the Greenland, Iceland and Norwegian Seas (Nordic Seas). This process has been central to or part of previous scientific drilling expeditions in the North Atlantic region and their research outputs with the conclusion that these connections played a significant role in causing, or amplifying environmental changes during the Cenozoic through its influence on water mass circulation (Laughton, 1975; Miller and Tucholke, 1983; Jakobsson et al., 2007; Boyle et al., 2017; Coxall et al., 2018; Vahlenkamp et al., 2018). Current questions are focusing again on the role and timing of mantle upwelling beneath Iceland in dynamically supporting regional bathymetry and the height of oceanic gateways that control the strength of deep-water flow over geologic timescales (Miller and Tucholke, 1983; Poore et al., 2006; Parnell-Turner, 2014; Stärz et al., 2017), yet existing records are insufficient to move forward. Recovery of early Cenozoic sediments overlying Paleocene volcanics on the Vøring Plateau, which are captured impressively in seismic profiles, will provide improved constraints on the evolving oceanic environment of the Nordic Seas, especially the transition from non-marine to marine facies. Moreover, we suggest drilling a specified core in the through 'Judd Fall Drift', situated in the Faeroe Bank Channel (one of the deep intersections of the Greenland-Scotland Ridge (850 m water depth) Hohbein et al., 2012). Judd Fall Drift contains a thick sedimentary section (up to 900m) of early middle Eocene to late Miocene (or early Pliocene) sediments and is interpreted from industry seismic evidence to contain a history of Nordic Seas overflow extending back to the middle Eocene (Hohbein et al., 2012). IODP coring of the sequence will be critical for testing this and competing hypothesis about the timing of Greenland-Scotland Ridge subsidence and associated onset of formation of deep water in the North Atlantic in the early Cenozoic (Via and Thomas, 2006; Hohbein et al., 2012; Boyle et al., 2017; Coxall et al., 2018; Vahlenkamp et al., 2018). These paleo ocean gateway objectives will provide an older and more northly perspective on the links between plume activity and ocean circulation to complement an existing IODP proposal focused on similar question in the Neogene, i.e. IODP proposal 892 Full (Reykjanes Mantle Convection, Parnell-Turner et al., 2014).

5.2. Groundwater systems in break-up basalts and carbon storage

Submarine groundwater discharge is a global phenomenon contributing 3-30% of fresh water budget in various locations (Taniguchi et al., 2002; Post et al., 2013). In regions covered by glaciers and/or permafrost in the past, circulation of meteoric water has been shown to relate to large hydraulic head contrast as a result of the excess weight from glaciers (DeFoor et al., 2011). Signs of meteoric water circulation have been detected from the stable isotopes ($\delta^{18}O$ and δD) of water from ODP Leg104 Site 642 and 643 at Vøring Plateau. Such observation is unexpected as these two drill sites are ca. 500 km from the shelf edge, where the maximum extend of glacier ice was during the Last Glacial Maximum (Patton et al., 2016). Similar signs of meteoric water were also observed along the continental shelf of Norwegian margin (Egeberg and Aagaard 1989) and ca. 100 km southeast off Greenland shelf (DeFoor et al., 2011).

The presence of meteoric water from the Norwegian and Greenland margins may associate with the thick basaltic formation as a result of the break-up volcanism in the North Atlantic Ocean. Large-scale basaltic formations serve as quality aquifers at many places around the world. For example, the Columbia River Basalt Group from western USA, one of the large igneous provinces, is a 163,687 km^2 aquifer that supplies fresh water to three states (Vaccaro, 1999). In addition to the potential for storing fresh water, basaltic formations are also good candidates for permanent CO_2 sequestration. Alteration of basaltic rocks can release calcium ion, which is one of the most essential ingredients for carbonate mineral formation. By injecting solutions into the basaltic formations, the dissolved CO_2 can be sequestrated in the formation as carbonate minerals. For example, the investigation of fluid geochemistry around the Mt. Hekla from Iceland has shown that dissolution of basaltic material can stimulate carbonate mineral precipitation and drawdown of inorganic carbon content in the solution (Flaathen et al., 2009).

The observations of meteoric water and high dissolved calcium concentration from the bottom of ODP Site 642 and 643 have shown that Vøring plateau is an ideal place to study the circulation of fresh water within such large basaltic formation and to assess its potential for CO_2 sequestration. However, what was not answered from the early studies are the origin of the meteoric water and the trigger(s) for such large-scale circulation. Furthermore, this will have repercussions on the role of meteoric water circulation and water-rock interactions on carbon cycling and deep microbial. Dating of the water samples from the borehole with tracers such as ^{14}C, ^{36}Cl, and $^{234}U/^{238}U$ (IAEA 2013) and a systematic analysis of fluid geochemistry (Inagaki et al. 2015) will shed lights on some of these questions.

6. Relationship to IODP Science Plan for 2013–2023 and beyond

The breakup of continents is a fundamental component of the plate tectonic cycle and major episodes of the agglomeration of crustal blocks into supercontinents and their subsequent rifting and the formation of new oceans has punctuated Earth's evolution since the Archean. Rifting episodes result in major changes in the surficial conditions of our planet impacting Earth's atmosphere, climate, ocean circulation and chemistry, and life on-land and in the oceans. Some of these events have resulted in the development of the major energy resources that have powered world economies for the past century. Consequently, the mechanisms and consequences of continental and the nature of the still poorly defined transitions from continents to oceanic crust have been important targets for scientific ocean drilling since its inception in the Deep Sea Drilling Project 50 years ago.

The current phase of ocean drilling, the International Ocean Discovery Program (IODP) is guided by a community-derived science plan "Illuminating Earth's Past Present and Future: Exploring the Earth under the sea" (IODP Science Plan for 2013-2023). This document comprises 14 challenges within four major themes:

- Climate and Ocean Change - Reading the Past, Informing the Future;
- Biosphere Frontiers - Deep Life, Biodiversity, and Environmental Forcing of Ecosystems;
- Earth Connections, - Deep Earth Processes and their Impacts on Earth's Surface Environment; and
- Earth in Motion - Processes and Hazards on Human Time Scales.

A number of the challenges can be directly or indirectly related to the magmatic and tectonic processes occurring during continental rifting and the formation of passive margins. These include aspects of the "Composition, structure, and dynamics of Earth's upper mantle (Challenge 8); How seafloor spreading and mantle melting links to ocean crustal architecture (Challenge 9); and the chemical exchanges between the oceanic crust and seawater (Challenge 10). Continental break up, whether accompanied by large scale magmatism or principally tectonic, may have major impacts on global chemical cycles and the elemental and isotopic composition of seawater, but to date these effects remain poorly quantified for either volcanic or non-volcanic margins. Passive margins host major potential hazards from submarine landslides and the resulting tsunami (Challenge 12), offer possibilities for the industrial scale storage of carbon dioxide (Challenge 13), and the loci for the flow of sub-seafloor fluids and consequent tectonic, thermal and biogeochemical processes (Challenge 14). Although the climatic drivers and effects of magmatism and igneous sill intrusion on the Norwegian margin remain debated (see section 3.3), the temporal coincidence of magmatism, North Atlantic break up, and the major, geologically short-lived, carbon isotopic excursion of the PETM, indicate that that the sedimentary sequences bordering the North Atlantic margins are compelling targets to test models of sedimentary or igneous gas release, gas hydrate de-stabilisation, or thermogenic methane production during contact metamorphism. Direct, subseafloor observations of purported gas escape structures may be of direct relevance to anthropogenic scale industrial carbon dioxide storage. These geological records could directly address on-going science debates regarding the Earth's response to elevated CO2 (Challenge 1) and other greenhouse gases, in particular methane, and the resilience of the oceans to chemical perturbations (Challenge 4). The science plan also includes a number of cross-cutting topics, a number of which can be partly addressed by a campaign of expeditions to the North Atlantic region, including hydrocarbon and other resources needed for the 21st century, the calibration of climate models through core observations and analyses, and serpentinisation, which is a major process on some rifted margins.

7. Conclusions

The North Atlantic Volcanic Province is as thrilling a drilling target as ever. During the MagellanPlus Workshop an impressive amount of new data and ideas were presented. They showed that since the last drilling campaign in 1996 science has moved on and new industry data do reveal drilling targets that would allow testing two sets of hypotheses that had not been around for consideration when the last ODP drilling campaign took place. New IODP and ICDP campaigns will lead to a step increase in our understanding of the fundamental processes that lead to large-scale break-up volcanism and to understanding the consequences that break-up volcanism has for climate evolution. The workshop brought together the scientific community and an IODP 944 proposal has already been submitted and an ICDP proposal is being prepared for the March 2019 deadline.

8. Acknowledgements

The Magellan workshop was made possible by ECORD funding and GEOMAR Helmholtz Centre for Ocean Research Kiel funding. We thank Jasmin Mögeltönder and Anne Völsch for workshop organization and logistics.

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10. References

Aarnes, I., Planke, S., Trulsvik, M. and Svensen, H., (2015). Contact metamorphism and thermogenic gas generation in the Vøring and Møre basins, offshore Norway, during the Paleocene–Eocene thermal maximum. *Journal of the Geological Society, 172*: 588-598.

Aarnes, I., Svensen, H., Connolly, J. A., & Podladchikov, Y. Y. (2010). How contact metamorphism can trigger global climate changes: Modeling gas generation around igneous sills in sedimentary basins. *Geochimica et Cosmochimica Acta*, *74*(24), 7179-7195.

Aarnes, I., Svensen, H., Polteau, S., & Planke, S. (2011). Contact metamorphic devolatilization of shales in the Karoo Basin, South Africa, and the effects of multiple sill intrusions. *Chemical Geology*, *281* (3-4), 181-194.

Albarède, F. (2005). The survival of mantle geochemical heterogeneities. *Washington DC American Geophysical Union Geophysical Monograph Series*, *160*, 27-46.

Allègre, C. J., & Lewin, E. (1995). Isotopic systems and stirring times of the Earth's mantle. *Earth and Planetary Science Letters*, *136*(3-4), 629-646.

Berndt, C., Hensen, C., Mortera-Gutiérrez, C., Sarkar, S., Geilert, S., Schmidt, M., et al. (2016). Rifting under steam—How rift magmatism triggers methane venting from sedimentary basins. *Geology*, *44*(9), 767–770.

Berndt, C., Planke, S., Alvestad, E., Tsikalas, F., & Rasmussen, T. (2001). Seismic volcanostratigraphy of the Norwegian Margin: constraints on tectonomagmatic break-up processes. *Journal of the Geological Society*, *158*(3), 413-426.

Bijwaard, H., & Spakman, W. (1999). Tomographic evidence for a narrow whole mantle plume below Iceland. *Earth and Planetary Science Letters*, *166*(3-4), 121-126.Ritsema, 1999

Bonatti, E., (1990). Not So Hot Hot-Spots in the Oceanic Mantle. *Science*, *250* (4977), 107–111.

Bond, D.P.G. and Wignall, P.B., (2014). Large igneous provinces and mass extinctions: An update. *The Geological Society of America Special Paper, 505*: 29-55.

Boutilier, R. R., & Keen, C. E. (1999). Small-scale convection and divergent plate boundaries. *Journal of Geophysical Research: Solid Earth*, *104*(B4), 7389-7403.

Boyle, P. R., Romans, B. W., Tucholke, B. E., Norris, R. D., Swift, S. A., & Sexton, P. F. (2017). Cenozoic North Atlantic deep circulation history recorded in contourite drifts, offshore Newfoundland, Canada. *Marine Geology*, *385*, 185-203.

Breivik, A. J., Mjelde, R., Faleide, J. I., & Murai, Y. (2006). Rates of continental breakup magmatism and seafloor spreading in the Norway Basin–Iceland plume interaction. *Journal of Geophysical Research: Solid Earth*, *111*(B7).

Brekke, H. (2000). The tectonic evolution of the Norwegian Sea continental margin, with emphasis on the Voring and More basins. *Special Publication-Geological Society of*

London, *167*, 327-378.

Brown, E. L., & Lesher, C. E. (2014). North Atlantic magmatism controlled by temperature, mantle composition and buoyancy. *Nature Geoscience*, *7*(11), 820–824.

Burgess, S. D., Muirhead, J. D., & Bowring, S. A. (2017). Initial pulse of Siberian Traps sills as the trigger of the end-Permian mass extinction. *Nature communications*, *8*(1), 164.

Charles, A., Condon, D., Harding, I., Pälike, H., Marshall, J., Cui, Y., Kump, L. and Croudace, I., (2011). Constraints on the numerical age of the Palaeocene-Eocene boundary. *Geochemistry, Geophysics, Geosystems, 12*: Q0AA17.

Coffin, M. F., & Eldholm, O. (1992). Volcanism and continental break-up: a global compilation of large igneous provinces. In *Magmatism and the Causes for Continental Break-up* (Vol. 68, pp. 17–30). Geological Society of London.

Coxall, H. K., Huck, C. E., Huber, M., Lear, C. H., Legarda-Lisarri, A., O'regan, M., ... & Backman, J. (2018). Export of nutrient rich Northern Component Water preceded early Oligocene Antarctic glaciation. *Nature Geoscience*, *11*(3), 190.

Davies G.F. (1983). Geophysical and Isotopic evidence for an unlayered, multiple-source mantle *EOS, 64*, p. 324.

DeFoor, W., M. Person, H. C. Larsen, D. Lizarralde, D. Cohen and B. Dugan (2011). "Ice sheet–derived submarine groundwater discharge on Greenland's continental shelf." *Water Resources Research* **47**(7).

Doré, A. G., Lundin, E. R., Jensen, L. N., Birkeland, Ø., Eliassen, P. E., & Fichler, C. (1999, January). Principal tectonic events in the evolution of the northwest European Atlantic margin. In *Geological society, London, petroleum geology conference series* (Vol. 5, No. 1, pp. 41-61). Geological Society of London.

Duncan, R.A., Larsen, H.C., Allan, J.F., et al., (1996). *Proc. ODP, Init. Repts.,* 163: College Station, TX (Ocean Drilling Program).

Egeberg, P. K. and P. Aagaard (1989). "Origin and evolution of formation waters from oil fields on the Norwegian shelf." *Applied Geochemistry* ***4***(2): 131-142.

Eldholm, O. (1989). Evolution of the Vöring Volcanic Margin. In *Proc. ODP, Sci. Results* (Vol. 104, pp. 1033-1065). College Station, TX (Ocean Drilling Program).

Eldholm, O., Gladczenko, T. P., Skogseid, J., & Planke, S. (2000). Atlantic volcanic margins: a comparative study (Vol. 167, pp. 411–428). Geological Society of London.

Eldholm, O., & Grue, K. (1994). North Atlantic volcanic margins: dimensions and production rates. *Journal of Geophysical Research: Solid Earth*, *99*(B2), 2955-2968.

Eldholm, O., Thiede, J., Taylor, E., et al., (1987). *Proc. ODP, Init. Repts.,* 104: College Station, TX (Ocean Drilling Program).

Eldholm, O., Thiede, J., Taylor, E., et al., (1989). *Proc. ODP, Sci. Results,* 104: College Station, TX (Ocean Drilling Program).

Eldholm, O., & Thomas, E. (1993). Environmental impact of volcanic margin formation. *Earth and Planetary Science Letters*, *117*, 319–329.

Eldholm, O., Tsikalas, F., & Faleide, J. I. (2002). Continental margin off Norway 62–75° N: Palaeogene tectono-magmatic segmentation and sedimentation. *Geological Society, London, Special Publications*, *197*(1), 39-68.

Fitton, J. G., Larsen, L. M., Saunders, A. D., Hardarson, B. S., & 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*, *41*(7), 951-966.

Fitton, J. G., Saunders, A. D., Larsen, L. M., Hardarson, B. S., & Norry, M. J. (1998). 28. VOLCANIC ROCKS FROM THE SOUTHEAST GREENLAND MARGIN AT 63 N: COMPOSITION, PETROGENESIS, AND MANTLE SOURCES. *Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 15*.

Flaathen, T. K., S. R. Gislason, E. H. Oelkers and Á. E. Sveinbjörnsdóttir (2009). "Chemical evolution of the Mt. Hekla, Iceland, groundwaters: A natural analogue for CO2 sequestration in basaltic rocks." *Applied Geochemistry* ***24****(3)*: 463-474.

Foulger, G. R., Pritchard, M. J., Julian, B. R., Evans, J. R., Allen, R. M., Nolet, G., ... & Ragnarsson, S. (2001). Seismic tomography shows that upwelling beneath Iceland is confined to the upper mantle. *Geophysical Journal International*, *146*(2), 504-530

Fram, M. S., Lesher, C. E., & Volpe, A. M. (1998). 31. MANTLE MELTING SYSTEMATICS: TRANSITION FROM CONTINENTAL TO OCEANIC VOLCANISM ON THE SOUTHEAST GREENLAND MARGIN. *Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 152*.

French, S.W., Romanowicz B., (2015). Broad plumes rooted at the base of the Earth's mantle beneath major hotspots. *Nature*. 2015 3;525(7567):95-9.

Frieling, J., Svensen, H.H., Planke, S., Cramwinckel, M.J., Selnes, H. and Sluijs, A., (2016). Thermogenic methane release as a cause for the long duration of the PETM. *Proceedings of the National Academy of Sciences USA, 113(43)*: 12059-12064.

Gernigon, L., Ringenbach, J. C., Planke, S., Le Gall, B., & Jonquet-Kolstø, H. (2003). Extension, crustal structure and magmatism at the outer Vøring Basin, Norwegian margin. *Journal of the Geological Society*, *160*(2), 197-208.

Gudlaugsson, S. T., Gunnarsson, K., Sand, M., & Skogseid, J. (1988). Tectonic and volcanic events at the Jan Mayen Ridge microcontinent. *Geological Society, London, Special Publications*, *39*(1), 85-93.

Hamann, N. E., Whittaker, R. C., & Stemmerik, L. (2005, January). Geological development of the Northeast Greenland shelf. In *Geological Society, London, Petroleum Geology Conference series* (Vol. 6, No. 1, pp. 887-902). Geological Society of London.

Hansen, D.M., (2006). The morphology of intrusion-related vent structures and their implications for constraining the timing of intrusive events along the NE Atlantic margin. *Journal of the Geological Society, 163*: 789-800.

Heister, L.E., O'Day, P.A., Brooks, C.K., Neuhoff, P.S. and Bird, D.K., (2001). Pyroclastic deposits within the East Greenland Tertiary flood basalts. *Journal of the Geological Society, 158*: 269-284.

Hohbein, M. W., Sexton, P. F., & Cartwright, J. A. (2012). Onset of North Atlantic Deep Water production coincident with inception of the Cenozoic global cooling trend. *Geology*, *40*(3), 255-258.

Holbrook, W. S., & Kelemen, P. B. (1993). Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup. *Nature*, *364*(6436), 433.

Holbrook, W. S., Larsen, H. C., Korenaga, J., Dahl-Jensen, T., Reid, I. D., Kelemen, P. B., ... & Detrick, R. S. (2001). Mantle thermal structure and active upwelling during continental breakup in the North Atlantic. *Earth and Planetary Science Letters*, *190*(3-4), 251-266.

Hole, M. J., & Millett, J. M. (2016). Controls of mantle potential temperature and lithospheric thickness on magmatism in the North Atlantic Igneous Province. *Journal of Petrology*, *57*(2), 417–436.

Horni, J. Á., Hopper, J. R., Blischke, A., Geisler, W. H., Stewart, M., McDermott, K., ... & Árting, U. (2017). Regional distribution of volcanism within the North Atlantic Igneous Province. *Geological Society, London, Special Publications*, *447*(1), 105-125.

IAEA (2013). Isotope Methods for Dating Old Groundwater, International Atomic Energy Agency.

Inagaki, Fumio, et al. "Exploring deep microbial life in coal-bearing sediment down to~ 2.5 km below the ocean floor." *Science* 349.6246 (2015): 420-424.

J. Jenkins, S. Cottaar, R. S. White, A. Deuss, (2016). Depressed mantle discontinuities beneath Iceland: Evidence of a garnet controlled 660 km discontinuity? *Earth and Planetary Science Letters, Volume 433*, 1 January 2016, Pages 159-168.

Jones, M.T., Jerram, D.A., Svensen, H.H. and Grove, C., (2016). The effects of large igneous provinces on the global carbon and sulphur cycles. *Palaeogeography Palaeoclimatology Palaeoecology*, 441: 4-21.

Keen, C. E., & Boutilier, R. R. (2000). Interaction of rifting and hot horizontal plume sheets at volcanic margins. *Journal of Geophysical Research: Solid Earth*, *105*(B6), 13375–13387.

Kellogg, J. B., Jacobsen, S. B., & O'Connell, R. J. (2002). Modeling the distribution of isotopic ratios in geochemical reservoirs. *Earth and Planetary Science Letters*, *204*(1-2), 183-202.

Korenaga, J., Holbrook, W. S., Kent, G. M., Kelemen, P. B., Detrick, R. S., Larsen, H. C., ... & Dahl Jensen, T. (2000). Crustal structure of the southeast Greenland margin from joint refraction and reflection seismic tomography. *Journal of Geophysical Research: Solid Earth*, *105*(B9), 21591-21614.

Korenaga, J., Kelemen, P. B., & Holbrook, W. S. (2002). Methods for resolving the origin of large igneous provinces from crustal seismology. *Journal of Geophysical Research: Solid Earth*, *107*(B9).

Larsen, H.C., Duncan, R.A., Allan, J.F., and Brooks, K. (Eds.), (1999). *Proc. ODP, Sci. Results,* 163: College Station, TX (Ocean Drilling Program).

Larsen, L., Pedersen, A., Tegner, C., Duncan, R., Hald, N. and Larsen, J., (2016). Age of Tertiary volcanic rocks on the West Greenland continental margin: volcanic evolution and event correlation to other parts of the North Atlantic Igneous Province. *Geological Magazine: 1-25.*

Larsen, H.C., Saunders, A.D., Clift, P.D., et al., (1994). *Proc. ODP, Init. Repts,* 152: College Station,TX (Ocean Drilling Program).

Larsen, H. C., & Saunders, A. D. (1998). 41. Tectonism and volcanism at the Southeast Greenland rifted margin: a record of plume impact and later continental rupture. In *Proceedings of the Ocean Drilling Program, Scientific Results* (Vol. 152, pp. 503-533).

Larsen, L., Waagstein, R., Pedersen, A. and Storey, M., (1999). Trans-Atlantic correlation of the Palaeogene volcanic successions in the Faeroe Islands and East Greenland. *Journal of the Geological Society, London, 156*: 1081-1095.

Larsen, R.B. and Tegner, C., (2006). Pressure conditions for the solidification of the Skaergaard intrusion: Eruption of East Greenland flood basalts in less than 300,000 years. *Lithos, 92*: 181-197.

Laughton, A. S. (1975). Tectonic evolution of the northeast Atlantic Ocean; a review. *Norges Geol. Unders*, *316*, 169-193.

Lundin, E. R., & Doré, A. G. (1997). A tectonic model for the Norwegian passive margin with implications for the NE Atlantic: Early Cretaceous to break-up. *Journal of the Geological Society*, *154*(3), 545-550

Lundin, E. R., & Doré, A. G. (2005, January). NE Atlantic break-up: a re-examination of the Iceland mantle plume model and the Atlantic–Arctic linkage. In *Geological Society, London, Petroleum Geology Conference series* (Vol. 6, No. 1, pp. 739-754). Geological Society of London.

Lundin, E. R., & Doré, A. G. (2005). Fixity of the Iceland “hotspot” on the Mid-Atlantic Ridge: Observational evidence, mechanisms, and implications for Atlantic volcanic margins. *Geological Society of America Special Papers*, *388*, 627-651.

McKenzie, D., & Bickle, M. J. (1988). The Volume and Composition of Melt Generated by Extension of the Lithosphere. *Journal of Petrology*, *29*(3), 625–679.

Meibom, A., & Anderson, D. L. (2004). The statistical upper mantle assemblage. *Earth and Planetary Science Letters*, *217*(1-2), 123-139.

Miller, K. G., & Tucholke, B. E. (1983). Development of Cenozoic abyssal circulation south of the

Greenland-Scotland Ridge. In *Structure and development of the Greenland-Scotland Ridge* (pp. 549-589). Springer, Boston, MA.

Minshull, T. A., Marín-Moreno, H., Armstrong McKay, D. I., & Wilson, P. A. (2016). Mechanistic insights into a hydrate contribution to the Paleocene-Eocene carbon cycle perturbation from coupled thermohydraulic simulations. *Geophysical Research Letters*, *43*(16), 8637–8644.

Mjelde, R., Raum, T., Breivik, A., Shimamura, H., Murai, Y., Takanami, T., & Faleide, J. I. (2005, January). Crustal structure of the Vøring Margin, NE Atlantic: a review of geological implications based on recent OBS data. In *Geological Society, London, Petroleum Geology Conference series* (Vol. 6, No. 1, pp. 803-813).

Mjelde, R., Raum, T., Myhren, B., Shimamura, H., Murai, Y., Takanami, T., ... & Næss, U. (2005). Continent-ocean transition on the Vøring Plateau, NE Atlantic, derived from densely sampled ocean bottom seismometer data. *Journal of Geophysical Research: Solid Earth*, *110*(B5).

Montelli, R., Nolet, G., Dahlen, F. A., Masters, G., Engdahl, E. R., & Hung, S. H. (2004). Finite frequency tomography reveals a variety of plumes in the mantle. *Science*, *303*(5656), 338-343.

Morgan, J. P., & Morgan, W. J. (1999). Two-stage melting and the geochemical evolution of the mantle: a recipe for mantle plum-pudding. *Earth and Planetary Science Letters*, *170*(3), 215 239.

Müller, R. D., Gaina, C., Roest, W. R., & Hansen, D. L. (2001). A recipe for microcontinent formation. *Geology*, *29*(3), 203-206.

Mutter, J. C., Buck, W. R., & Zehnder, C. M. (1988). Convective partial melting: 1. A model for the formation of thick basaltic sequences during the initiation of spreading. *Journal of Geophysical Research: Solid Earth*, *93*(B2), 1031-1048.

Nielsen, T. K., & Hopper, J. R. (2004). From rift to drift: Mantle melting during continental breakup. *Geochemistry, Geophysics, Geosystems*, *5*(7).

Nunns, A. (1982). The Structure and Evolution of the Jan Mayen Ridge and Surrounding Regions: Rifted Margins: Field Investigations of Margin Structure and Stratigraphy. *Studies in Continental Margin Geology.*

Osmundsen, P. T., Sommaruga, A., Skilbrei, J. R., & Olesen, O. (2002). Deep structure of the Mid Norway rifted margin. *Norwegian Journal of Geology/Norsk Geologisk Forening*, *82*(4).

Patton, H., A. Hubbard, K. Andreassen, M. Winsborrow and A. P. Stroeven (2016). "The build-up, configuration, and dynamical sensitivity of the Eurasian ice-sheet complex to Late Weichselian climatic and oceanic forcing." *Quaternary Science Reviews 153*: 97-121.

Planke, S., Rasmussen, T., Rey, S. and Myklebust, R., (2005). Seismic characteristics and distribution of volcanic intrusions and hydrothermal vent complexes in the Vøring and Møre basins. In: A.G. Doré and B.A. Vining (Editors), *Petroleum Geology: North-West Europe* *and Global Perspectives - Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London, pp. 833-844.

Planke, S., Symonds, P. A., Alvestad, E., & Skogseid, J. (2000). Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins. *Journal of Geophysical Research*, *105*(B8), 19–335–19–351.

Parnell-Turner, R., White, N., Henstock, T., Murton, B., Maclennan, J., & Jones, S. M. (2014). A continuous 55-million-year record of transient mantle plume activity beneath Iceland. *Nature Geoscience*, *7*(12), 914.

Poore, H. R., Samworth, R., White, N. J., Jones, S. M., & McCave, I. N. (2006). Neogene overflow of northern component water at the Greenland-Scotland Ridge. *Geochemistry, Geophysics, Geosystems*, *7*(6).

Post, V. E., J. Groen, H. Kooi, M. Person, S. Ge and W. M. Edmunds (2013). "Offshore fresh groundwater reserves as a global phenomenon." *Nature 504(7478)*: 71-78.

Raum, T (2000). Crustal structure and evolution of the Faeroe, Møre and Vøring margins from wide-angle seismic and gravity data. *PhD Thesis, University of Bergen*.

Ren, S., Faleide, J. I., Eldholm, O., Skogseid, J., & Gradstein, F. (2003). Late Cretaceous–Paleocene tectonic development of the NW Vøring basin. *Marine and Petroleum Geology*, *20*(2), 177 206.

Reynolds, P., Planke, S., Millett, J.M., Jerram, D.A., Trulsvik, M. and Schofield, N., (2017). Hydrothermal vent complexes offshore Northeast Greenland: A potential role in driving the PETM. *Earth and Planetary Science Letters, 467*: 72-78.

Roberts, D.G.; Schnitker, D.; et al., (1984). Initial Reports of the Deep Sea Drilling Project, U.S. Government *Printing Office*, LXXXI, 701-723,

Roberts, D.G. (1984). Evolution of volcanic rifted margins: Synthesis of Leg 81 results on the west margin of Rockall. In: Roberts DG, Schneider ED (eds) Init Rep deep sea drilling project Leg 81 US government printing office, Washington, pp 883–923.

Saunders, A., Jones, S., Morgan, L., Pierce, K., Widdowson, M. and Xu, Y., (2007). Regional uplift associated with continental large igneous provinces: The roles of mantle plumes and the lithosphere. *Chemical Geology, 241*: 282-318.

Saunders, A.D., Larsen, H.C., and Wise, S.W., Jr. (Eds.), (1998). *Proc. ODP, Sci. Results,* 152: College Station, TX (Ocean Drilling Program). doi:10.2973/odp.proc.sr.152.1998

Scaife, J. D., Ruhl, M., Dickson, A. J., Mather, T. A., Jenkyns, H. C., Percival, L. M. E., ... & Minisini, D. (2017). Sedimentary mercury enrichments as a marker for submarine large igneous province volcanism? Evidence from the Mid-Cenomanian event and Oceanic Anoxic Event 2 (Late Cretaceous). *Geochemistry, Geophysics, Geosystems*, *18*(12), 4253-4275.

Skogseid, J., Planke, S., Faleide, J. I., Pedersen, T., Eldholm, O., & Neverdal, F. (2000). NE Atlantic continental rifting and volcanic margin formation. *Geological Society, London, Special Publications*, *167*(1), 295-326.

Stärz, M., Jokat, W., Knorr, G., & Lohmann, G. (2017). Threshold in North Atlantic-Arctic Ocean circulation controlled by the subsidence of the Greenland-Scotland Ridge. *Nature communications*, *8*, 15681.

Storey, M., Duncan, R., Pedersen, A., Larsen, L. and Larsen, H., (1998). ^{40}Ar/^{39}Ar geochronology of the West Greenland Tertiary volcanic province. *Earth and Planetary Science Letters, 160(3)*: 569-586.

Storey, M., Duncan, R. and Swisher III, C., (2007a). Paleocene-Eocene Thermal Maximum and the opening of the Northeast Atlantic. *Science*, 316: 587-589.

Storey, M., Duncan, R. and Tegner, C., (2007b). Timing and duration of volcanism in the North Atlantic Igneous Province: Implications for geodynamics and links to the Iceland hotspot. *Chemical Geology 241*: 264-281.

Svensen, H., Planke, S., Chevallier, L., Malthe-Sørenssen, A., Corfu, F., & Jamtveit, B. (2007). Hydrothermal venting of greenhouse gases triggering Early Jurassic global warming. *Earth and Planetary Science Letters*, *256*(3-4), 554–566.

Svensen, H., Planke, S. and Corfu, F., (2010). Zircon dating ties NE Atlantic sill emplacement to initial Eocene global warming. *Journal of the Geological Society, London, 167(3)*: 433-436.

Svensen, H., Planke, S., Malthe-Sørenssen, Jamtveit, B., Myklebust, R., Rasmussen Eidem, T. and Rey, S., (2004). Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. *Nature*, 429: 542-545.

Talwani, M., & And 11 others. (1976). *Initial Reports of the Deep Sea Drilling Project, Vol. 38. Dublin, Ireland to Amsterdam, The Netherlands*. US Government Printing Office.

Talwani, M., & Eldholm, O. (1977). Evolution of the Norwegian-Greenland sea. *Geological Society of America Bulletin*, *88*(7), 969-999.

Taniguchi, M., W. C. Burnett, J. E. Cable and J. V. Turner (2002). "Investigation of submarine groundwater discharge." *Hydrological Processes 16*(11): 2115-2129.

Tegner, C., Duncan, R. A., Bernstein, S., Brooks, C. K., Bird, D. K., & Storey, M. (1998). 40Ar39Ar geochronology of Tertiary mafic intrusions along the East Greenland rifted margin: Relation to flood basalts and the Iceland hotspot track. *Earth and Planetary Science Letters*, *156*(1-2), 75-88.

Tsikalas, F., Eldholm, O., & Faleide, J. I. (2005). Crustal structure of the Lofoten–Vesterålen continental margin, off Norway. *Tectonophysics*, *404*(3-4), 151-174.

Tsikalas, F., Faleide, J. I., & Eldholm, O. (2001). Lateral variations in tectono-magmatic style along the Lofoten–Vesterålen volcanic margin off Norway. *Marine and Petroleum Geology*, *18*(7), 807-832.

Vaccaro, J. J. (1999). Summary of the Columbia Plateau, Regional Aquifer-system Analysis, Washington, Oregon, and Idaho, US Geological Survey.

Vahlenkamp, M., Niezgodzki, I., De Vleeschouwer, D., Bickert, T., Harper, D., Turner, S. K., ... & Pälike, H. (2018). Astronomically paced changes in deep-water circulation in the western North Atlantic during the middle Eocene. *Earth and Planetary Science Letters*, *484*, 329-340.

Via, R. K., & Thomas, D. J. (2006). Evolution of Atlantic thermohaline circulation: Early Oligocene onset of deep-water production in the North Atlantic. *Geology*, *34*(6), 441-444.

White, R. and McKenzie, D., (1995). Mantle plumes and flood basalts. *Journal of Geophysical Research, 100*: 17543-17585.

White, R., & McKenzie, D. (1989). Magmatism at Rift Zones - the Generation of Volcanic Continental Margins and Flood Basalts. *Journal of Geophysical Research*, *94*(B6), 7685–7729.

White, R. S., & McKenzie, D. (1995). Mantle Plumes and Flood Basalts. *Journal of Geophysical Research: Solid Earth*, *100*(B9), 17543–17585.

White, Stan; Warnke, Detlef A; Nilsen, T H; *Petroleum Geology Conference*, Carla; Morris, D A; Kharin, Gennady S; Faas, Richard W; Caston, V S D; Bjorklund, Kjell R; Talwani, Manik; Udintsev, Gleb B (1976): Initial Reports of the Deep Sea Drilling Project. *Initial Reports of the Deep Sea Drilling Project, U.S. Government Printing Office*, XXXVIII, 1256 pp.

Wilkinson, C., Ganerød, M., Hendriks, B. and Eide, E., (2016). Compilation and appraisal of geochronological data from the North Atlantic Igneous Province (NAIP). *Geological Society, London, Special Publications, 447*.

Wotzlaw, J., Bindeman, I., Schaltegger, U., Brooks, C. and Naslund, H., (2012). High-resolution insights into episodes of crystallization, hydrothermal alteration and remelting in the Skaergaard intrusive complex. *Earth and Planetary Science Letters, 355*: 199-212.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., & Billups, K. (2001). Trends, rhythms, and aberrations in global climate 65 Ma to present. *science*, *292*(5517), 686-693.

Zindler, A., Staudigel, H., & 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*, *70*(2), 175-195.