The NE Atlantic conjugate passive margins are characterized by extensive break-up related magmatic products including extrusive basalt lava flows and volcanogenic sediments, shallow intrusive complexes emplaced within marginal sedimentary basins, and deep magmatic underplating at the base of the crust. The volume of generated magma cannot be explained by passive decompression melting of sub-lithospheric mantle with a normal mantle temperature. Competing geodynamic end-member hypotheses exist for the formation of this excess magmatism: 1) elevated mantle potential temperatures associated with mantle plume processes, 2) enhanced material flux through the melt window during rifting caused by small-scale convection at the base of the lithosphere, and 3) mantle source heterogeneity which may contribute to anomalously high melt production during continental breakup. While we have unsurpassed constraints on crustal structure of the Norwegian-Jan Mayen-Greenland conjugate rifted margins, the relative importance of hypothesized mechanisms responsible for excess magmatic productivity remains unresolved. Voluminous magmatism also coincides with global greenhouse (hot) climate in the early Paleogene and, via various mechanisms (e.g. magmatic volatile release; sill-induced gas generation from organic rich sediments and released to the atmosphere via hydrothermal vents etc.), proposed as a driver of both short-term (Paleocene-Eocene Thermal Maximum) and long-term (early Eocene Climate Optimum) global warming. However, the timing of the magmatism is not sufficiently constrained to test the proposed mechanisms or to evaluate volcanic and gas fluxes. Improved constraints on melting conditions, timing of magmatism, magmatic fluxes in time and space, eruption environment, sedimentary proxy data, and relative timing of climate events are required to resolve these linked controversies. Systematic IODP drilling is the only way to provide these constraints and the proposed drilling effort will provide a quantitatively testable framework for volcanic rifted margin formation and consequences for global climate. New 3D seismic data collected by the hydrocarbon industry during the past decade have provided unique insights into the nature and distribution of both the volcanic and sub-basalt sequences along the margin, enabling the identification of optimal drill sites. To meet our objectives, volcanic and sedimentary sequences are targeted in a series of boreholes along and across the Mid-Norwegian margin. The targeted material is essential in achieving our primary goals: testing the end-member models for the formation of excess magmatism during continental breakup and testing the influence of tectonic and magmatic events on Paleogene global climate.
Scientific Objectives

The primary objectives of drilling the Vøring and Møre volcanic margins sections are:

• To determine the conditions of mantle melting (e.g. mantle sources, temperature, pressure, degree of melting).
• To determine spatial and temporal variations in along axis volcanic fluxes in order to test predictions made by fundamentally different geodynamic models for volcanic rifted margin formation including segmentation.
• To determine variations in the depositional environment (sub-aerial vs sub-marine) of inner and outer lava flows (e.g. seaward dipping reflectors) in order to test correlations between magma genesis and dynamic thermal support during late syn-rift, break-up, and early post-rift oceanic spreading.
• To assess the temporal evolution of the styles of volcanic and magmatic activity in relation to paleoclimate proxies to test the relationship between large-scale volcanism and climate change events.
• To investigate the relative importance environmental consequences of two key processes during the initial opening of the North Atlantic: Direct volcanic degassing and explosive thermogenic release through hydrothermal vent complexes from contact metamorphism.

The proposal will also address two important secondary objectives mainly resulting from recovered sedimentary archives:

• Early Eocene hot-house and fresh water incursions into the Atlantic
• Carbon capture and storage in basalt provinces

Non-standard measurements technology needed to achieve the proposed scientific objectives

None
### Proposed Sites (Total proposed sites: 23; pri: 9; alt: 14; N/S: 0)

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## Contact Information

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<tr>
<td>Sverre Planke</td>
<td>Centre for Earth Evolution and Dynamics (CEED), University of Oslo</td>
<td>Centre for Earth Evolution and Dynamics (CEED), University of Oslo</td>
<td>PO Box 1028 Blindern, Oslo Norway 00315 Norway</td>
<td><a href="mailto:planke@vbpr.no">planke@vbpr.no</a>; Phone: +47 22 85 40 97</td>
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## Proponent List

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1. INTRODUCTION
1.1 General introduction

Continental extension, breakup, and the formation of new mid-oceanic spreading centers are fundamental parts of the plate tectonic cycle and have wide implications for the global environment. Passive rifted margin studies have been at the core of the international ocean drilling program since the 1960's. DSDP and ODP drilling along with extensive seismic surveying of the NE Atlantic conjugate margins demonstrated anomalously high volumes of volcanic activity during continental break up classifying these margins as ‘volcanic rifted margins’ (Talwani and Eldholm, 1977; Eldholm et al., 1989; Saunders et al., 1998; Sengör and Burke, 1978; Ziegler and Cloetingh, 2004; Abdelmalak et al., 2016a).

This IODP application builds on previous successful drilling campaigns in the NE Atlantic: Legs 38 (1974), 104 (1985), 152 (1993), and 163 (1995) (Fig. 1) that were instrumental for development of the concepts of 'volcanic rifted margins' and 'Large Igneous Provinces' (LIPs) (see Mahoney and Coffin (1997) and Ernst (2014) for a summary). There are, however, many unresolved scientific questions related to formation and environmental implications of massive breakup volcanism that can be resolved by future scientific drilling. An international initiative in the mid-2000's to drill volcanic rifted margins in the NE Atlantic (ODC - Ocean Drilling Consortium) was abandoned after loss of industry participation during the financial crisis in 2008. The current proposal is motivated from the planning work done during the ODC initiative. Meanwhile, comprehensive 3D seismic data, new aeromagnetic data acquisition, seabed surveys, analysis of existing ODP data, and new scientific development have emerged during the past decade, leading to a vastly improved proposal and drilling strategy. In particular, the paleo-environmental objectives have been substantiated, and an independent application (PVOLC) has been submitted to ICDP for drilling Paleogene sediments in Denmark to resolve NAIP eruptions and environmental impact in a more distal setting.
Figure 1. Distribution of Paleogene igneous breakup complexes and oceanic structures in the NE and NW Atlantic. Scientific boreholes and proposed drilling sites are located. Compiled from (Boldreel and Andersen, 1994; Ritchie et al., 1999; Berndt et al., 2001b; Elliott and Parson, 2008; Davison et al., 2010; Abdelmalak et al., 2016; Geissler et al., 2016; Reynolds et al., 2017; Abdelmalak et al., 2018).
1.2. Rift-related magma production

Despite unsurpassed constraints on conjugate crustal structure between NE Atlantic Norwegian-Jan Mayen-Greenland rifted margins, the mechanisms responsible for rift related, anomalous excess magmatic productivity are still debated (Lundin and Doré, 2005; Brown and Lesher, 2014). The controversy centers on three competing hypotheses: 1) excess magmatism derived 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 breakup, and 3) mantle source heterogeneity contributed to anomalously high melt production during continental breakup. Whereas the mantle plume mechanism requires anomalous high temperatures resulting in high degrees of melting during asthenosphere upwelling, small-scale convection at the base of the lithosphere operates without elevated potential temperatures and is inherently connected to the rifting process (Boutilier and Keen, 1999).

1.3 Influence of LIPs on global climate and environment

Temporal correlations between mass-extinctions, global warming, and formation of LIPs have long been recognized (Vogt, 1972; Wignall, 2001). However, the mechanisms for the rapid paleo-environmental crises are highly debated in the scientific literature (Bond and Wignall, 2014; Courtillot and Renne, 2003). For example, volcanic eruptions release large volumes of sulfur, halogens, and carbon to the atmosphere (Jones et al., 2016), which may cause environmental disturbances on a variety of timescales. An alternative, although not mutually exclusive mechanism, is that large volumes of greenhouse gases can be released from metamorphic aureoles around sill intrusions emplaced in sedimentary basins (Svensen et al., 2004). New information of eruption styles, volumes and rates, and sedimentological data in a proximal region to the eruptions, is important to document and understand the environmental impact of LIPs.

1.4 Objectives

The key objective of this proposal is to understand the relationship between rifting, excess magmatism, and paleoclimate, and to resolve the relative contribution from plume upwelling, small-scale convection, and mantle heterogeneity and their relation to the formation of volcanic rifted margins in the NE Atlantic. This requires additional constraints on 1) melting conditions (degree, pressure, and temperature of melting), 2) age distribution of volcanic products, essential to constrain magmatic productivity in time and space, 3) variation of pre-, syn-,
post-breakup magmatic activity across the margin, 4) variation of magmatic activity along strike, across the major Møre and Vøring margin segments, 5) eruption rates, environment and basalt morphologies, and 6) the relationship between climate change, timing, volume, and style of magma emplacement. The sedimentary-proxy based environmental reconstruction also provides a semi-quantitative record of paleo-elevations (water depth) and vertical motions as early rifting progresses to seafloor spreading, with the potential additional influence of dynamic support originating from the plume-pulsing hypothesis (e.g. Shaw-Champion et al., 2008; Parnell-Turner et al., 2014).

The mid-Norwegian margin is among the best-studied volcanic rifted margins around the world. It has unsurpassed geophysical data coverage owing to excellent collaboration between government, industry, and academia in Norway and can be considered the type example of volcanic margins (Figs. 2 and 3; Eldholm et al., 1995). However, key questions regarding the origin and implications of excess magmatism along with margin segmentation and rifting remain. Sampling of breakup volcanics and proximal sediment cores through IODP drilling, in conjunction with geochemical constraints on melt conditions and integrated quantitative models of melting and mantle convection, is crucial to advance our understanding of breakup processes and resolving competing hypotheses for excess magmatism and paleoenvironmental consequences.
Figure 2. Distribution and formation of igneous complexes on the mid-Norwegian margin. A: Crustal profile across the northern Vøring margin (Zastrozhnov et al., 2018; see Fig. 1 for location). B: Schematic figure showing characteristic features of volcanic seismic facies units. C: Cartoon showing formation of key volcanic seismic facies units (yellow boxes) in a sedimentary basin (Abdelmalak et al., 2016). D: Schematic structure of pipe-like hydrothermal vent complexes (HTVC; Svensen et al., 2004; Planke et al., 2005; Kjoberg et al., 2017). COB: Continent-Ocean Boundary. SDR: Seaward Dipping Reflectors. LCB: Lower Crustal Body.
Figure 3. Maps showing key data and structures in the study area. Data courtesy of TGS.
2.0 CONTINENTAL BREAK-UP, VOLCANISM, AND CLIMATE

2.1 Geological framework

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 (Talwani and Eldholm, 1977; White and McKenzie, 1989; Skogseid et al., 2000; Abdelmalak et al., 2016a). The mid-Norwegian margin is well covered by 2D and 3D reflection and refraction seismic surveys, potential field and heat flow data, and borehole data that allow a refined structural and stratigraphic framework (Fig. 3; Brekke, 2000; Gernigon et al., 2003; Mjelde et al., 2005; Breivik et al., 2006; Gernigon et al., 2012; Theissen-Krah et al., 2017; Zastrozhnov et al., 2018).

The mid-Norwegian margin is segmented by the NW-trending Jan Mayen Fracture Zone, separating the Møre and Vøring margins (Fig. 3). The margin segments are characterized by different tectono-magmatic style and sediment distribution (Figs. 3 and 4; Berndt et al., 2001a; Gernigon et al., 2012). 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 connected to Greenland) conjugate margins in the Paleocene-Eocene.

Rifting and passive margin formation in the NE Atlantic was accompanied by strong volcanic activity (White and McKenzie, 1989; Eldholm and Grue, 1994; Larsen and Saunders, 1998; Wright et al., 2012). 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 (Figs. 2 and 4; Berndt et al., 2001a; 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. Drilled rocks (Legs 152, 163) range from pre-break-up continental tholeiitic flood basalt, syn-break-up picrites, to oceanic-type basalts that form the main part of the SDRs (Fitton et al., 2000). Oceanic-type lavas show increasing degree of melting and contribution from asthenospheric mantle sources with time (Fram et al., 1998; Fitton et al., 1998). 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 (Holbrook et al., 2001). Similarly, geochemical enrichment of volcanics of the East Greenland margin (chondrite-
normalized \((\text{Ce}/\text{Y})_N\) and isotopes; Fitton et al., 1998; Tegner et al., 1998a; Brown and Lesher, 2014), increases from south to north.

Correlation of crustal thickness and compositional enrichment suggests a combination of changes in source composition, source temperature, and/or melting dynamics. It is not known if a similar correlation of crustal thicknesses and magma compositions exists along the Norwegian margin. To establish the relationship between chemistry of the volcanics and crustal configuration is a milestone of the proposed investigations. Geochemical data 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, pointing to substantial differences in either pre-breakup lithosphere composition at the two localities, or to different styles of mantle-crust interaction (Abdelmalak et al., 2016a).

Periods of elevated magmatism such as the emplacement of the North Atlantic Igneous Province (NAIP) often coincide with considerable environmental perturbations such as the Paleocene-Eocene Thermal Maximum (PETM; 56 Ma) and/or long-term climate warming such as the early Eocene Climate Optimum (EECO; ~50-53 Ma), suggesting a causal relationship (Bond and Wignall, 2014; Eldholm and Thomas, 1993). The total volume of magma emplaced during the Paleogene is estimated to be \(6-10 \times 10^6\) 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., 2007), although the full emplacement spans several million years (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; Frielings 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 or as an instigator of positive climate feedbacks such as methane hydrate melting.

While both volcanism and contact metamorphism degassing appears 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 and asses 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. Although both
volcanism and contact metamorphism release greenhouse gases (CO$_2$, CH$_4$), the latter is likely to be rich in organic material and should therefore have a different stable carbon isotope signature ($\delta^{13}$C) to mantle-derived carbon. Differences in eruption style and location (e.g. subaerial vs. submarine) may impact the volume dispersal of metals used as volcanic proxies, such as mercury (Sanei et al., 2012). There may also be a systematic temporal evolution in the magmatic system, such as a shift from eruptive to intrusive activity (e.g., Burgess et al., 2017). Better age constraints on the eruptive stratigraphy and on subvolcanic rocks in proximity to hydrothermal vent complexes may resolve potential diachroneities and shed light on degassing mechanisms responsible for climatic perturbations.

2.2 Theoretical framework

Breakup volcanism along rifted passive margins is highly variable both in time and in space. Whereas mantle melting during the formation of mid oceanic ridges is relatively well understood and mostly a function of spreading rate and mantle potential temperature with melting below the mid oceanic ridge leading to accretion of 6-8 km of magmatic crust at standard mantle potential temperature and full spreading rates larger than 2 cm/yr (Fig. 5b; Bown and White, 1994), factors controlling magmatic activity during continental rifting and breakup are not resolved. The variation in the degree of magmatism at rifted margins can to first order be characterised in three contrasting modes of behaviour (Fig. 5a). Mode 1 margins with little to no magmatism at the continent-ocean boundary (COB) and a broad transition zone with a-magmatic exposed mantle at the sea floor preceding formation of mature oceanic crust (Fig. 5b; e.g., Huismans and Beaumont, 2011, 2014). Mode 2 margins characterised by a sharp transition from the COB to normal thickness (6-8 km) magmatic ocean crust (Fig. 5a and 5c). Mode 3 margins where magmatic productivity exceeds that expected from decompression melting at normal mantle temperature (Fig. 5a). A comprehensive understanding what controls this range of behaviours, the volume, distribution, and timing of magmatism during continental rifting and breakup is, however, lacking. Excess magmatism at volcanic Mode 2 margins such as in the North Atlantic has been related to mantle plume and contrasting non-plume mechanisms (McKenzie and Bickle, 1988; Mutter et al., 1988; White and McKenzie, 1989).
Figure 4. Selected seismic profiles across the Voring and Møre margins, located in Fig. 3. Proposed drill sites schematically located. A: Volcanic seismic facies units on the Skoll High on the central Voring margin. B: Møre Basin structure across the Kolga High. C: Crustal velocity structure across the northern Voring margin (Breivik et al., 2009). Data courtesy of TGS (A, B).
Continental breakup may be associated with extensive volcanism over large distances along strike of the rifted margins as exemplified in the NE Atlantic (Fig. 1). The causes for the anomalous magmatic activity and the implications on the paleoenvironment are, however, still debated. Magmatic products emplaced along these volcanic rifted margins have four major characteristics: 1) wedges of seaward dipping reflectors (SDRs) and associated volcanic seismic facies units interpreted as massive subaerial and submarine lava flows and volcaniclastic 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 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 (Figs. 2, 4, and 5b). It appears that volcanic rifted margins require mantle that is either 1) anomalously hot, 2) is actively upwelling at rates higher than the plate half-spreading rate, or 3) is anomalously fertile, or some combination of these factors.

**Hypothesis I: Mantle plume involvement produces excess magmatism**

Hypotheses on 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; Montelli et al., 2004) and have led to the hypothesis that excessive magmatic productivity resulted from high mantle temperatures caused by a mantle plume (McKenzie and Bickle, 1988; White and McKenzie, 1989; Brown and Lesher, 2014). 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 (Fig. 5d; McKenzie and Bickle, 1988; White and McKenzie, 1989). Petrological modeling suggests that excess mantle potential temperatures were common during the Paleocene to Eocene and beneath present day Iceland (e.g. Fram and Lesher, 1993; Hole and Millett, 2016; Brown and Lesher, 2014; Matthews et al., 2016). 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 at a rate higher than the half spreading rate of the rift zone (Holbrook and Kelemen, 1993) without a thermal anomaly provides an alternative mechanism for excess magmatism at volcanic rifted margins. 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. Numerical models demonstrate that the excess igneous thicknesses observed on the Møre and Vøring margins may be explained by a combination of small-scale convection and a small thermal anomaly (e.g. Fig. 5e; Simon et al., 2009). While this hypothesis has attracted considerable study (Mutter et al. 1988; Boutilier and Keen, 1999; Keen and Boutilier, 2000; Nielsen and Hopper, 2004; Simon et al., 2009), 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

Mantle source heterogeneity may also contribute to anomalously high melt production during continental breakup (Davies, 1981; Zindler et al., 1984; Allègre and Turcotte, 1986; Allègre and Lewin, 1995; Phipps Morgan and Morgan, 1999; Kellogg et al., 2002; Meibom and Anderson, 2004; Foulger and Anderson, 2005; Albarède, 2006). The mantle is characterized by significant chemical and isotopic heterogeneity, and appears to be a heterogeneous assemblage of depleted and enriched peridotite, and recycled subducted oceanic crust, lithosphere, and sediments (Sobolev et al., 2007). Inherited enriched domains in the sub-lithospheric mantle with anomalously low melt temperatures (e.g. eclogite/pyroxenite) may therefore deliver more melt during their ascent beneath extending lithosphere and the ridge axis than peridotite (e.g. Anderson, 2005; Sobolev et al., 2007; Hole, 2018).

These end member processes have distinct characteristic and diagnostic features that may be used to differentiate their relative roles during volcanic margin formation. 1) Plume related anomalously high mantle temperatures result in high melt fractions, high pressure melting, and distinct geochemical characteristics. 2) Active upwelling (small-scale convection) without a thermal anomaly will result in low average pressure of melting (Holbrook et al., 2001; Korenaga et al., 2002), lower degrees of melting, and geochemical signatures closer to MORB. 3) A fertile source should result in high average pressure of melting and distinct isotope geochemistry of the melts indicating an enriched source.
a) Riffed margins, magmatic modes

Mode 1 a-magmatic margins
Continent crust A-magmatic exhumed mantle
Normal oceanic crust

Mode 2 normal magmatic margins
Continent crust
Normal oceanic crust

Mode 3 excess magmatic margins
Continental crust
Intrusions
Magnetic underplate
Magnetic flows
Normal oceanic crust

b) Igneous Crustal Thickness vs. Spreading Rate

Observation
Model Results

Full Spreading Rate $V_{sp}$ (cm/yr)

Igneous Crustal Thickness [km]

0 2 4 6 8 10

0 1 2 3 4 5 6 7 8 9 10

1000 600 2000 4000 6000 8000 10000

h (km)

Oceanic crustal thickness (h)

Melt window

Depth (km)

200 400 600 800 1000

Tp = 1400° C
Tp = 1300° C
Tp = 1200° C

T = 60 Myr
Sx = 1200 km

T = 40 Myr
Sx = 800 km

Global oceanic crust thickness

d) Predicted igneous crust thickness as a function of Mantle temperature

e) Comparison forward model prediction with Norwegian margin
effect small scale convection, small thermal anomaly (dT = 0 or 50° C)
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 contentious. The thermal anomaly associated with the plume is not well resolved with estimates ranging from 50 to 300 °C excess mantle potential temperature. The relative roles of plume versus the non-plume processes are 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) what is the evidence for and importance of mantle source heterogeneity in melt production along the margin?

Hypothesis IV: Volcanism and magmatism drove Paleocene and Eocene climate perturbations

The Paleocene-Eocene Thermal Maximum (PETM) is marked by a sharp negative carbon isotope excursion (δ13C) of 3–5 ‰ (McInerney and Wing, 2011) that represented voluminous release of 13C-depleted carbon to the ocean-atmosphere system (Dickens et al., 1995; Zachos et al., 2008). The North Atlantic Igneous Province (NAIP) was in its most voluminous magma productivity phase across the Paleocene-Eocene boundary, suggesting a possible causal relationship. The magma volume, eruption duration, and emplacement environment are critical parameters for the paleoenvironmental implications of LIPs. There are two potential NAIP sources that could have led to environmental disruption.
**H4.1 Continental flood basalt volcanism**

The NAIP was particularly active in the late Paleocene and early Eocene (Larsen et al., 1999; Storey et al., 2007a). A huge outpouring of continental flood basalts in East Greenland, resulting in a lava pile up to 5.3–6.3 ± 2.7 km thick, temporally constrained to between 56.0 to 55.6 Ma (Larsen and Tegner, 2006; Storey et al., 2007b; Wotzlaw et al., 2012) encompassing the PETM at 55.8 Ma (Charles et al., 2011), and was accompanied by basaltic and silicic volcanism. Such large scale volcanism would lead to considerable degassing of climate-sensitive molecules such as CO₂ and SO₂, which could have contributed to the observed global warming of the late Paleocene and Early Eocene if released in sufficient quantities.

**H4.2 Contact metamorphism of organic-rich sediments**

Magma emplaced into sedimentary sequences leads to heating of surrounding country rocks, potentially resulting in generation of large volumes of greenhouse gases (CH₄, CO₂; Svensen et al., 2004). Gas generation may cause overpressure build-up and formation of hydrothermal vent complexes, transporting fluids and sediments to the hydrosphere and atmosphere (Aarnes et al., 2010; 2015). Thousands of hydrothermal vent complexes are observed along the northeast Atlantic margins terminating close to the Paleocene-Eocene boundary (Svensen et al., 2004; Hansen, 2006; Reynolds et al., 2017).

**2.3 Relevance for science plan**

The proposal is highly relevant to two of the research themes in the IODP 2013-2023 science plan: 1) *Climate and ocean change: Reading the past, informing the future*, and 2) *Earth connections: Deep processes and their impact on Earth's surface environment*.

A primary objective of the proposal is to understand how igneous processes might have triggered increased CO₂ levels during the Paleogene (Early Eocene Climate Optimum), and in particular the short-termed PETM. These research topics are central to Challenge 1 ("How does Earth's climate system respond to elevated levels of atmospheric CO₂?" and Challenge 4 ("How resilient is the ocean to chemical perturbations?") in the science plan.

The proposal also focuses on the formation of initial thick oceanic crust along rifted continental margins, and how the melt anomaly can be linked to processes in the upper mantle. These topics are central for Challenge 8 ("What are the composition, structure, and dynamics of the Earth's upper mantle?") and Challenge 9 ("How are seafloor spreading and mantle melting linked to ocean crustal architecture?").
One of the secondary objectives, permanent storage of CO$_2$ as carbonates in basalt, is furthermore related to Challenge 13 ("What properties and processes govern the flow of carbon in the subseafloor?").

2.4 Past achievements

Scientific drilling of NE Atlantic continental margins since the 1970's has been essential for understanding the architecture and implications of igneous deposits associated with continental breakup. In particular, drilling of deep boreholes in the featheredge of the SDRs offshore mid-Norway and SE Greenland (Eldholm et al., 1989b; Larsen et al., 1994; Duncan et al., 1996; Saunders et al., 1998; Larsen et al., 1999a) demonstrated that voluminous sub aerial volcanic flows are common along rifted margins (Fig. 6). The drilling results further suggested that continental breakup magmatism has had major impact on global environment and mass extinctions (Hinz, 1981; Eldholm and Thomas, 1993). Interpretation of industry seismic and borehole data from the Vøring Basin (Fig. 6) later lead to the hypothesis that voluminous intrusion of magma in organic-rich sedimentary basin may have triggered the PETM by release of aureole gases through hydrothermal vent complexes (Svensen et al., 2004). This hypothesis will be tested by the current proposal.
Figure 6. Synthesis of igneous complexes previously drilled by petroleum exploration wells and ODP on the Vøring margin. A: Hydrothermal vent complex drilled by 6607/12-1 (Frielings et al., 2016). B: Igneous sheet intrusions drilled by 6607/5-2 (Neumann et al., 2013; Planke et al., 2015). C: Feather edge of SDR’s drilled by ODP Hole 642E. D: Summary of ODP Site 642 Lower Series flows, intrusions and sediments based on recent re-analyses of legacy core data (Meyer et al., 2009; Abdelmalak et al., 2016). Well locations shown in Figure 3.
3.0 SCIENTIFIC OBJECTIVES

3.1 Main scientific objectives

The conjugate Norwegian-Jan Mayen-Greenland margin system is characterized by extensive breakup volcanism recorded as sill intrusions, flood basalt sequences, hyaloclastite buildups, and magmatic underplating. Three main hypotheses for the formation of these massive magmatic constructions are related to a mantle plume, non-mantle plume active upwelling, or an enriched source scenario. A further related hypothesis aims to constrain the influence of this extensive volcanic activity on Paleogene global climate. A combined interpretation of existing geophysical data, well data, and dredging samples cannot confidently distinguish between the proposed hypotheses. New core data will provide the required high-resolution insights into magmatic evolution in time.

The mid-Norwegian margin is a unique area in which well characterized volcanic features, related to volcanic rifted margins world-wide, are readily drillable (Figs. 2 and 4). Here, igneous rocks and Paleogene sediments are locally buried by minor post-breakup sediments (Fig. 7). Large regions along the outer margins have recently been covered by industry 3D seismic surveys, and this unique database allows the identification of shallow (<200 mbsf) volcanic and Paleogene sedimentary targets.

The main scientific objectives of this proposal are:

1. Determine the role of the Iceland plume in producing excess magma along the Norwegian segment of the NE Atlantic volcanic rifted margin during the Paleogene by constraining the conditions of melting (temperature, pressure, mantle sources, total degree of melting).

2. Determine the cause for along axis variation in melt production. In the case of the NE Atlantic volcanic margins magmatic productivity changes from the More margin (~12-15 km thick magmatic crust) in the south toward the Vøring margin (>20 km thick magmatic crust) and the Lofoten margin (~8 km regular thickness magmatic crust). This pattern suggests a local, structural control, as plume models would suggest largest excess magmatic activity in the southern most conjugate sections (e.g. More – Jan Mayen) closest to the Iceland thermal anomaly.

3. Determine the depositional environment (sub-aerial vs sub-marine) of inner and outer lava flows (e.g. SDRs) and implications for vertical motions during late syn-rift, break-up, and early post-rift oceanic spreading. Some of the lava flows may not have extruded sub-aerially (e.g. Planke et al., 2000; 2017). This has important
Implications for the distribution of buoyancy forces and isostasy during breakup where sections without continental crust would under normal conditions be expected at water depths of >2 km (e.g. Kusznir et al., 2004).

4. Determine the timing of magmatic activity and document the occurrence and temporal evolution of paleoclimate and volcanic proxies in sedimentary sequences proximal to the North Atlantic Igneous Province.

5. Use the integrated paleoclimate and paleoenvironment proxies and geochronological data to assess the relative importance of volcanism and thermogenic release from hydrothermal vent complexes as potential drivers of climate change events.

**Figure 7.** A, B: Basalt distribution and thickness on the N Møre and Vøring margins based on extensive seismic mapping of regional 2D and recent industry 3D seismic cubes. C: Thickness of post-breakup sediments, showing regions with sediment thickness less than 200 m in color scale. Seismic database shown in Figure 3. Data courtesy of TGS.

IODP drilling along and across the mid-Norwegian margin will provide key constraints on the spatial and temporal evolution of magmatic activity, its relation with the rift history, and consequences for paleoclimate. While extinction and climate records can be readily apparent in sedimentary sections worldwide, it is uncommon to find contemporaneous volcanic products such as tephra layers in these sequences. Therefore, the close proximity to the magmatism allows for numerous regionally important volcanic and paleoclimate proxies to be used to assess
proposed linkages. The drill sites in conjunction with the high quality geophysical data will provide key constraints enabling the above questions to be comprehensively tackled by the development of a quantitatively testable framework for conjugate volcanic rifted margin formation in the NE Atlantic.

3.2 Secondary objectives

The choice and location of all drill sites is fully determined by the main objectives of the proposal (see also Section 4 and 5). However, drilling at the proposed locations will also provide valuable information on the sediments under- and over-lying the break-up volcanic deposits and will allow to test secondary hypotheses on the Early Eocene hot house, fresh water incursion in the North Atlantic, and on carbon capture.

*Early Eocene hot-house and fresh water incursions into the North Atlantic*

The early Paleogene (~66–45 Ma) was characterized by warm global greenhouse conditions culminating in the EECO (~53–50 Ma), the warmest sustained climates of the last 65 Myr (Bijl et al., 2009; Anagnostou et al., 2016; Cramwinckel et al., 2018) inducing an intensified hydrological cycle with strongly increased precipitation at high latitudes (e.g. Pagani et al., 2006; Suan et al., 2017). Paleogene sediments obtained during the Arctic Coring Expedition (ACEX, Leg 302), show large quantities of free-floating fresh-water *Azolla*, which grew and reproduced in the Arctic Ocean by the onset of the middle Eocene (~48 Ma) (Brinkhuis et al., 2006). The proposed sites penetrate the Eocene sediments and allow testing the extent of fresh water incursions, constraining paleoceanographic boundary conditions for the excursions including the evolution of oceanic gateways and their influence on global ocean circulation. The early Eocene sediments also provide a unique opportunity to reconstruct mid-high Northern latitude climate allowing a detailed comparison to Southern Ocean records (e.g. Bijl et al., 2009; 2013; Hollis et al., 2012).

*Carbon capture and storage in basalt provinces*

Observations of meteoric water and high dissolved calcium concentration from the bottom of ODP sites 642 and 643 show that the Vøring Plateau is ideal to study circulation of fresh water within such large basaltic formations and assess its potential for CO₂ sequestration. Previous ODP holes did not address the origin of meteoric water and trigger(s) for such large-scale circulation. Dating of borehole water samples with ¹⁴C, ³⁶Cl, and ²³⁴U/²³⁸U tracers (IAEA, 2013) and systematic analyses of fluid geochemistry (Inagaki et al., 2015) will allow
determining the source of meteoric waters and provide constraints on their circulation systems, crucial for assessing the CO₂ storage potential of break-up basalts. Pore fluids will be sampled along the complete proposed drilling transect to investigate the potential extent of meteoric water flow. We hypothesize that meteoric water will be detected from the sites reaching the basaltic basement (e.g., VMVM-20A, 23A, 61A, 7A) but will be absent from the sites without (e.g., VMVM-31A, 40A, 50A). The outcome of fluid geochemical analyses will be quantitatively interpreted with hydrological modeling using software such as MODFLOW to investigate the flow path of meteoric water. The sampling for water geochemistry follow the standard IODP protocol for pore fluid analyses.

4.0 DRILLING STRATEGY

The mid-Norwegian margin is the type locality for volcanic rifted margins, and is probably the best-studied volcanic margin worldwide. The detailed geometry and amounts of volcanic products in the form of underplated bodies, intrusive, and extrusive volcanic rocks are currently extremely well constrained through geophysical imaging (e.g. Mjelde et al., 2005; Berndt et al., 2001b; Planke et al., 2017; Abdelmalak et al., 2016a; 2017). However, new information on the age, nature, and depositional environment of the volcanics is required to constrain melt production rates and vertical motions. Furthermore, causes for excess magmatic productivity are not well understood and highly debated. Answering the fundamental questions outlined in the scientific objectives (Section 3.1) requires extensive sampling of both late syn-rift/early post-rift sediments and magmatic products from the continental into the oceanic domain. Collection of sedimentary records proximal to the volcanic and magmatic activity allows for use of numerous proxies to distinguish between volcanic and hydrothermal vent complex sources. Additional sedimentary records will be examined by a companion ICDP drilling proposal 'PVOLC' in Denmark submitted in January 2019.

Geochemical, geochronological, and petrological analyses of drilled volcanic rocks and sediments will provide constraints on timing of magmatism relative to rifting and breakup, the conditions of melting (pressure, temperature, composition of the source and degree of melting), the volcanic emplacement environment (sub-aerial vs. sub-aqueous), and paleo-environmental changes. Ocean drilling provides the only means of obtaining these samples and is therefore essential for meeting these objectives.

Access to modern industry-standard 2D and 3D seismic data are particularly important for optimizing the drill site selection (Figs. 3 and 7). Nine primary sites were selected for the initial proposal. In this revised proposal, the primary sites have been slightly shifted to address the
IODP SEP review comments, keeping the original scientific targets. A number of alternative sites have also been identified. In total, 26 sites are proposed. Owing to government safety regulations, most sites are less than 200 m deep. This is a limit normally applied for geotechnical and stratigraphic drilling in sedimentary basin environments. Some proposed sites in the oceanic domain or near the continent-ocean boundary are deeper. There are no specific logistical problems in the region, but drilling should be done during the summer time.

4.1 Drilling plan

The drilling strategy for the proposed IODP boreholes is summarized in Fig. 8 and Table 1. The proposal will provide one along-strike and one cross-strike margin transect, and two high-resolution Paleogene sedimentary sites.

1. The sub-basalt and initial volcanic flows are the targets of VMVM-20A and VMVM-23A. If successful, these will be the first boreholes to sample pre-breakup volcanics and the onset basalt flows on the mid-Norwegian margin.

2. Paleogene sediments in hydrothermal vent complexes and sedimentary reference holes across the Paleocene-Eocene boundary in VMVM-31A, VMVM-40A, and VMVM-50A. These sites will for the first time document the nature of hydrothermal vent complexes in the outer Vøring Basin and provide geochemical proxy data and age constraints for the Paleogene succession. We suggest dual coring of key stratigraphic intervals. For VMVM-50A one deep hole (800 m) is proposed, whereas four offset holes of 200 m each are alternative sites.

3. Sampling of volcanic seismic facies units across the central Vøring margin to assess the spatial and temporal development of the breakup volcanic complex in sites VMVM-61A, VMVM-7A, VMVM-80A, and VMVM-9A. The sites will be integrated with results from existing scientific boreholes, such as ODP Hole 642E. Particular focus is on understanding the emplacement environment, characterizing sequence boundaries, and sampling of basalt for geochemical and geochronological studies.

Standard JOIDES Resolution drilling and logging procedures will be followed. The drilling plan has been discussed and revised with IODP, who have estimated the total expedition time to 56.6 days (transit: 6.0; operation: 37.2; logging: 8.5). In most cases, one RCB hole will be drilled to 200 mbsf and logged with Triple Combo and FMS Sonic for continuous stratigraphic imaging. XCB will be attempted to get higher recovery of Paleogene sediments in sites VMVM-
31A to VMVM-58A. APC will be done in holes VMVM-7A and VMVM-9A with thick Neogene sediments. Most holes are located on 3D data (sites VMVM-20A, VMVM-23A, VMVM-31A, VMVM-61A, VMVM-7A), whereas the outermost sites are located on industry-standard 2D data (sites VMVM-50A, VMVM-80A, VMVM-9A). On some of these sites, crossing lines are not always available exactly at the site, but 2D and 3D high-resolution site survey data is planned to be acquired prior to drilling.

We expect to reach 200 mbsf in all the holes, however basement recovery of ca 50 m should be sufficient for most sites. None of the sites require full recovery, however a high recovery of stratigraphic sites VMVM-31A and VMVM-50A is important. The sites are numbered in prioritized order, and downtime due to weather and technical problems may cause us to skip some of the outer margin sites (e.g. VMVM-9A).

4.2 Industry collaboration and relevance

Norway has a long tradition of close industry-academia collaboration. We have had a fruitful collaboration between research groups, industry, and government during the planning of this proposal, and plan to continue close collaboration with this group and other industry partners during the evolution of this project. The collaboration will be in terms of research funding, technology transfer, data acquisition, and data interpretation.
Figure 8. Volcanic seismic facies unit cartoon showing schematic location of the proposed drill sites (upper) (Planke et al., 2000) and seismic reflection data across the proposed sites. Data courtesy of TGS.
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<th>Location</th>
<th>Target</th>
<th>Primary Line</th>
<th>Crossing Line</th>
<th>Location (Lat/Lon)</th>
<th>Water (m)</th>
<th>Sed. (m)</th>
<th>Basalt (m)</th>
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**5.0 DISCUSSION AND SUMMARY**

**5.1 Interpretation of expected results**

The overall expected outcome of this proposal is one along-strike and one cross-strike margin transect, and two high-resolution Paleogene sedimentary sites. The cross-strike margin transect is located in the northern Vøring margin segment, consisting of four sites located in a typical volcanic rifted margin setting, covering the entire age range of breakup volcanics to understand syn- and post-breakup volcanism, melting, and margin dynamics. The inner two sites (VMVM-61A and 7A) are located on modern 3D seismic profiles, whereas the outer two sites (VMVM-80A and 9A) are located on 2D seismic profiles. The holes are complimentary to the previous DSDP and ODP holes (Fig. 3) in the region.

Expected results of the along-strike transect is sampling of volcanic rocks in the northern part of the Møre margin, the Kolga High, combined with borehole data along the Vøring margin. The Kolga High has recently been covered by high-resolution 3D industry data, revealing very thin basalt above a non-reflective structural high. The two sites VMVM-20A and 23A will sample sub-basalt sediments and initial basalt deposits. The along-strike profile will include the existing deep ODP 642 Site on the southern Vøring margin, DSDP Sites (Fig. 3), and the two proposed sites (VMVM-61A, VMVM-7A) on the Vøring Marginal High.

Two high-resolution Paleogene sediment sites are proposed along the Vøring transform margin (VMVM-31A, VMVM-50A), and one site in the center of a hydrothermal vent complex (VMVM-40A). The Paleogene is within the 200 mbsf limit only in two places, the northern Kolga High, and the Mimir High (Fig. 7). Two holes are proposed on the northern Kolga High to ensure 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 complete sampling of the succession lowermost Eocene and uppermost Paleocene section.

**5.2 Geochemistry, petrology, and geochronology**

Geochemical analysis of volcanic samples will be used to constrain 1) crustal processes, 2) mantle melting conditions including temperature, depth and dynamics of melting, 3) mantle source(s) composition and lithologies, and 4) temporal and spatial variability of magmatic indicators along the margin. Data to be collected include 1) major and trace element compositions including Rare Earth Elements (REE) and Platinum Group Elements (PGEs); 2) radiogenic isotopes (Rb-Sr, Sm-Nd, Lu-Hf, U-Pb, Re-Os); 3) stable isotopes (e.g. O and Li) and; 4) Ar-Ar and U-Pb age determinations.
A prerequisite to decipher mantle dynamics is that the geochemical characteristics are not completely obscured by continental crustal contamination and/or hydrothermal alteration (Ellam and Stuart, 2000; Peate et al., 2008; Meade et al., 2014; Hole et al., 2015; Hole and Millett, 2016). Although alteration is an issue for the mobile elements, results from previous ODP campaigns and industry boreholes demonstrate that useful trace element and isotopic data can be obtained for most volcanic samples hitherto drilled in the North Atlantic (Eldholm, 1989a; Fram et al., 1998; Tegner and Duncan, 1999; Fitton et al., 2000; Brown and Lesher, 2014; Millett et al., 2015). Existing drilling results at the Norwegian and Greenland margins (Fig. 9) show that the basal volcanics overlying extended continental crust are highly contaminated by continental crust (Viereck et al. 1989; Fitton et al., 2000, Abdelmalak et al., 2016a). However, in the overlying thick sequences of extrusive volcanic rocks in East Greenland and Vøring, the reaction with continental crust is moderate to minimal and allows robust interpretation of mantle processes (Tegner et al., 1998a; Fitton et al., 2000; Meyer et al., 2009; Brown and Lesher, 2014).

To distinguish between the three hypotheses for the formation of excess magmatism we propose the following analytical plan. First, source heterogeneity will be assessed based on geochemistry (major and trace elements, platinum group elements, and Sr-Nd-Hf-Pb-Os-O isotopes), allowing identification of contributions from crust, asthenospheric mantle lithologies (e.g. enriched, depleted or recycled mantle) and sub-continental lithospheric mantle. Second, we will apply state-of-the-art modeling to constrain mantle potential temperature for primary magma compositions from (i) major element compositions (e.g. PRIMELT3, Herzberg and Gazel, 2009; Hole, 2018) and (ii) from trace elements (e.g. REEBOX PRO; Brown and Lesher, 2016). Third, the dynamics of mantle melting (active vs. passive upwelling), lithospheric lid thickness, and magma pooling conditions will be constrained from geochemical modeling (e.g. REEBOX PRO). These models will allow distinguishing between relatively deep melting of an actively upwelling thermal and compositional mantle plume (hypothesis 1), shallow melting of ambient mantle undergoing active upwelling (hypothesis 2), and deep melting of passively upwelling cool mantle containing significant amounts of enriched, recycled components (hypothesis 3).
Figure 9. Geochemical and geochronological data. A: Total alkali-silica (TAS) diagram used to illustrate the composition of the ODP Hole 642E magma (Meyer et al., 2009; Abdelmalak et al., 2016). The Utgaard High sill is also plotted in the diagram (Neumann et al., 2013). B: Average rare earth element patterns of the Lower Series Flows, the SDR Upper Series and the East Greenland volcanics. Average from Meyer et al. (2009) and Hansen et al. (2002), with normalizing values from McDonough and Sun (1995). C: Comparison of the $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ isotope ratios of the Lower Series flows with available data from the North Atlantic area. D: Comparison of the $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios of the Lower Series flows with available data from the North Atlantic area. E: U–Pb concordia diagrams for the Utgard Upper Sill (Svensen et al. 2010). The ages are interpreted to represent the sill emplacement ages. NHRL: Northern Hemisphere Reference Line; MAR: Mid-Atlantic Ridge.
5.3 Seismic volcanostratigraphy and petrophysics

The proposed drill sites will sample many of the interpreted seismic facies units, including several for the first time (Fig. 2; e.g. Planke et al., 2017). We will also sample different seismic SDR sequences (Fig. 10), important for understanding the construction of these thick basalt units. An expected result is that Sequence 1 is formed in a shallow marine environment, whereas Sequence 2 is sub-aerial basalts with a distinctly different age. The Outer High and Outer SDRs have not been drilled and may either represent shallow marine and submarine basalt facies. Subaerial Outer SDRs would require substantial dynamic uplift during magma emplacement. The determination of the emplacement environment of the basalts sampled by the other sites will similarly provide important constraints on dynamic development of the volcanic margins allowing comparisons to sites of proposed dynamic support during rifting associated with the Iceland Plume (e.g. Hartley et al., 2011; Parnell-Turner et al., 2014).

Detailed petrophysical measurements and wire-line data will primarily be used for core-log-seismic integration and research on intra-basalt wave-propagation and sub-basalt imaging challenges. Core-log-seismic integration is important to utilize detailed core data in a regional context (e.g. Planke et al., 2001). The proposed boreholes penetrate several intra-sedimentary reflections, and an important aspect of the core-log-seismic integration is to better determine the origin of these reflections. A more challenging problem is to improve the sub-basalt imaging. The core and log data will be used to improve velocity models for processing of seismic reflection data.

5.4 PETM and Paleogene paleoclimate and paleo-environment

Main outcomes of Paleogene sedimentary drill sites VMVM-31A, VMVM-40A, and VMVM-50A are to test sediment degassing hypothesis 4 and to provide high-resolution sampling of Paleogene sediments to determine the relationship between the evolution of magmatism and impact on the paleoenvironment. This includes 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 paleotemperatures. The main result will be a major high-resolution update of current understanding of the stratigraphic, geochemical, and igneous development of the mid-Norwegian continental margin (Fig. 11).
An expected outcome of VMVM-40A is the documentation of nature and origin of hydrothermal vent complexes in the outer Vøring Basin. The vent complexes likely consist of fragmented and thermally altered sediments, similar to the ones found in the Karoo Basin and sampled by cuttings in well 6607/12-1 (Figs. 2 and 6). Sites VMVM-31A and VMVM-50A aim to provide high-resolution correlation between vent complex ejecta deposits and the carbon isotope excursion defining the PETM. The main risk is that the boundary layer is missing due to erosion/non-deposition or poor recovery. Differentiating between volcanic and contact metamorphic sources may be tested by collecting a stratigraphically complete section proximal to the magmatic activity, such as the Vøring Basin (Frieling et al., 2016).

Mercury anomalies expected from both volcanism and contact metamorphism (Jones et al., 2019). The subsequent distribution of Hg is strongly controlled by the manner of release to the environment. Subaerially degassed Hg\(^0\) has an atmospheric residence time of 1-2 years (Bagnato et al., 2011), whereas Hg released to the marine realm has a residence time much shorter than the mixing time of the oceans (Gworek et al., 2016). This means that submarine sources of Hg, such as submarine hydrothermal venting above sill intrusions, result in much more regionally constrained Hg anomalies (Scaife et al., 2017). Therefore, results from a Vøring Basin core could be compared to distal sequences to assess whether magmatic sources
are subaerial or submarine, and volcanic or metamorphic in origin (Jones et al., 2019). Recent studies also suggest that $\Delta^{199}$Hg isotopic compositions can differentiate between volcanic and organic sources (Them II et al., 2019; Shen et al., 2019), allowing for the pinpointing the origin of elevated Hg concentrations in proximal sediments. These are ideally complemented by screening of polycyclic aromatic hydrocarbons (PAHs), as the weight of these molecules increases with higher burning temperatures, and PAH distributions provide evidence for LIP activity (e.g. van der Schootbrugge et al., 2009). Integration with organic microfossil studies and occurrence of thermally altered organic microfossils can help establish which sedimentary sequences were affected by venting and/or which were close to intrusions (e.g. Svensen et al. 2004).

Biostratigraphic dating of sediments and radiometric dating of potential ash layers will give new understanding of absolute age and duration of the PETM. While radiometric dating may be somewhat limited by the availability of sample material, previous studies have successfully used U-Pb dating of Zircon on even heavily weathered bentonites from cores (e.g. Charles et al., 2011; Jones et al., 2017), and by Ar-Ar methods on fresh material of Sandine (e.g., Storey et al., 2007b). Numerous late Paleocene and early Eocene silicic tephra layers in the North Sea (Knox and Morton, 1988), Denmark (Larsen et al., 2003), and DSDP Site 550 (Westerhold et al. 2009), suggest that there will be plausible targets for such dating techniques.

In addition, the Paleogene sediment records obtained from offset drilling on the Mimir High (VMVM-50A) should provide new information about Paleocene and Eocene paleoclimate development, including short-lived hyperthermals, allowing detailed paleoclimate and paleoenvironment reconstructions close to the NAIP (e.g. Harding et al. 2011; Kender et al. 2012; Schoon et al. 2015; Kemp et al. 2016). While these studies provide a solid basis to compare newly recovered material, they are typically limited in temporal extent. Relative timings of extrusive and intrusive magmatic activity can be directly compared to paleoclimate proxies within the Vøring core(s), providing fine detail across the PETM and an insight into long-term Paleogene paleoclimate variation with evolving NAIP emplacement.

Organic microfossils (marine dinoflagellate cysts, pollen, spores), well established for the North Atlantic (Köthe, 2012; Thomsen et al., 2012), are instrumental for the acquired sediments. Integration of organic and carbonate microfossil biostratigraphy, high-resolution XRF and carbon isotope analyses will provide the basis of age-depth models for the cores. These established techniques will be complemented by quantitative paleothermometry (glycerol dialkyl glycerol tetraethers and alkenone based; e.g. TEX$_{86}$ and MBT; Schouten et al., 2002; Brassell et al. 1986; Weijers et al., 2007). Palynological assemblages will indicate
changes to nutrient regimes and primary productivity in both marine and terrestrial realms, complemented by carbonate micro and nannofossil assemblages where available. These techniques have strong proven track record in this region. The combination of geochemical climate proxy data, including but not limited to lipid biomarker based paleothermometry, bulk sediment chemistry, clay mineral assemblages and biotic data, allows for assessment of impact of environmental and volcanic perturbations on paleoclimate and ecosystems.

Figure 11. Synthesis of the stratigraphic, geochemical, and igneous events of the mid-Norwegian continental margin based on (Zachos et al., 2001; Storey et al., 2007a; Passey and Jolley, 2008; Svensen et al., 2010; Wotzlaw et al., 2012; Frieling et al., 2016; Wilkinson et al., 2016). Palynozones from Kjoberg et al. (2017).
5.5 Summary

The proposed drill holes along the Norwegian rifted margin provide an outstanding opportunity to test causes and paleoenvironmental implications of excess magmatism during breakup across the NE Atlantic. In classic plume models, a large symmetric plume head is supposed to spread out at the base of the lithosphere. Four drilling legs to SE Greenland, seismic refraction and reflection profiles on offshore East Greenland tested this hypothesis in distal to central transects and showed systematic and correlated changes in crustal thickness and compositions of the volcanics; thick crust and geochemical enrichment at Greenland-Iceland Rise and thin crust with little geochemical enrichment in the south (e.g. Fig. 6). Do the volcanics of the Vøring and Møre margin witness melting of the same mantle components as in SE Greenland? Does the along strike volcanism witness elevated temperatures consistent with a plume? Do volcanic facies reveal evidence for dynamic topography consistent with plume-ponding models? Do hydrothermal vents in the basin link precisely with onset of the PETM? These first order questions will be addressed by the proposed drilling and will allow us to unravel the distinct end member models for the formation of excess volcanism during breakup (temperature anomaly related to a mantle plume, small scale convection, source composition), as well as the link between volcanism and global climate in the Paleogene.

The relationship between the excess magmatism in the NE Atlantic and the observed climate perturbations throughout the Paleogene remain a topic of intense debate (e.g. Gutjahr et al. 2017). There is compelling evidence that both continental flood basalt volcanism and thermogenic generation of greenhouse gases from sill intrusions occurred around the time of the Paleocene-Eocene boundary, but there remains significant gaps in our understanding of the timing and volumes of greenhouse gas fluxes from these sources. The recovery of a continuous sedimentary sequence using offset cores on the Mimir High and N Kolga High will allow differentiation between these two processes, and put the volcanic, magmatic and tectonic activity in a geochronological framework with climate change events such as the Paleocene-Eocene Thermal Maximum, early Eocene Climate Optimum, and the Azolla-event.
6.0 References


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### Section A: Proposal Information

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#### General Lithologies:
- Thin Neogene sediments (30 m) above Mesozoic or older sequence.

#### Coring Plan: (Specify or check)
- APC
- XCB
- RCB
- Re-entry
- PCS

#### Wireline Logging Plan:
- Standard Measurements:
  - WL
  - Porosity
  - Density
  - Gamma Ray
  - Resistivity
  - Sonic (\(\Delta t\))
  - Formation Image (Res)
  - VSP (zero offset)
  - Formation Temperature & Pressure

- Special Tools:
  - Magnetic Susceptibility
  - Borehole Temperature
  - Formation Image (Acoustic)
  - VSP (walkaway)
  - LWD
  - Other tools:

- Other Measurements:

#### Estimated Days:
- Drilling/Coring: 3.4
- Logging: 0.8
- Total On-site: 4.2

#### Observatory Plan:
- Longterm Borehole Observation Plan/Re-entry Plan

#### Potential Hazards/Weather:
- Shallow Gas
- Complicated Seabed Condition
- Hydrothermal Activity
- Hydrocarbon
- Soft Seabed
- Landslide and Turbidity Current
- Shallow Water Flow
- Currents
- Gas Hydrate
- Abnormal Pressure
- Fracture Zone
- Diapir and Mud Volcano
- Man-made Objects (e.g., sea-floor cables, dump sites)
- Fault
- High Temperature
- H₂S
- High Dip Angle
- Ice Conditions
- CO₂
- Sensitive marine habitat (e.g., reef, vent)

#### Preferred weather window
- April-September

Other:

Generated: 2020-03-11T23:00:22+00:00
### IODP Site Forms

**Form 5 - Lithologies**

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 30</td>
<td>Neogene sediments</td>
<td>2</td>
<td>1800</td>
<td>Shale</td>
<td>Deep marine</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>30 - 200</td>
<td>Unknown</td>
<td>Unknown</td>
<td>3000</td>
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<td>Unknown</td>
</tr>
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### Section A: Proposal Information

<table>
<thead>
<tr>
<th>Proposal Title</th>
<th>The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date Form Submitted</td>
<td>2020-03-10 06:05:56</td>
</tr>
<tr>
<td>Site-Specific Objectives with Priority (Must include general objectives in proposal)</td>
<td>The main site objective is to sample sub-basalt sediments of unknown age on the Kolga High to characterize pre-eruption environment.</td>
</tr>
<tr>
<td>List Previous Drilling in Area</td>
<td>6403/1-U-1 6402/3-U-2</td>
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### Section B: General Site Information

<table>
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<th>VMVM-21A</th>
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<tbody>
<tr>
<td>Area or Location</td>
<td>N Atlantic</td>
</tr>
<tr>
<td>Jurisdiction</td>
<td>Norway</td>
</tr>
<tr>
<td>Distance to Land (km)</td>
<td>400</td>
</tr>
<tr>
<td>Water Depth (m)</td>
<td>2078</td>
</tr>
<tr>
<td>Priority of Site</td>
<td>Alternate: ✓</td>
</tr>
</tbody>
</table>

- The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

- The main site objective is to sample sub-basalt sediments of unknown age on the Kolga High to characterize pre-eruption environment.

- Previous drilling sites: 6403/1-U-1, 6402/3-U-2

- Site Name: VMVM-21A

- Area or Location: N Atlantic

- Jurisdiction: Norway

- Distance to Land: 400 km

- Water Depth: 2078 m

- Priority: Alternate

Generated: 2020-03-11T23:00:22+00:00
### Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Sediment Thickness (m):</td>
<td>200</td>
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</tr>
<tr>
<td>Total Penetration (m):</td>
<td></td>
<td>200</td>
</tr>
</tbody>
</table>

**General Lithologies:**
- Thin Neogene sediments (45 m) above Mesozoic or older sequence.

**Coring Plan:**
- (Specify or check)
- APC
- XCB
- RCB
- Re-entry
- PCS

**Wireline Logging Plan:**

- **Standard Measurements**
  - WL
  - Porosity
  - Density
  - Gamma Ray
  - Resistivity
  - Sonic ($\Delta t$)
  - Formation Image (Res)
  - VSP (zero offset)
  - Formation Temperature & Pressure

- **Special Tools**
  - Magnetic Susceptibility
  - Borehole Temperature
  - Formation Image (Acoustic)
  - VSP (walkway)
  - LWD

**Other Measurements:**

**Estimated Days:**
- Drilling/Coring: 3.4
- Logging: 0.8
- Total On-site: 4.2

**Observatory Plan:**
- Longterm Borehole Observation Plan/Re-entry Plan

**Potential Hazards/Weather:**
- Shallow Gas
- Complicated Seabed Condition
- Hydrothermal Activity
- Hydrocarbon
- Soft Seabed
- Landslide and Turbidity Current
- Shallow Water Flow
- Currents
- Gas Hydrate
- Abnormal Pressure
- Fracture Zone
- Diapir and Mud Volcano
- Man-made Objects (e.g., sea-floor cables, dump sites)
- Fault
- High Temperature
- H,S
- High Dip Angle
- Ice Conditions
- CO₂
- Sensitive marine habitat (e.g., reef, vent)

**Other:**

**Preferred weather window**
- April-September

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<tr>
<th>Subbottom depth (m)</th>
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<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
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<tbody>
<tr>
<td>0 - 45</td>
<td>Neogene sediments</td>
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<td>1800</td>
<td>Shale</td>
<td>Deep marine</td>
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<tr>
<td>45 - 200</td>
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<td>3000</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
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**Section A: Proposal Information**

- **Proposal Title**: The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup
- **Date Form Submitted**: 2020-03-10 06:05:56
- **Site-Specific Objectives with Priority**: The main site objective is to sample sub-basalt sediments of unknown age on the Kolga High to characterize pre-eruption environment.
- **List Previous Drilling in Area**:
  - 6403/1-U-1
  - 6402/3-U-2

**Section B: General Site Information**

- **Site Name**: VMVM-22A
- **Latitude**: Deg: 64.9449
- **Longitude**: Deg: 002.7889
- **Coordinate System**: WGS 84
- **Priority of Site**: Alternate: ✓
- **Area or Location**: N Atlantic
- **Jurisdiction**: Norway
- **Distance to Land**: 400 km
- **Water Depth (m)**: 2017
## Section C: Operational Information

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<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Sediment Thickness (m):</td>
<td>200</td>
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</tr>
<tr>
<td>Total Penetration (m):</td>
<td></td>
<td>200</td>
</tr>
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### General Lithologies:

- Thin Neogene sediments (85 m) above Mesozoic or older sequence.

### Coring Plan:

- **(Specify or check)**

### Wireline Logging Plan:

<table>
<thead>
<tr>
<th>Standard Measurements</th>
<th>Special Tools</th>
<th>Other Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL</td>
<td>Magnetic Susceptibility</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>Borehole Temperature</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>Formation Image (Acoustic)</td>
<td></td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>VSP (walkaway)</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>LWD</td>
<td></td>
</tr>
<tr>
<td>Sonic (Δt)</td>
<td>Formation Temperature &amp; Pressure</td>
<td></td>
</tr>
<tr>
<td>Other tools:</td>
<td></td>
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</tr>
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### Estimated Days:

- **Drilling/Coring:** 3.4
- **Logging:** 0.8
- **Total On-site:** 4.2

### Observatory Plan:

- **Longterm Borehole Observation Plan/Re-entry Plan**

### Potential Hazards/Weather:

- Shallow Gas
- Complicated Seabed Condition
- Hydrothermal Activity
- Preferred weather window
- Hydrocarbon
- Soft Seabed
- Landslide and Turbidity Current
- Shallow Water Flow
- Currents
- Gas Hydrate
- Abnormal Pressure
- Fracture Zone
- Diapir and Mud Volcano
- Man-made Objects (e.g., sea-floor cables, dump sites)
- Fault
- High Temperature
- H₂S
- High Dip Angle
- Ice Conditions
- Sensitive marine habitat (e.g., reefs, vents)
- Other:

---

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<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
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<td>1800</td>
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</tr>
<tr>
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<td>3000</td>
<td>Unknown</td>
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<td>Unknown</td>
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<td>6403/1-U1 6402/3-U2</td>
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**Section B: General Site Information**

<table>
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<th>Site Name:</th>
<th>VMVM-23A</th>
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</thead>
<tbody>
<tr>
<td>Area or Location:</td>
<td>N Atlantic</td>
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<td>Jurisdiction:</td>
<td>Norway</td>
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<tr>
<td>Distance to Land: (km)</td>
<td>400</td>
</tr>
<tr>
<td>Water Depth (m):</td>
<td>2137</td>
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<tr>
<td>Latitude:</td>
<td>Deg: 64.9651</td>
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<tr>
<td>Longitude:</td>
<td>Deg: 002.7312</td>
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<tr>
<td>Coordinate System:</td>
<td>WGS 84</td>
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<tr>
<td>Priority of Site:</td>
<td>Primary: ✓ Alternate: □</td>
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</table>
# Section C: Operational Information

<table>
<thead>
<tr>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proposed Penetration (m):</strong></td>
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</tr>
<tr>
<td><strong>Total Sediment Thickness (m):</strong></td>
<td>25</td>
</tr>
<tr>
<td><strong>Total Penetration (m):</strong></td>
<td><strong>200</strong></td>
</tr>
</tbody>
</table>

## General Lithologies:
- **Neogene mud**
- **Basalt flows**

## Coring Plan:
- **APC**
- **XCB**
- **RCB**
- **Re-entry**
- **PCS**

## Wireline Logging Plan:

<table>
<thead>
<tr>
<th>Standard Measurements</th>
<th>Special Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL</td>
<td>Magnetic Susceptibility</td>
</tr>
<tr>
<td>Porosity</td>
<td>Borehole Temperature</td>
</tr>
<tr>
<td>Density</td>
<td>Formation Image (Acoustic)</td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>VSP (walkaway)</td>
</tr>
<tr>
<td>Resistivity</td>
<td>LWD</td>
</tr>
<tr>
<td>Sonic (Δt)</td>
<td></td>
</tr>
<tr>
<td>Formation Image (Res)</td>
<td></td>
</tr>
<tr>
<td>VSP (zero offset)</td>
<td></td>
</tr>
<tr>
<td>Formation Temperature &amp; Pressure</td>
<td></td>
</tr>
</tbody>
</table>

## Estimated Days:
- **Drilling/Coring:** 3.2
- **Logging:** 0.8
- **Total On-site:** 4

## Observatory Plan:
- **Longterm Borehole Observation Plan/Re-entry Plan**

## Potential Hazards/Weather:

<table>
<thead>
<tr>
<th>Shallow Gas</th>
<th>Complicated Seabed Condition</th>
<th>Hydrothermal Activity</th>
<th>Preferred weather window</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocarbon</td>
<td>Soft Seabed</td>
<td>Landslide and Turbidity Current</td>
<td>April-September</td>
</tr>
<tr>
<td>Shallow Water Flow</td>
<td>Currents</td>
<td>Gas Hydrate</td>
<td></td>
</tr>
<tr>
<td>Abnormal Pressure</td>
<td>Fracture Zone</td>
<td>Diapir and Mud Volcano</td>
<td></td>
</tr>
<tr>
<td>Man-made Objects (e.g., sea-floor cables, dump sites)</td>
<td>Fault</td>
<td>High Temperature</td>
<td></td>
</tr>
<tr>
<td>H₂S</td>
<td>High Dip Angle</td>
<td>Ice Conditions</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
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</tr>
</tbody>
</table>

Other:

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<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>0 - 25</td>
<td>Seabed to Top Basalt</td>
<td>2</td>
<td>1800</td>
<td>Mud</td>
<td>Deep marine</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>25 - 200</td>
<td>Base basalt</td>
<td>56</td>
<td>3000</td>
<td>Basalt flows</td>
<td>Subaerial</td>
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</table>

Proposal #: 944 - Add 2  
Site #: VMVM-23A  
Date Form Submitted: 2020-03-10 06:05:56
### Section A: Proposal Information

**Proposal Title:**

The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

**Date Form Submitted:**

2020-03-10 06:05:56

**Site-Specific Objectives with Priority (Must include general objectives in proposal):**

The main target of this site is emergent basalts, intra-basalt sediments, and the base-basalt contact for geochemical, volcanological, and geochronological studies.

**List Previous Drilling in Area:**

6403/1-U1
6402/3-U2

### Section B: General Site Information

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<td>Longitude: Deg: 002.7282</td>
<td>Water Depth (m): 2145</td>
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<td>Coordinate System: WGS 84</td>
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</table>
## Section C: Operational Information

### Sediments

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<tr>
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<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>170</td>
</tr>
</tbody>
</table>

Total Sediment Thickness (m): 30

Total Penetration (m): 200

### General Lithologies:

- Neogene mud
- Basalt flows

### Coring Plan:

<table>
<thead>
<tr>
<th>Specify or check</th>
</tr>
</thead>
<tbody>
<tr>
<td>APC</td>
</tr>
<tr>
<td>XCB</td>
</tr>
<tr>
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</tr>
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</tr>
<tr>
<td>PCS</td>
</tr>
</tbody>
</table>

### Wireline Logging Plan:

<table>
<thead>
<tr>
<th>Standard Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL</td>
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</tr>
<tr>
<td>VSP (zero offset)</td>
</tr>
<tr>
<td>Formation Temperature &amp; Pressure</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Special Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Susceptibility</td>
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<td>Formation Image (Acoustic)</td>
</tr>
<tr>
<td>VSP (walkaway)</td>
</tr>
<tr>
<td>LWD</td>
</tr>
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Other tools:

Other Measurements:

### Estimated Days:

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<th>Drilling/Coring:</th>
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<tbody>
<tr>
<td>3.2</td>
<td>0.8</td>
<td>4</td>
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### Observatory Plan:

Longterm Borehole Observation Plan/Re-entry Plan

### Potential Hazards/Weather:

- Shallow Gas
- Complicated Seabed Condition
- Hydrothermal Activity
- Hydrocarbon
- Soft Seabed
- Landslide and Turbidity Current
- Shallow Water Flow
- Currents
- Gas Hydrate
- Abnormal Pressure
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- Man-made Objects (e.g., sea-floor cables, dump sites)
- Fault
- High Temperature
- H₂S
- High Dip Angle
- Ice Conditions
- CO₂
- Sensitive marine habitat (e.g., reefs, vents)

Preferred weather window: April-September

Other:
### Form 5 - Lithologies

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
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<th>Paleo-environment</th>
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<td>0 - 30</td>
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<td>2</td>
<td>1800</td>
<td>Mud</td>
<td>Deep marine</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>30 - 200</td>
<td>Base basalt</td>
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<td>3000</td>
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<td>6403/1-U1  6402/3-U2</td>
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### Section B: General Site Information

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<td>Deg: 002.7235</td>
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<tr>
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<td>WGS 84</td>
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<td>Area or Location:</td>
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<tr>
<td>Jurisdiction:</td>
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<td>Water Depth (m):</td>
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<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>175</td>
</tr>
<tr>
<td>Total Sediment Thickness (m):</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Total Penetration (m):</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

### General Lithologies:
- Neogene mud
- Basalt flows

### Coring Plan:
- APC
- XCB
- RCB
- Re-entry
- PCS

### Wireline Logging Plan:
- Standard Measurements:
  - WL
  - Porosity
  - Density
  - Gamma Ray
  - Resistivity
  - Sonic (Δt)
  - Formation Image (Res)
  - VSP (zero offset)
  - Formation Temperature & Pressure
- Special Tools:
  - Magnetic Susceptibility
  - Borehole Temperature
  - Formation Image (Acoustic)
  - VSP (walkaway)
  - LWD
  - Other tools:

### Estimated Days:
- Drilling/Coring: 3.2
- Logging: 0.8
- Total On-site: 4

### Observatory Plan:
- Long term Borehole Observation Plan/Re-entry Plan

### Potential Hazards/Weather:
- Shallow Gas
- Complicated Seabed Condition
- Hydrothermal Activity
- Hydrocarbon
- Soft Seabed
- Landslide and Turbidity Current
- Shallow Water Flow
- Currents
- Gas Hydrate
- Abnormal Pressure
- Fracture Zone
- Diapir and Mud Volcano
- Man-made Objects (e.g., sea-floor cables, dump sites)
- Fault
- High Temperature
- HS
- High Dip Angle
- Ice Conditions
- CO₂
- Sensitive marine habitat (e.g., reef, vents)

### Preferred weather window
- April-September

Other:
<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 25</td>
<td>Seabed to Top Basalt</td>
<td>2</td>
<td>1800</td>
<td>Mud</td>
<td>Deep marine</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>25 - 200</td>
<td>Base basalt</td>
<td>56</td>
<td>3000</td>
<td>Basalt flows</td>
<td>Subaerial</td>
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<td></td>
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</table>
## Section A: Proposal Information

<table>
<thead>
<tr>
<th>Proposal Title</th>
<th>The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date Form Submitted</td>
<td>2020-03-10 06:05:56</td>
</tr>
<tr>
<td>Site-Specific Objectives with Priority (Must include general objectives in proposal)</td>
<td>The primary objective of the site is to drill Paleocene-Eocene sediments for lithological, geochemical and geochronological characterization.</td>
</tr>
<tr>
<td>List Previous Drilling in Area</td>
<td>6403/1-U1 6402/3-U2</td>
</tr>
</tbody>
</table>

## Section B: General Site Information

| Site Name: | VMVM-31A |
| Site Name: | VMVM-31A |
| If site is a reoccupation of an old DSDP/ODP Site, Please include former Site# |  |
| Latitude: | Deg: 65.3645 |
| Longitude: | Deg: 003.0563 |
| Coordinate System: | WGS 84 |
| Priority of Site: | Primary: ✓ Alternate:  |
| Area or Location: | N Atlantic |
| Jurisdiction: | Norway |
| Distance to Land: (km) | 400 |
| Water Depth (m): | 1707 |
**Section C: Operational Information**

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
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<tr>
<td>Total Sediment Thickness (m):</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Total Penetration (m):</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

**General Lithologies:**
- Mud, shale

**Coring Plan:**
- Try with XCB first, then continue with RCB

**Wireline Logging Plan:**

<table>
<thead>
<tr>
<th>Standard Measurements</th>
<th>Special Tools</th>
<th>Other Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL</td>
<td>Magnetic Susceptibility</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>Borehole Temperature</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>Formation Image (Acoustic)</td>
<td></td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>VSP (walkaway)</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>LWD</td>
<td></td>
</tr>
<tr>
<td>Sonic (Δt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation Image (Res)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VSP (zero offset)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation Temperature &amp; Pressure</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Estimated Days:**
- Drilling/Coring: 3.1
- Logging: 0.9
- Total On-site: 4

**Observatory Plan:**
- Longterm Borehole Observation Plan/Re-entry Plan

**Potential Hazards/Weather:**
- Shallow Gas
- Hydrocarbon
- Shallow Water Flow
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H2S
- CO2
- Sensitive marine habitat (e.g., reef, vent)

- Complicated Seabed Condition
- Soft Seabed
- Currents
- Fracture Zone
- High Dip Angle
- High Temperature

- Hydrothermal Activity
- Landslide and Turbidity
- Gas Hydrate
- Diapir and Mud Volcano
- High Temperature
- Ice Conditions

**Other:**

Generated: 2020-03-11T23:00:23+00:00
### Subbottom Depth (m) Table

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 55</td>
<td>Top Paleocene</td>
<td>2</td>
<td>1800</td>
<td>Mud</td>
<td>Deep marine</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>55 - 200</td>
<td>Paleogene</td>
<td>40-60</td>
<td>2200</td>
<td>Shale, sandstones</td>
<td>Shallow to deep marine</td>
<td>Unconstrained as age dating is poor</td>
<td></td>
</tr>
</tbody>
</table>
# IODP Site Forms

## Form 1 – General Site Information

### Section A: Proposal Information

**Proposal Title:**
The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

**Date Form Submitted:**
2020-03-10 06:05:56

**Site-Specific Objectives with Priority**
The primary objective of the site is to drill Paleocene-Eocene sediments for lithological, geochemical and geochronogical characterization.

**List Previous Drilling in Area**
- 6403/1-U1
- 6402/3-U2

### Section B: General Site Information

**Site Name:**
VMVM-32A

**If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#**

**Latitude:**
Deg: 65.3717

**Longitude:**
Deg: 003.0605

**Coordinate System:**
WGS 84

**Priority of Site:**
- Primary: 
- Alternate: ✓

**Area or Location:**
N Atlantic

**Jurisdiction:**
Norway

**Distance to Land:**
400 (km)

**Water Depth (m):**
1695

Generated: 2020-03-11T23:00:23+00:00
Section C: Operational Information

<table>
<thead>
<tr>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0</td>
</tr>
</tbody>
</table>

Total Sediment Thickness (m): 200

General Lithologies:
- Mud, shale

Coring Plan:
- Try with XCB first, then continue with RCB

Wireline Logging Plan:
- Standard Measurements:
  - Porosity
  - Density
  - Gamma Ray
  - Resistivity
  - Sonic (Δt)
  - Formation Image (Res)
  - VSP (zero offset)
  - Formation Temperature & Pressure

- Special Tools:
  - Magnetic Susceptibility
  - Borehole Temperature
  - Formation Image (Acoustic)
  - VSP (walkaway)
  - LWD

Other Measurements:

Estimated Days:
- Drilling/Coring: 3.1
- Logging: 0.9
- Total On-site: 4

Observatory Plan:
- Longterm Borehole Observation Plan/Re-entry Plan

Potential Hazards/Weather:
- Shallow Gas
- Complicated Seabed Condition
- Hydrothermal Activity
- Hydrocarbon
- Soft Seabed
- Landslide and Turbidity Current
- Shallow Water Flow
- Currents
- Gas Hydrate
- Abnormal Pressure
- Fracture Zone
- Diapir and Mud Volcano
- Man-made Objects (e.g., sea-floor cables, dump sites)
- Fault
- High Temperature
- H2S
- High Dip Angle
- Ice Conditions
- CO2
- Sensitive marine habitat (e.g., reefs, vents)

Other:

Preferred weather window: April-September

APC

Coring Plan:
(Specify or check)

APC

Tools:

Other:

Estimated Days:

Generates: 2020-03-11T23:00:23+00:00
<table>
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<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 55</td>
<td>Top Paleocene</td>
<td>2</td>
<td>1800</td>
<td>Mud</td>
<td>Deep marine</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>55 - 200</td>
<td>Paleogene</td>
<td>40-60</td>
<td>2200</td>
<td>Shale, sandstones</td>
<td>Shallow to deep marine</td>
<td>Unconstrained as age dating is poor</td>
<td></td>
</tr>
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</table>
# IODP Site Forms

## Form 1 – General Site Information

### Section A: Proposal Information

<table>
<thead>
<tr>
<th>Proposal Title</th>
<th>The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date Form Submitted</td>
<td>2020-03-10 06:05:56</td>
</tr>
<tr>
<td>Site-Specific Objectives with Priority (Must include general objectives in proposal)</td>
<td>The primary objective of the site is to drill Paleocene-Eocene sediments for lithological, geochemical and geochronological characterization.</td>
</tr>
<tr>
<td>List Previous Drilling in Area</td>
<td>6403/1-U1 6402/3-U2</td>
</tr>
</tbody>
</table>

### Section B: General Site Information

<table>
<thead>
<tr>
<th>Site Name</th>
<th>VMVM-33A</th>
</tr>
</thead>
<tbody>
<tr>
<td>If site is a reoccupation of an old DSDP/ODP Site, Please include former Site #</td>
<td></td>
</tr>
<tr>
<td>Latitude</td>
<td>Deg: 65.4065</td>
</tr>
<tr>
<td>Longitude</td>
<td>Deg: 003.0947</td>
</tr>
<tr>
<td>Coordinate System</td>
<td>WGS 84</td>
</tr>
<tr>
<td>Priority of Site</td>
<td>Primary:  Alternate: ✓</td>
</tr>
<tr>
<td>Area or Location</td>
<td>N Atlantic</td>
</tr>
<tr>
<td>Jurisdiction</td>
<td>Norway</td>
</tr>
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<td>Distance to Land (km)</td>
<td>400</td>
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<tr>
<td>Water Depth (m)</td>
<td>1673</td>
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### Section C: Operational Information

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<thead>
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</thead>
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<tr>
<td>200</td>
</tr>
<tr>
<td>Total Penetration (m):</td>
</tr>
<tr>
<td>200</td>
</tr>
</tbody>
</table>

**General Lithologies:**
- Mud, shale

**Coring Plan:**
- Try with XCB first, then continue with RCB
- **APC**
- **XCB**
- **RCB**
- **Re-entry**
- **PCS**

**Wireline Logging Plan:**
- **WL**
- **Porosity**
- **Density**
- **Gamma Ray**
- **Resistivity**
- **Sonic (Δt)**
- **Formation Image (Res)**
- **VSP (zero offset)**
- **Formation Temperature & Pressure**

**Standard Measurements**
- Magnetic Susceptibility
- Borehole Temperature
- Formation Image (Acoustic)
- VSP (walkway)
- LWD

**Special Tools**
- Other tools:

**Estimated Days:**
- Drilling/Coring: **3.1**
- Logging: **0.9**
- Total On-site: **4**

**Observatory Plan:**
- **Longterm Borehole Observation Plan/Re-entry Plan**

**Potential Hazards/Weather:**
- Shallow Gas
- Hydrocarbon
- Shallow Water Flow
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H₂S
- CO₂
- Sensitive marine habitat (e.g., reefs, vents)
- Complicated Seabed Condition
- Soft Seabed
- Currents
- Fracture Zone
- Fault
- High Dip Angle
- High Temperature
- Ice Conditions

**Prefered weather window:**
- April-September

**Other:**

<table>
<thead>
<tr>
<th>Sediments Basement</th>
<th>General Lithologies: Mud, shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed Penetration (m):</td>
<td>Total Sediment Thickness (m):</td>
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<tr>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Total Penetration (m):</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

**Coring Plan:**
- Try with XCB first, then continue with RCB
- **APC**
- **XCB**
- **RCB**
- **Re-entry**
- **PCS**

**Wireline Logging Plan:**
- **WL**
- **Porosity**
- **Density**
- **Gamma Ray**
- **Resistivity**
- **Sonic (Δt)**
- **Formation Image (Res)**
- **VSP (zero offset)**
- **Formation Temperature & Pressure**

**Standard Measurements**
- Magnetic Susceptibility
- Borehole Temperature
- Formation Image (Acoustic)
- VSP (walkway)
- LWD

**Special Tools**
- Other tools:

**Estimated Days:**
- Drilling/Coring: **3.1**
- Logging: **0.9**
- Total On-site: **4**

**Observatory Plan:**
- **Longterm Borehole Observation Plan/Re-entry Plan**

**Potential Hazards/Weather:**
- Shallow Gas
- Hydrocarbon
- Shallow Water Flow
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H₂S
- CO₂
- Sensitive marine habitat (e.g., reefs, vents)
- Complicated Seabed Condition
- Soft Seabed
- Currents
- Fracture Zone
- Fault
- High Dip Angle
- High Temperature
- Ice Conditions

**Preferred weather window:**
- April-September

**Other:**

Generated: 2020-03-11T23:00:23+00:00
<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 110</td>
<td>Top Paleocene</td>
<td>2</td>
<td>1800</td>
<td>Mud, shale</td>
<td>Deep marine</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>110 - 200</td>
<td>Paleogene</td>
<td>40-60</td>
<td>2200</td>
<td>Shale, sandstones</td>
<td>Shallow to deep marine</td>
<td>Unconstrained as age dating is poor</td>
<td></td>
</tr>
</tbody>
</table>
Section A: Proposal Information

Proposal Title: The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

Date Form Submitted: 2020-03-10 06:05:56

Site-Specific Objectives with Priority (Must include general objectives in proposal):
The primary objective for this site is to drill the hydrothermal vent complex, including the base of the eye structure, to determine the lithology, age, and nature of the vent complexes.

List Previous Drilling in Area:
6403/1-U1
6402/3-U2

Section B: General Site Information

Site Name: VMVM-40B

Area or Location: N Atlantic
Jurisdiction: Norway

Latitude: 65.3602 Deg
Longitude: 003.0538 Deg
Coordinate System: WGS 84

Distance to Land: 400 km
Water Depth (m): 1696

Priority of Site: Primary ✓ Alternate ☐
### Section C: Operational Information

<table>
<thead>
<tr>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Sediment Thickness (m)</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Penetration (m)</td>
<td>400</td>
</tr>
</tbody>
</table>

**General Lithologies:**
- XCB to TD, then RCB to 200 m

**Coring Plan:**
- (Specify or check)
  - XCB
  - RCB

**Wireline Logging Plan:**
- Standard Measurements
  - WL
  - Porosity
  - Density
  - Gamma Ray
  - Resistivity
  - Sonic (Δt)
  - Formation Image (Res)
  - VSP (zero offset)
  - Formation Temperature & Pressure

- Special Tools
  - Magnetic Susceptibility
  - Borehole Temperature
  - Formation Image (Acoustic)
  - VSP (walkway)
  - LWD

**Tools:**
- APC
- XCB ✓
- RCB ✓
- Re-entry
- PCS

**Estimated Days:**
- Drilling/Coring: 2.9
- Logging: 0.8
- Total On-site: 3.7

**Observatory Plan:**
- Longterm Borehole Observation Plan/Re-entry Plan

**Potential Hazards/Weather:**
- Shallow Gas ✓
- Hydrocarbon ✓
- Shallow Water Flow ✓
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H₂S
- CO₂

- Complicated Seabed Condition
- Soft Seabed ✓
- Currents
- Fracture Zone
- Fault
- High Dip Angle
- High Temperature
- Ice Conditions
- Hydrothermal Activity
- Landslide and Turbidity Current
- Gas Hydrate ✓
- Diapir and Mud Volcano
- Fault
- High Temperature
- Ice Conditions
- Preferred weather window: April-September

**Other:**

---

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## Form 5 - Lithologies

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 40</td>
<td>Base Naust</td>
<td>2</td>
<td>1800</td>
<td>Mud</td>
<td>Deep marine</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>40 - 200</td>
<td>Vent Complex</td>
<td>55</td>
<td>2200</td>
<td>Mudstone and mud breccia</td>
<td>Hydrothermal vent complex</td>
<td>Unconstrained</td>
<td></td>
</tr>
</tbody>
</table>

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Section A: Proposal Information

Proposal Title
The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

Date Form Submitted
2020-03-10 06:05:56

Site-Specific Objectives with Priority (Must include general objectives in proposal)
The primary objective for this site is to drill the central part of a hydrothermal vent complex, including the base of the eye structure, to determine the lithology, age, and nature of the vent complexes.

List Previous Drilling in Area
6403/1-U1
6402/3-U2

Section B: General Site Information

Site Name: VMVM-41A

Area or Location: N Atlantic

Jurisdiction: Norway

Distance to Land: 400 km

Water Depth (m): 1686

Latitude: 65.3762 Deg:

Longitude: 003.0632 Deg:

Coordinate System: WGS 84

Priority of Site: Alternate: ✓
### Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
<td>0</td>
</tr>
</tbody>
</table>

**Total Sediment Thickness (m):** 200

**Total Penetration (m):** 200

**General Lithologies:**
- 65 m Neogene mud, then Paleogene shales, breccia, and possibly sandstone

**Coring Plan:**
- XCB to TD, then RCB to 200 m

**Wireline Logging Plan:**
- **Standard Measurements**
  - WL
  - Porosity
  - Density
  - Gamma Ray
  - Resistivity
  - Sonic (Δt)
  - Formation Image (Res)
  - VSP (zero offset)
  - Formation Temperature & Pressure

- **Special Tools**
  - Magnetic Susceptibility
  - Borehole Temperature
  - Formation Image (Acoustic)
  - VSP (walkaway)
  - LWD

**Other:***

**Estimated Days:**
- Drilling/Coring: 2.9
- Logging: 0.8
- Total On-site: 3.7

**Observatory Plan:**
- Long-term Borehole Observation Plan/Re-entry Plan

**Potential Hazards/Weather:**
- Shallow Gas
- Hydrocarbon
- Shallow Water Flow
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H2S
- CO2
- Sensitive marine habitat (e.g., reef, vent)

**Other:**

**Preferred weather window:**
- April-September

**APC Coring Plan:**
- (Specify or check)

**Other Measurements:**

---

Generated: 2020-03-11T23:00:23+00:00
## IODP Site Forms

### Form 5 - Lithologies

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 65</td>
<td>Top vent</td>
<td>2</td>
<td>1800</td>
<td>Mud</td>
<td>Deep marine</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>65 - 200</td>
<td>Vent complex</td>
<td>55</td>
<td>2200</td>
<td>Mudstone and mud breccia</td>
<td>Hydrothermal vent complex</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Section A: Proposal Information

Proposal Title: The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

Date Form Submitted: 2020-03-10 06:55:56

Site-Specific Objectives with Priority (Must include general objectives in proposal):
The primary objective for this site is to drill the central part of a hydrothermal vent complex, including the base of the eye structure, to determine the lithology, age, and nature of the vent complexes.

List Previous Drilling in Area:
6403/1-U1
6402/3-U2

Section B: General Site Information

Site Name: VMVM-42A
Area or Location: N Atlantic
If site is a reoccupation of an old DSDP/ODP Site, please include former Site#:
Jurisdiction: Norway
Latitude: 65.4086
Distance to Land: 400 km
Longitude: 003.0735
Water Depth (m): 1695
Coordinate System: WGS 84
Priority of Site: Alternate: ✓
### Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300</td>
<td>0</td>
</tr>
<tr>
<td>Total Sediment Thickness (m)</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Total Penetration (m):</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

**General Lithologies:**

- 135 m Neogene mud, then Paleogene shales, breccia, and possibly sandstone

**Coring Plan:**
- XCB to TD, then RCB to 200 m

**Wireline Logging Plan:**

- **Standard Measurements:**
  - WL
  - Porosity
  - Density
  - Gamma Ray
  - Resistivity
  - Sonic (Δt)
  - Formation Image (Res)
  - VSP (zero offset)
  - Formation Temperature & Pressure

- **Special Tools:**
  - Magnetic Susceptibility
  - Borehole Temperature
  - Formation Image (Acoustic)
  - VSP (walkaway)
  - LWD

**Other Measurements:**

**Estimated Days:**

- Drilling/Coring: 2.9
- Logging: 0.8
- Total On-site: 3.7

**Observatory Plan:**

- **Longterm Borehole Observation Plan/Re-entry Plan**

**Potential Hazards/Weather:**

- Shallow Gas
- Hydrocarbon
- Shallow Water Flow
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H₂S
- CO₂
- Sensitive marine habitat (e.g., reef, vent)

- Complicated Seabed Condition
- Soft Seabed
- Currents
- Fracture Zone
- Fault
- High Dip Angle
- Ice Conditions

- Hydrothermal Activity
- Landslide and Turbidity Current
- Gas Hydrate
- Diapir and Mud Volcano
- High Temperature
- Preferred weather window:
  - April-September

**Other:**

**Coring Plan:**

- APC
- XCB
- RCB
- Re-entry
- PCS

**Tools:**

- [✓] Magnetic Susceptibility
- [✓] Borehole Temperature
- [✓] Formation Image (Acoustic)
- [✓] VSP (walkaway)
- [✓] LWD
- [✓] Porosity
- [✓] Density
- [✓] Gamma Ray
- [✓] Resistivity
- [✓] Sonic (Δt)
- [✓] Formation Image (Res)
- [✓] VSP (zero offset)
- [✓] Formation Temperature & Pressure

**Other Measurements:**

**April-September**

*Generated: 2020-03-11T23:00:23+00:00*
**IODP Site Forms**

**Form 5 - Lithologies**

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 135</td>
<td>Top vent</td>
<td>2</td>
<td>1800</td>
<td>Mud</td>
<td>Deep marine</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>135 - 300</td>
<td>Vent complex</td>
<td>55</td>
<td>2200</td>
<td>Mudstone and mud breccia</td>
<td>Hydrothermal vent complex</td>
<td>.</td>
<td></td>
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</table>

Generated: 2020-03-11T23:00:23+00:00
Section A: Proposal Information

Proposal Title

The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

Date Form Submitted

2020-03-10 06:05:56

Site-Specific Objectives with Priority

The primary objective is to drill hole of 800 m to obtain an extended sedimentary sequence across the Paleocene-Eocene boundary for paleoclimate studies.

(List Previous Drilling in Area)

Section B: General Site Information

Site Name:

VMVM-51A

Area or Location:

N Atlantic

If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#

Latitude:

65.8735 Deg:

Longitude:

001.9606 Deg:

Coordinate System:

WGS 84

Jurisdiction:

Norway

Distance to Land:

450 (km)

Priority of Site:

Primary: [ ] Alternate: [✓]

Water Depth (m):

2147

Generated: 2020-03-11T23:00:23+00:00
### Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>800</td>
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</table>

<table>
<thead>
<tr>
<th>Total Sediment Thickness (m)</th>
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</table>

<table>
<thead>
<tr>
<th>General Lithologies:</th>
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</thead>
<tbody>
<tr>
<td>Paleogene shale and possibly sandstone</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coring Plan:</th>
<th>(Specify or check)</th>
<th>Initially XCB to TD and then RCB</th>
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<tbody>
<tr>
<td>APC</td>
<td>XCB ✓</td>
<td>RCB ✓</td>
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<table>
<thead>
<tr>
<th>Wireline Logging Plan:</th>
<th>Standard Measurements</th>
<th>Special Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL</td>
<td>Magnetic Susceptibility</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>Borehole Temperature</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>Formation Image (Acoustic)</td>
<td></td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>VSP (walkway)</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>LWD</td>
<td></td>
</tr>
<tr>
<td>Sonic (∆t)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation Image (Res)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VSP (zero offset)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation Temperature &amp; Pressure</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other Measurements:</th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Estimated Days:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling/Coring:</td>
<td>9.9</td>
</tr>
<tr>
<td>Logging:</td>
<td>1.5</td>
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<tr>
<td>Total On-site:</td>
<td>11.4</td>
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</table>

<table>
<thead>
<tr>
<th>Observatory Plan:</th>
<th>Longterm Borehole Observation Plan/Re-entry Plan</th>
<th></th>
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</thead>
</table>

<table>
<thead>
<tr>
<th>Potential Hazards/Weather:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow Gas</td>
<td>✓</td>
</tr>
<tr>
<td>Complicated Seabed Condition</td>
<td>✓</td>
</tr>
<tr>
<td>Hydrothermal Activity</td>
<td>✓</td>
</tr>
<tr>
<td>Hydrocarbon</td>
<td>✓</td>
</tr>
<tr>
<td>Soft Seabed</td>
<td>✓</td>
</tr>
<tr>
<td>Landslide and Turbidity</td>
<td>✓</td>
</tr>
<tr>
<td>Shallow Water Flow</td>
<td>✓</td>
</tr>
<tr>
<td>Currents</td>
<td>✓</td>
</tr>
<tr>
<td>Gas Hydrate</td>
<td>✓</td>
</tr>
<tr>
<td>Abnormal Pressure</td>
<td>✓</td>
</tr>
<tr>
<td>Fracture Zone</td>
<td>✓</td>
</tr>
<tr>
<td>Diapir and Mud Volcano</td>
<td>✓</td>
</tr>
<tr>
<td>Man-made Objects (e.g., sea-floor cables, dump sites)</td>
<td>✓</td>
</tr>
<tr>
<td>Fault</td>
<td>✓</td>
</tr>
<tr>
<td>High Temperature</td>
<td>✓</td>
</tr>
<tr>
<td>H₂S</td>
<td>✓</td>
</tr>
<tr>
<td>High Dip Angle</td>
<td>✓</td>
</tr>
<tr>
<td>Ice Conditions</td>
<td>✓</td>
</tr>
<tr>
<td>CO₂</td>
<td>✓</td>
</tr>
<tr>
<td>Sensitive marine habitat (e.g., reef, vent)</td>
<td></td>
</tr>
</tbody>
</table>

Other: |  |

Preferred weather window: April-September

Generated: 2020-03-11T23:00:23+00:00
## IODP Site Forms

### Form 5 - Lithologies

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 200</td>
<td>Top Paleocene</td>
<td>2 and above</td>
<td></td>
<td>Mud, shale</td>
<td>Deep marine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 - 800</td>
<td>Outgoing stratigraphy</td>
<td>40-60</td>
<td></td>
<td>Shale and sandstones</td>
<td>Marine</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Section A: Proposal Information

<table>
<thead>
<tr>
<th>Proposal Title</th>
<th>The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date Form Submitted</td>
<td>2020-03-10 06:05:56</td>
</tr>
<tr>
<td>Site-Specific Objectives with Priority (Must include general objectives in proposal)</td>
<td>The primary objective is to drill hole of 800 m to obtain an extended sedimentary sequence across the Paleocene-Eocene boundary for paleoclimate studies.</td>
</tr>
<tr>
<td>List Previous Drilling in Area</td>
<td></td>
</tr>
</tbody>
</table>

### Section B: General Site Information

<table>
<thead>
<tr>
<th>Site Name:</th>
<th>VMVM-55B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area or Location:</td>
<td>N Atlantic</td>
</tr>
<tr>
<td>Jurisdiction:</td>
<td>Norway</td>
</tr>
<tr>
<td>Distance to Land: (km)</td>
<td>450</td>
</tr>
<tr>
<td>Water Depth (m):</td>
<td>2186</td>
</tr>
<tr>
<td>Latitude:</td>
<td>65.8316 Deg.</td>
</tr>
<tr>
<td>Longitude:</td>
<td>002.0289 Deg.</td>
</tr>
<tr>
<td>Coordinate System:</td>
<td>WGS 84</td>
</tr>
<tr>
<td>Priority of Site:</td>
<td>Primary: ✓ Alternate: □</td>
</tr>
</tbody>
</table>
## Section C: Operational Information

<table>
<thead>
<tr>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>0</td>
</tr>
<tr>
<td>Total Sediment Thickness (m)</td>
<td>800</td>
</tr>
<tr>
<td>Total Penetration (m):</td>
<td>800</td>
</tr>
</tbody>
</table>

### General Lithologies:
- Paleogene shale and possibly sandstone
- 

### Coring Plan:
- (Specify or check)

#### Wireline Logging Plan:

<table>
<thead>
<tr>
<th>Standard Measurements</th>
<th>Special Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL</td>
<td>Magnetic Susceptibility</td>
</tr>
<tr>
<td>Porosity</td>
<td>Borehole Temperature</td>
</tr>
<tr>
<td>Density</td>
<td>Formation Image (Acoustic)</td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>VSP (walkway)</td>
</tr>
<tr>
<td>Resistivity</td>
<td>LWD</td>
</tr>
<tr>
<td>Sonic ((\Delta t))</td>
<td></td>
</tr>
<tr>
<td>Formation Image (Res)</td>
<td></td>
</tr>
<tr>
<td>VSP (zero offset)</td>
<td></td>
</tr>
<tr>
<td>Formation Temperature &amp; Pressure</td>
<td></td>
</tr>
</tbody>
</table>

- Other Measurements:

### Estimated Days:
- Drilling/Coring: 9.9
- Logging: 1.5
- Total On-site: 11.4

### Observatory Plan:
- Long term Borehole Observation Plan/Re-entry Plan

### Potential Hazards/Weather:
- Shallow Gas: Complicated Seabed Condition
- Hydrocarbon: Soft Seabed
- Shallow Water Flow: Currents
- Abnormal Pressure: Fracture Zone
- Man-made Objects (e.g., sea-floor cables, dump sites): Fault
- H\(_2\)S: High Dip Angle
- CO\(_2\): Ice Conditions

### Other:
- Preferred weather window
  - April-September

---

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## IODP Site Forms

### Form 5 - Lithologies

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 800</td>
<td>Top Paleocene</td>
<td>2 and above</td>
<td>-</td>
<td>Mud, shale and sandstones</td>
<td>Marine</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Proposal #: 944 - Add 2  
Site #: VMVM-55B  
Date Form Submitted: 2020-03-10 06:05:56
### Section A: Proposal Information

<table>
<thead>
<tr>
<th>Proposal Title</th>
<th>The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date Form Submitted</td>
<td>2020-03-10 06:05:56</td>
</tr>
<tr>
<td>Site-Specific Objectives with Priority (Must include general objectives in proposal)</td>
<td>The primary objective is to drill hole of 200 m to obtain an extended sedimentary sequence across the Paleocene-Eocene boundary for paleoclimate studies.</td>
</tr>
<tr>
<td>List Previous Drilling in Area</td>
<td></td>
</tr>
</tbody>
</table>

### Section B: General Site Information

<table>
<thead>
<tr>
<th>Site Name:</th>
<th>VMVM-56A</th>
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<tbody>
<tr>
<td>If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#:</td>
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<td>Latitude:</td>
<td>Deg: 65.8303</td>
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<tr>
<td>Longitude:</td>
<td>Deg: 001.9928</td>
</tr>
<tr>
<td>Coordinate System:</td>
<td>WGS 84</td>
</tr>
<tr>
<td>Priority of Site: Primary:</td>
<td>Alternate: ✓</td>
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<tr>
<td>Area or Location:</td>
<td>N Atlantic</td>
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<tr>
<td>Jurisdiction:</td>
<td>Norway</td>
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<tr>
<td>Distance to Land: (km)</td>
<td>450</td>
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<td>Water Depth (m):</td>
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Generated: 2020-03-11T23:00:23+00:00
### Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
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<tr>
<td>Total Sediment Thickness (m):</td>
<td>200</td>
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<tr>
<td>Total Penetration (m):</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

**General Lithologies:**
Paleogene shale and possibly sandstone

**Coring Plan:**
Initially XCB to TD and then RCB

**Wireline Logging Plan:**
- Standard Measurements: WL, Porosity, Density, Gamma Ray, Resistivity, Sonic (Δt), Formation Image (Res), VSP (zero offset), Formation Temperature & Pressure
- Special Tools: Magnetic Susceptibility, Borehole Temperature, Formation Image (Acoustic), VSP (walkaway), LWD
- Other Measurements:

**Estimated Days:**
- Drilling/Coring: 2
- Logging: 0.8
- Total On-site: 2.8

**Observatory Plan:**
Longterm Borehole Observation Plan/Re-entry Plan

**Potential Hazards/Weather:**
- Shallow Gas
- Hydrocarbon
- Shallow Water Flow
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H2S
- CO2

- Other Measurements:

- Other:

- Preferred weather window: April-September

*Generated: 2020-03-11T23:00:23+00:00*
<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 60</td>
<td>Top Paleocene</td>
<td>2 and above</td>
<td></td>
<td>Mud, shale</td>
<td>Deep marine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 - 200</td>
<td>Outgoing stratigraphy</td>
<td>40-60</td>
<td></td>
<td>Shale and sandstones</td>
<td>Marine</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Section A: Proposal Information

**Proposal Title**
The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

**Date Form Submitted**
2020-03-10 06:05:56

**Site-Specific Objectives with Priority (Must include general objectives in proposal)**
The primary objective is to sample basalt flows of the subaerial and faulted Landward Flow unit (Sequence 1) to obtain volcanic facies, geochemistry, and geochronology.

**List Previous Drilling in Area**
ODP 642

### Section B: General Site Information

<table>
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<th>Site Name: VMVM-61A</th>
<th>Area or Location: N Atlantic</th>
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<td>Jurisdiction: Norway</td>
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<tr>
<td>Latitude: Deg: 67.3069</td>
<td>Distance to Land: km 450</td>
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<td>Longitude: Deg: 003.7396</td>
<td>Water Depth (m): 1200</td>
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<td>Coordinate System: WGS 84</td>
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</table>
## Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
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<tbody>
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<td>115</td>
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</table>

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>Total Penetration (m):</td>
<td>240</td>
</tr>
</tbody>
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### General Lithologies:
- Neogene mud
- Basalt flows

### Coring Plan:
- **RCB drilling of the basaltic basement to TD of 240 mbsf or bit destruction**

### Wireline Logging Plan:
- **APC**
- **XCB**
- **RCB**
- **Re-entry**
- **PCS**

#### Standard Measurements
- WL
- Porosity
- Density
- Gamma Ray
- Resistivity
- Sonic (∆t)
- Formation Image
- Formation Image (Res)
- VSP (walkaway)
- VSP (zero offset)
- LWD
- Borehole Temperature
- Magnetic Susceptibility
- Formation Image (Acoustic)
- Other tools:

#### Other Measurements:

### Estimated Days:
- Drilling/Coring: 2.4
- Logging: 0.8
- Total On-site: 3.2

### Observatory Plan:
- **Longterm Borehole Observation Plan/Re-entry Plan**

### Potential Hazards/Weather:
- Shallow Gas: ✓
- Complicated Seabed Condition: ❌
- Hydrothermal Activity: ❌
- Hydrocarbon: ✓
- Soft Seabed: ❌
- Landslide and Turbidity: ❌
- Shallow Water Flow: ✓
- Currents: ❌
- Gas Hydrate: ✓
- Abnormal Pressure: ❌
- Fracture Zone: ❌
- Diapir and Mud Volcano: ❌
- Man-made Objects (e.g., sea-floor cables, dump sites): ❌
- Fault: ❌
- High Temperature: ❌
- H₂S: ❌
- High Dip Angle: ❌
- Ice Conditions: ❌
- CO₂: ❌
- Sensitive marine habitat (e.g., reefs, vents): ❌

### Other:

**Preferred weather window**: April-September
<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
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<tbody>
<tr>
<td>0 - 125</td>
<td>Top Basalt</td>
<td>0 to 50</td>
<td></td>
<td>Mud and mudstone</td>
<td>Marine</td>
<td></td>
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<tr>
<td>125 - 200</td>
<td>Top Basalt</td>
<td>55</td>
<td>3500</td>
<td>Basalt flows</td>
<td>Subaerial</td>
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Proposal #: 944 - Add 2
Site #: VMVM-61A
Date Form Submitted: 2020-03-10 06:05:56
IODP Site Forms

Form 1 – General Site Information

Section A: Proposal Information

Proposal Title: The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

Date Form Submitted: 2020-03-10 06:05:56

Site-Specific Objectives with Priority (Must include general objectives in proposal):
The primary objective is to sample basalt flows of the subaerial and faulted Landward Flow unit (Sequence 1) to obtain volcanic facies, geochemistry, and geochronology.

List Previous Drilling in Area: ODP 642

Section B: General Site Information

Site Name: VMVM-62A

Latitude: 67.2893 Deg.

Longitude: 003.6779 Deg.

Coordinate System: WGS 84

Priority of Site: Alternate: ✓

Area or Location: N Atlantic

Jurisdiction: Norway

Distance to Land: 450 km

Water Depth (m): 1198

Generated: 2020-03-11T23:00:23+00:00
### Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>115</th>
<th>115</th>
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</thead>
<tbody>
<tr>
<td>Total Sediment Thickness (m)</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>Total Penetration (m):</td>
<td>230</td>
<td></td>
</tr>
</tbody>
</table>

**General Lithologies:** Neogene mud

**Coring Plan:** RCB drilling of the basaltic basement to TD of 230 mbsf or bit destruction

**Wireline Logging Plan:**
- Standard Measurements: WL, Porosity, Density, Gamma Ray, Resistivity, Sonic (∆t), Formation Image (Res), VSP (zero offset), Formation Temperature & Pressure
- Special Tools: Magnetic Susceptibility, Borehole Temperature, Formation Image (Acoustic), VSP (walkway), LWD

**Coring Plan:**
- APC
- XCB
- RCB ✓
- Re-entry
- PCS

**Estimated Days:**
- Drilling/Coring: 2.4
- Logging: 0.8
- Total On-site: 3.2

**Observatory Plan:** Longterm Borehole Observation Plan/Re-entry Plan

**Potential Hazards/Weather:**
- Shallow Gas ✓
- Hydrocarbon ✓
- Shallow Water Flow ✓
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H₂S
- CO₂
- Complicated Seabed Condition ✓
- Soft Seabed ✓
- Currents
- Gas Hydrate ✓
- Fault
- High Dip Angle
- High Temperature
- Ice Conditions
- Hydrothermal Activity
- Landslide and Turbidity Current
- Diapir and Mud Volcano
- Fault
- High Temperature
- Ice Conditions

**Preferred weather window:** April-September

**Other:**
<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 115</td>
<td>Top Basalt</td>
<td>0-50</td>
<td></td>
<td>Mud and mudstone</td>
<td>Marine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>115 - 230</td>
<td>Top Basalt</td>
<td>55</td>
<td>3500</td>
<td>Basalt flows</td>
<td>Subaerial</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## IODP Site Forms

### Form 1 – General Site Information

**Section A: Proposal Information**

<table>
<thead>
<tr>
<th>Proposal Title</th>
<th>The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup</th>
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</thead>
<tbody>
<tr>
<td>Date Form Submitted</td>
<td>2020-03-10 06:05:56</td>
</tr>
<tr>
<td>Site-Specific Objectives with Priority</td>
<td>The primary objective of the site is to sample basalt flows in the uppermost part of the SDR (Sequence 2) with a pitted surface (likely sub-acqueous), and if possible, reach the Sequence 1 - Sequence 2 boundary, for facies, geochemistry, and geochronology.</td>
</tr>
<tr>
<td>List Previous Drilling in Area</td>
<td>ODP 642</td>
</tr>
</tbody>
</table>

**Section B: General Site Information**

<table>
<thead>
<tr>
<th>Site Name</th>
<th>VMVM-07A</th>
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</thead>
<tbody>
<tr>
<td>If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#</td>
<td></td>
</tr>
<tr>
<td>Latitude:</td>
<td>67.3310 Deg:</td>
</tr>
<tr>
<td>Longitude:</td>
<td>03.6215 Deg:</td>
</tr>
<tr>
<td>Coordinate System:</td>
<td>WGS 84</td>
</tr>
<tr>
<td>Priority of Site:</td>
<td>Primary: ✓ Alternate:</td>
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<tr>
<td>Area or Location:</td>
<td>N Atlantic</td>
</tr>
<tr>
<td>Jurisdiction:</td>
<td>Norway</td>
</tr>
<tr>
<td>Distance to Land: (km)</td>
<td>450</td>
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<tr>
<td>Water Depth (m):</td>
<td>1206</td>
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### Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>220</td>
<td>100</td>
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<tr>
<td>Total Sediment Thickness (m):</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>Total Penetration (m):</td>
<td>320</td>
<td></td>
</tr>
</tbody>
</table>

**General Lithologies:**
- Neogene and Paleogene mud and mudstones
- Subaqueous basalt flows.

**Coring Plan:**
(APC/XCB of shallow sediments to 220 m; RCB to 320 m or bit destruction.)

**Wireline Logging Plan:**
- Standard Measurements: WL, Porosity, Density, Gamma Ray, Resistivity, Sonic (Δt), Formation Image (Res), VSP (zero offset), Formation Temperature & Pressure
- Special Tools: Magnetic Susceptibility, Borehole Temperature, Formation Image (Acoustic), VSP (walkaway), LWD
- Other Tools:
- Other Measurements:

**Estimated Days:**
- Drilling/Coring: 3
- Logging: 0.9
- Total On-site: 3.9

**Observatory Plan:**
(Generate Longterm Borehole Observation Plan/Re-entry Plan)

**Potential Hazards/Weather:**
- Shallow Gas
- Hydrocarbon
- Shallow Water Flow
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H2S
- CO2
- Sensitive marine habitat (e.g., reef, vents)

- Complicated Seabed Condition
- Soft Seabed
- Currents
- Fracture Zone
- Fault
- High Dip Angle
- Ice Conditions

- Hydrothermal Activity
- Landslide and Turbidity
- Gas Hydrate
- High Temperature

- Other:

**Preferred weather window:**
April to September

**Section C: Operational Information**

<table>
<thead>
<tr>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>100</td>
</tr>
<tr>
<td>220</td>
<td></td>
</tr>
<tr>
<td>320</td>
<td></td>
</tr>
</tbody>
</table>

**APC**
- Coring Plan:
  (Specify or check)

**Tools:**

**Other Measurements:**

**Other:**

**Generated:** 2020-03-11T23:00:23+00:00
<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 220</td>
<td>Top basalt</td>
<td>0 to 50</td>
<td>2000</td>
<td>Mud and mudstone</td>
<td>Marine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>220 - 320</td>
<td>Top basalt</td>
<td>55</td>
<td>3500</td>
<td>Basalt flows</td>
<td>Subaerial</td>
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</table>
# IODP Site Forms

## Form 1 – General Site Information

### Section A: Proposal Information

<table>
<thead>
<tr>
<th>Proposal Title</th>
<th>The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date Form Submitted</td>
<td>2020-03-10 06:05:56</td>
</tr>
<tr>
<td>Site-Specific Objectives with Priority (Must include general objectives in proposal)</td>
<td>The primary objective of the site is to sample basalt flows in the uppermost part of the SDR (Sequence 2) with a pitted surface (likely sub-acqueous), and if possible, reach the Sequence 1 - Sequence 2 boundary, for facies, geochemistry, and geochronology.</td>
</tr>
<tr>
<td>List Previous Drilling in Area</td>
<td>ODP 642</td>
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### Section B: General Site Information

<table>
<thead>
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<th>Site Name:</th>
<th>VMVM-71A</th>
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<td>Latitude:</td>
<td>Deg: 67.3386</td>
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<td>Longitude:</td>
<td>Deg: 003.6967</td>
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<td>Coordinate System:</td>
<td>WGS 84</td>
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<tr>
<td>Priority of Site:</td>
<td>Primary:</td>
</tr>
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<td>Area or Location:</td>
<td>N Atlantic</td>
</tr>
<tr>
<td>Jurisdiction:</td>
<td>Norway</td>
</tr>
<tr>
<td>Distance to Land: (km)</td>
<td>450</td>
</tr>
<tr>
<td>Water Depth (m):</td>
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## Section C: Operational Information

### Sediments and Basement

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>195</th>
<th>105</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Sediment Thickness (m):</td>
<td>195</td>
<td></td>
</tr>
</tbody>
</table>

Total Penetration (m): 300

### General Lithologies:
- Neogene and Paleogene mud and mudstones
- Subaqueous basalt flows.

### Coring Plan:
- APC/XCB of shallow sediments to 195 m: RCB to 300 m or bit destruction

### Wireline Logging Plan:
- Standard Measurements
  - WL
  - Porosity
  - Density
  - Gamma Ray
  - Resistivity
  - Sonic (Δt)
  - Formation Image (Res)
  - Formation Temperature & Pressure
- Special Tools
  - Magnetic Susceptibility
  - Borehole Temperature
  - Formation Image (Acoustic)
  - VSP (walkaway)
  - LWD
- Other Measurements:

### Estimated Days:
- Drilling/Coring: 3
- Logging: 0.9
- Total On-site: 3.9

### Observatory Plan:
- Longterm Borehole Observation Plan/Re-entry Plan

### Potential Hazards/Weather:
- Shallow Gas
- Hydrocarbon
- Shallow Water Flow
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H2S
- CO2
- Sensitive marine habitat (e.g., reef, vent)
- Complicated Seabed Condition
- Soft Seabed
- Currents
- Fracture Zone
- Fault
- High Temperature
- Ice Conditions
- Complications and Seabed Condition
- Landslide and Turbidity Current
- Gas Hydrate
- High Temperature
- Ice Conditions

Prefered weather window: April-September

### Coring Plan:
- APC ✓
- XCB ✓
- RCB ✓
- Re-entry ❌
- PCS ❌

### Other Measurements:

---

Generated: 2020-03-11T23:00:23+00:00
## IODP Site Forms
### Form 5 - Lithologies

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 195</td>
<td>Top Basalt</td>
<td>0 to 50</td>
<td>2000</td>
<td>Mud and mudstone</td>
<td>Marine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>195 - 300</td>
<td>Top Basalt</td>
<td>55</td>
<td>3500</td>
<td>Basalt flows</td>
<td>Subaerial</td>
<td></td>
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</tr>
</tbody>
</table>
IODP Site Forms
Form 1 – General Site Information

Section A: Proposal Information

Proposal Title

The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

Date Form Submitted

2020-03-10 06:55:56

Site-Specific Objectives with Priority

The primary objective is to sample volcaniclastic sediments and possibly basalt of the Outer High, to determine volcanic facies and age.

List Previous Drilling in Area

DSDP 343

Section B: General Site Information

Site Name:

VMVM-80A

If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#: 

Area or Location:

N Atlantic

Jurisdiction:

Norway

Latitude:

68.6004

Longitude:

004.6428

Coordinate System:

WGS 84

Distance to Land:

450

Water Depth (m):

2864

Priority of Site:

Primary: ✓ Alternate: 

Generated: 2020-03-11T23:00:23+00:00
**Section C: Operational Information**

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<thead>
<tr>
<th>Sediments</th>
<th>Basement</th>
</tr>
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<tbody>
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<td>Proposed Penetration (m):</td>
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<tr>
<td>Total Sediment Thickness (m):</td>
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<tr>
<td>Total Penetration (m):</td>
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</table>

<table>
<thead>
<tr>
<th>General Lithologies:</th>
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</thead>
<tbody>
<tr>
<td>Neogene mud and Paleogene volcanogenic sediments</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Coring Plan: (Specify or check)</th>
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<tbody>
<tr>
<td>RCB to 210 m or bit destruction</td>
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</table>

<table>
<thead>
<tr>
<th>Wireline Logging Plan:</th>
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</thead>
<tbody>
<tr>
<td>APC</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Standard Measurements</th>
<th>Special Tools</th>
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<tbody>
<tr>
<td>WL</td>
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<tr>
<td>Porosity</td>
<td></td>
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<tr>
<td>Density</td>
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<td>Gamma Ray</td>
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<td>Resistivity</td>
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<td>Sonic (Δt)</td>
<td></td>
</tr>
<tr>
<td>Formation Image (Res)</td>
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<td>VSP (zero offset)</td>
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<td>Formation Temperature &amp; Pressure</td>
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<thead>
<tr>
<th>Other Measurements:</th>
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<table>
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<tr>
<th>Estimated Days:</th>
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<tr>
<td>Drilling/Coring: 3.5</td>
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<table>
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<tr>
<th>Observatory Plan:</th>
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<tbody>
<tr>
<td>Longterm Borehole Observation Plan/Re-entry Plan</td>
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</table>

<table>
<thead>
<tr>
<th>Potential Hazards/Weather:</th>
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<tbody>
<tr>
<td>Shallow Gas</td>
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<tr>
<td>Hydrocarbon</td>
</tr>
<tr>
<td>Shallow Water Flow</td>
</tr>
<tr>
<td>Abnormal Pressure</td>
</tr>
<tr>
<td>Man-made Objects (e.g., sea-floor cables, dump sites)</td>
</tr>
<tr>
<td>H₂S</td>
</tr>
<tr>
<td>CO₂</td>
</tr>
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</table>

| Sensitive marine habitat (e.g., reefs, vents) |

| Other: |

<table>
<thead>
<tr>
<th>Preferred weather window</th>
</tr>
</thead>
<tbody>
<tr>
<td>April-September</td>
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</tbody>
</table>

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<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 210</td>
<td>Top Basalt</td>
<td>0-50</td>
<td>2000</td>
<td>Mud and mudstone</td>
<td>Marine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>210 - 310</td>
<td>Top Basalt</td>
<td>53</td>
<td>3000</td>
<td>Volcanic sediments</td>
<td>Shallow marine</td>
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</table>
IODP Site Forms
Form 1 – General Site Information

Section A: Proposal Information

Proposal Title: The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

Date Form Submitted: 2020-03-10 06:55:56

Site-Specific Objectives with Priority (Must include general objectives in proposal):
The primary objective is to sample volcaniclastic sediments and possibly basalt of the Outer High, to determine volcanic facies and age.

List Previous Drilling in Area:
DSDP 343

Section B: General Site Information

Site Name: VMVM-81A

If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#:

Latitude: 68.6266

Longitude: 004.5848

Coordinate System: WGS 84

Priority of Site:

Area or Location: N Atlantic

Jurisdiction: Norway

Distance to Land: 450 (km)

Water Depth (m): 2913

Generated: 2020-03-11T23:00:23+00:00
### Section C: Operational Information

**Proposed Penetration (m):**
- Sediments: 55
- Basement: 145
- Total Sediment Thickness (m): 55
- Total Penetration (m): 200

**General Lithologies:**
- Neogene mud and Paleogene volcanogenic sediments

**Coring Plan:**
- RCB to 55 m or bit destruction
- APC: ✓
- XCB: ✓
- RCB: ✓
- Re-entry: ✓
- PCS: ✓

**Wireline Logging Plan:**
- Standard Measurements:
  - WL
  - Porosity
  - Density
  - Gamma Ray
  - Resistivity
  - Sonic (Δt)
  - Formation Image (Res)
  - Formation Temperature & Pressure
  - VSP (zero offset)
- Special Tools:
  - Magnetic Susceptibility
  - Borehole Temperature
  - Formation Image (Acoustic)
  - VSP (walkaway)
  - LWD
  - Other tools:

**Estimated Days:**
- Drilling/Coring: 3.5
- Logging: 0.9
- Total On-site: 4.4

**Observatory Plan:**
- Longterm Borehole Observation Plan / Re-entry Plan

**Potential Hazards/Weather:**
- Shallow Gas
- Complicated Seabed Condition
- Hydrothermal Activity
- Hydrocarbon
- Soft Seabed
- Landslide and Turbidity Current
- Shallow Water Flow
- Currents
- Gas Hydrate
- Abnormal Pressure
- Fracture Zone
- Diapir and Mud Volcano
- Man-made Objects (e.g., sea-floor cables, dump sites)
- Fault
- High Temperature
- H₂S
- High Dip Angle
- Ice Conditions
- CO₂
- Sensitive marine habitat (e.g., reefs, vents)

**Preferred weather window:**
- April-September

**Other:**

---

Generated: 2020-03-11T23:00:23+00:00
<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accumulation rate (m/My)</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>0 - 55</td>
<td>Top Basalt</td>
<td>0-50</td>
<td>2000</td>
<td>Mud and mudstone</td>
<td>Marine</td>
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<tr>
<td>55 - 200</td>
<td>Top Basalt</td>
<td>53</td>
<td>3000</td>
<td>Volcanogenic sediments</td>
<td>Shallow marine</td>
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**Section A: Proposal Information**

<table>
<thead>
<tr>
<th>Proposal Title</th>
<th>The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date Form Submitted</td>
<td>2020-03-10 06:05:56</td>
</tr>
<tr>
<td>Site-Specific Objectives with Priority</td>
<td>The primary objective is to sample basalt in old oceanic crust associated with the Outer SDR for volcanic facies, geochemistry and geochronology</td>
</tr>
<tr>
<td>List Previous Drilling in Area</td>
<td>DSDP 343</td>
</tr>
</tbody>
</table>

**Section B: General Site Information**

| Site Name: | VMVM-09A |
| Area or Location: | N Atlantic |
| Jurisdiction: | Norway |
| Latitude: | 68.7605 Deg |
| Longitude: | 05.7971 Deg |
| Coordinate System: | WGS 84 |
| Distance to Land: | 450 km |
| Water Depth (m): | 3156 |

The primary objective is to sample basalt in old oceanic crust associated with the Outer SDR for volcanic facies, geochemistry and geochronology.
### Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>450</td>
<td>100</td>
</tr>
<tr>
<td>Total Sediment Thickness (m):</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>Total Penetration (m):</td>
<td>550</td>
<td></td>
</tr>
</tbody>
</table>

#### General Lithologies:
- Neogene to Eocene mud and mudstone
- Oceanicc basalt

#### Coring Plan:
- APC/XCB to top basement, second hole with RCB to TD or bit destruction

#### Wireline Logging Plan:
<table>
<thead>
<tr>
<th>Standard Measurements</th>
<th>Special Tools</th>
<th>Other Tools:</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL</td>
<td>Magnetic Susceptibility</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>Borehole Temperature</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>Formation Image (Acoustic)</td>
<td></td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>VSP (walkaway)</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>LWD</td>
<td></td>
</tr>
<tr>
<td>Sonic (Δt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation Image (Res)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VSP (zero offset)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation Temperature &amp; Pressure</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Estimated Days:
- Drilling/Coring: 5.6
- Logging: 1.2
- Total On-site: 6.8

#### Observatory Plan:
- Longterm Borehole Observation Plan/Re-entry Plan

#### Potential Hazards/Weather:
- Shallow Gas
- Complicated Seabed Condition
- Hydrothermal Activity
- Preferred weather window
- Hydrocarbon
- Soft Seabed
- Landslide and Turbidity Current
- Shallow Water Flow
- Currents
- Gas Hydrate
- Abnormal Pressure
- Fracture Zone
- Diapir and Mud Volcano
- Man-made Objects (e.g., sea-floor cables, dump sites)
- Fault
- High Temperature
- H₂S
- High Dip Angle
- Ice Conditions
- CO₂
- Sensitive marine habitat (e.g., reef, vent)

#### Other:
<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, unconformities, faults, etc</th>
<th>Age (My)</th>
<th>Assumed velocity (km/s)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. accum. rate (m/My)</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>0 - 450</td>
<td>Top basalt</td>
<td>0 to 50</td>
<td>2000</td>
<td>Mud and mudstone</td>
<td>Deep marine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>450 - 550</td>
<td>Top basalt</td>
<td>50</td>
<td>3000</td>
<td>Basalt flows</td>
<td>Deep marine</td>
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Section A: Proposal Information

Proposal Title: The Nature, Cause and Climate Implications of Excess Magmatism During the Northeast Atlantic Continental Breakup

Date Form Submitted: 2020-03-10 06:55:56

Site-Specific Objectives with Priority (Must include general objectives in proposal):

Alternate site for VMVM-9A. The key objective of the site is to sample old basalt associated with initial age.

List Previous Drilling in Area:

DSDP 343

Section B: General Site Information

Site Name: VMVM-10B

If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#

Latitude: 68.8306

Longitude: 004.1306

Coordinate System: WGS 84

Priority of Site: Alternate: ✓

Area or Location: N Atlantic

Jurisdiction: Norway

Distance to Land: 450 (km)

Water Depth (m): 3237

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### Section C: Operational Information

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</tr>
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<tr>
<td></td>
<td>CO²</td>
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| Other: | |

Preferred weather window: April-September
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