IODP Proposal Cover Sheet

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Reykjanes Mantle Convection

Received for: 2017-04-03

Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
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Keywords	Mantle heterogeneity, climate, hydrothermal alteration
Area	Iceland Basin

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Abstract

The intersection between the Mid-Atlantic Ridge and Iceland hotspot provides us with a natural laboratory where the composition and dynamics of Earth's upper mantle can be observed. Plume-ridge interaction drives variations in the melting regime, resulting in a range of crustal types including a series of V-shaped ridges and troughs south of Iceland. Time-dependent mantle upwelling beneath Iceland dynamically supports regional bathymetry, leading to changes in the height of oceanic gateways which control the strength of deep-water flow over geologic timescales. We propose a drilling program that contains three objectives: (1) to test contrasting hypotheses for the formation of V-shaped ridges; (2) to understand temporal changes in ocean circulation, and explore connections with plume activity; (3) to reconstruct the evolving chemistry of hydrothermal fluids with increasing crustal age, varying sediment thickness and crustal architecture. This drilling program will recover basaltic samples from crust that is blanketed by thick sediments and is thus inaccessible with dredging. Major, trace and isotope geochemistry of basalts will allow us to observe spatial and temporal variations in mantle melting processes. We will test the hypothesis that the Iceland plume thermally pulses on two timescales (5-10 Ma, and ~30 Ma), leading to fundamental changes in crustal architecture. This idea will be tested against alternative hypotheses involving propagating rifts and buoyant mantle upwelling. Millennial-scale paleoclimate records are contained within rapidly accumulated sediments of contourite drifts in this region. The accumulation rate of these sediments is a proxy for current strength, which is moderated by dynamic support of oceanic gateways such as the Greenland-Scotland Ridge. These sediments also provide constraints for climatic events including Pliocene warmth, the onset of Northern Hemisphere Glaciation and abrupt Late Pleistocene climate change. Our combined approach will explore relationships between deep Earth processes, ocean circulation and climate. Our objectives can only be addressed by recovering sedimentary and basaltic cores, and we plan to penetrate 200 m into igneous basement at five sites east of Reykjanes Ridge. Four sites intersect V-shaped ridges/troughs pairs, one of which coincides with Bjorn Drift. A fifth site is located over 32.4 Ma oceanic crust devoid of V-shaped features, chosen to intersect Oligo-Miocene sediments of Gardar Drift. Sediments and basalts recovered during this program will provide a major advance in our understanding of mantle dynamics, and of the coupled nature of Earth's deep and surfical domains.

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Scientific Objectives

Objective 1: Crustal Accretion and Mantle Plume Behavior
We will use the composition of drilled basalts to understand crustal formation south of Iceland at two temporal scales. On 5-10 Ma timescales we will test three hypotheses for V-shaped ridge formation: 1) thermal pulsing; 2) propagating rifts; and 3) buoyant mantle upwelling. These models predict differing depths, temperatures and degrees of melting between V-shaped ridges and troughs, expected to be reflected in basalt composition. On 30-40 Ma timescales, we aim to test the controls on crustal architecture by comparing basalts from smooth and fractured seafloor types, which are thought to arise from different melting regimes relating to plume activity.

Objective 2: Ocean Circulation and Sedimentation
We plan to quantify how oceanic circulation in the North Atlantic Ocean has varied since Oligocene times. These observations will allow us to test the hypothesis that deep-water flow in the North Atlantic Ocean has been moderated by transient activity of the Iceland mantle plume. This program will extend the high-resolution climate record into late Pliocene times. Thus, we aim to evaluate both the millennial- and million-year scale variability in Neogene climate during important intervals when temperatures were warmer than today.

Objective 3: Time-Dependent Hydrothermal Alteration of Oceanic Crust
We will investigate the nature, extent, timing and duration of hydrothermal alteration within the upper Reykjanes Ridge flank. Drilling will enable us to quantify the timing and extent of hydrothermal fluid-rock exchange, to assess the hydrothermal contributions from a rapidly sedimented slow-spreading ridge flank to global geochemical budgets.

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

None

Proposed Sites (Total proposed sites: 12; pri: 5; alt: 7; N/S: 0)

Site Name	Position (Lat, Lon)	Water Depth (m)	Penetration (m)			Brief Site-specific Objectives
			Sed	Bsm	Total	
REYK-13A (Primary)	60.2281 -28.5004	1520	210	200	410	Sample ~200 m of basalt at V-shaped trough 1. Primary site.
REYK-11A (Primary)	60.2000 -28.0000	1415	340	200	540	Sample ~200 m of basalt at V-shaped ridge 2a. Primary site.
REYK-6A (Primary)	60.1251 -26.7016	1871	705	200	905	Obtain continuous stratigraphic section through Bjorn Drift, then sample ~200 m of basaltic crust at V-shaped trough 2b. Primary site.
REYK-4A (Primary)	60.0992 -26.4436	2110	185	200	385	Sample ~200 m of basalt at V-shaped ridge 3. Primary site.
REYK-2A (Primary)	59.8506 -23.2664	2206	970	200	1170	Obtain continuous stratigraphic section through Gardar Drift, then sample ~200 m of basaltic rocks from the rough crustal domain. Primary site.
REYK-7A (Alternate)	60.1507 -27.1698	1735	330	200	530	Sample ~200 m of basalt at V-shaped ridge 2b. Alternate site.
REYK-9A (Alternate)	60.1702 -27.5310	1701	310	200	510	Sample ~200 m of basalt at V-shaped trough 2a. Alternate site.
REYK-1A (Alternate)	59.8496 -23.2473	2209	955	200	1155	Obtain continuous stratigraphic section through Gardar Drift, then sample ~200 m of basaltic rocks from the fractured crustal domain. Alternate site.
REYK-3A (Alternate)	60.0989 -26.4404	2110	205	200	405	Sample ~200 m of basalt at V-shaped ridge 3. Alternate site.
REYK-5A (Alternate)	60.1264 -26.7516	1894	675	200	875	Obtain continuous stratigraphic section through Bjorn Drift, then sample ~200 m of basaltic crust at V-shaped trough 2b. Alternate site.
REYK-8A (Alternate)	60.1491 -27.1370	1695	320	200	520	Sample ~200 m of basalt at V-shaped ridge 2b. Alternate site.
REYK-10A (Alternate)	60.1667 -27.4726	1689	155	200	355	Sample ~200 m of basalt at V-shaped trough 2a. Alternate site.

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Gabriele	Uenzelmann-Neben	Alfred Wegener Institute	Germany	Other Proponent	Geophysics

1 Introduction

This proposal builds upon Proposal 646-Full, which received positive feedback from the Science Steering and Evaluation Panels[1]. P646-Full was deactivated in 2007 pending acquisition of site survey data. Following site survey cruises in 2008 and 2010, we have developed this new proposal, which has been revised following encouraging input from SEP in 2016.

The convective behavior of plumes within Earth's mantle has long been the subject of debate[2–4]. The composition, temperature and dynamics of mantle plumes provide key constraints on the energy and chemical budgets of Earth's deep interior[5,6]. Plume material rises beneath the lithospheric plates and is deflected laterally, advecting thermal and compositional plume signals away from the upwelling stem. Buoyant upwelling material associated with mantle plumes is also thought to drive vertical motions at Earth's surface, called dynamic topography[7–10]. The time-dependent pattern of mantle convection beneath the lithospheric plates causes changes in the configuration of oceanic and terrestrial topography, which develops over geologic timescales of 1–100 Ma and influences broad areas spanning hundreds to thousands of kilometers[11]. The resulting changes in the bathymetric configuration of the oceans may have important consequences for the opening of oceanic gateways and for deep-water circulation[12,13].

The Rayleigh number of the mantle is 10^6–10^8, meaning that mantle convection is expected to be vigorous and transient on geologic timescales[14,15]. The global network mid-ocean ridge network provides a window into mantle convection[16], since the accretion of new oceanic crust records small fluctuations in underlying mantle properties. Where mid-ocean ridges intersect mantle plumes, V-shaped patterns in the oceanic crust have been suggested to reflect plume pulsing on 5–10 Ma timescales, such as along the Reykjanes and Kolbeinsey Ridges near Iceland, and the Mid-Atlantic Ridge near the Azores[17–19]. At non-ridge centered plumes such as Hawaii, variations in melt production along the Hawaii-Emperor Seamount Chain have also been interpreted to represent pulsing at a 5 million-year frequency[20,21]. Hence there is observational and theoretical evidence to suggest that pulsing behavior is a general property of mantle plumes.

In the North Atlantic Ocean, the obliquely spreading Reykjanes Ridge bisects the Iceland plume[22–25] (Figures 1 and 2), while the residual topographic anomaly associated with the Iceland plume extends over ∼1200 km[18,26–28] (Figure 1). An obvious sign of time-dependent plume behavior is the set of diachronous V-shaped ridges (VSRs) and troughs (VSTs) which straddle the Reykjanes Ridge, clearly resolved by the free-air gravity field (Figure 2b). *Vogt* (1971) first suggested that the VSRs reflect variations in crustal thickness[17], caused by pulses of hotter asthenosphere advecting horizontally away from the Iceland plume which episodically increase the thickness of crust formed at the axis. Since Vogt's early insight, the origin of the VSRs has been debated. Geodynamical models, geochemical sampling and geophysical imaging have led to the widely held view that the diachronous VSRs are caused by melting anomalies that propagate within the asthenosphere[18,28–34].

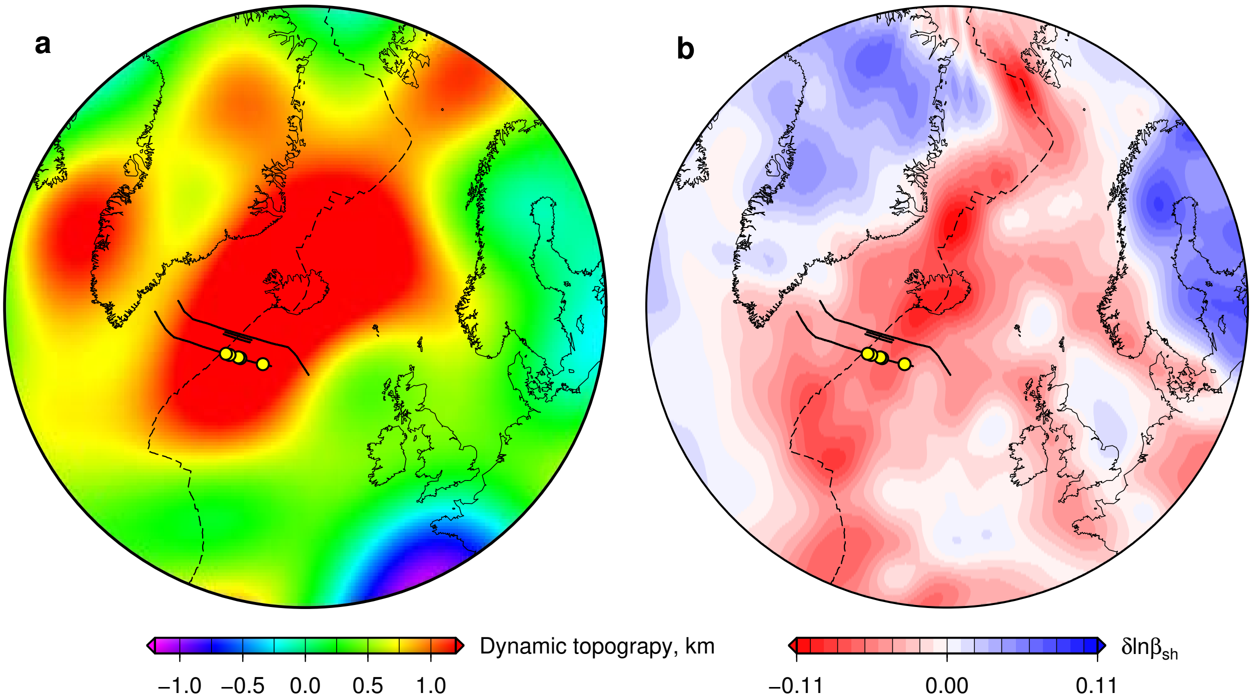

Figure 1: Plume-ridge interaction in the North Atlantic Ocean. a) Dynamic topography[35], showing plume swell centered on Iceland. Yellow circles are drilling sites; dashed line shows Mid-Atlantic Ridge. b) Horizontally-polarized S-wave velocity (β_{sh}) from full-waveform tomographic model at 120 km depth[27].

1.1 Crustal Geochemistry

The accretion of oceanic crust is sensitive to small temperature perturbations, which can change the thickness of newly formed material by hundreds of meters to kilometers[30]. The basalt trace element ratio, Nb/Y, is largely insensitive to crustal processes such as fractional crystallization, and reflects the depth and degree of melting (Figure 3). A southward decrease of Nb/Y between 63°N and 61°N on the Reykjanes Ridge correlates with deepening of the axis[37,42], with a decrease in crustal thickness but also with decreasing source enrichment estimated by isotopic indicators such as $^{87}Sr/^{86}Sr$.

Two complete cycles of variation in incompatible trace element ratios can be observed along axis[28] (Figure 3), which correlate with patterns in gravity anomaly, bathymetry and earthquake seismicity[28,43]. Compositional variations associated with VSRs cannot be explained by fractional

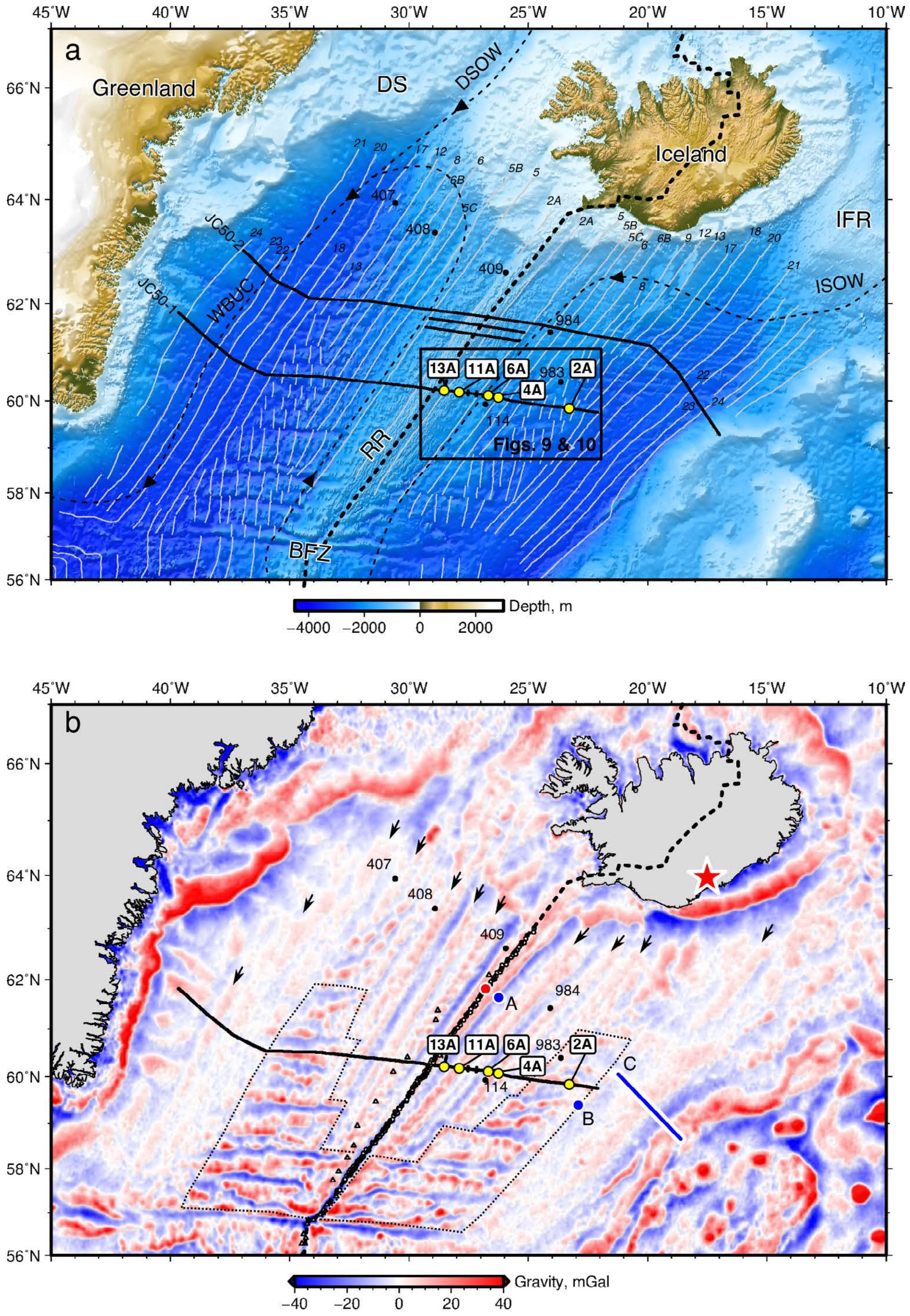

Figure 2: a) Bathymetry of North Atlantic Ocean showing location of proposed drilling sites and major deep-water pathways. Box shows location of Figure 10; yellow circles are drilling sites; numbered black circles are existing ODP/DSDP boreholes; labeled black lines are seismic reflection profiles; bold dashed black line is Mid-Atlantic Ridge; labelled gray lines are magnetic polarity chrons[18]; thin dotted lines with arrows are deep-water currents; WBUC is Western Boundary Under Current; DSOW is Denmark Strait Overflow Water; ISOW is Iceland-Scotland Overflow Water; DS is Denmark Strait; IFR is Iceland-Faroe Ridge; RR is Reykjanes Ridge; BFZ is Bight Fracture Zone. b) Satellite free-air gravity anomaly map[36], filtered to remove wavelengths greater than 250 km. Open circles/triangles along ridge axis show dredged basalt samples[28,37]; red star shows Iceland plume center[38]; arrows are VSRs; dotted polygons show transition from smooth to rough ocean floor; red/blue circles and line at A, B and C are crustal thickness measurements[39–41].

crystallization alone, since a corresponding variation in Mg number is absent (Figure 3c)[28]. Since enrichment in incompatible trace elements is inversely correlated with crustal thickness over the past 12 Ma, mantle temperature variation is thought to play an important role in controlling crustal thickness, in addition to changes in mantle source fusibility.

Although fluid dynamical models predict that periodic instabilities within the plume's stem are likely to trigger temperature fluctuations[3,31,44], two alternative hypotheses for VSR formation have been put forward. One idea is that the VSRs may be tectonic in origin, without a requirement

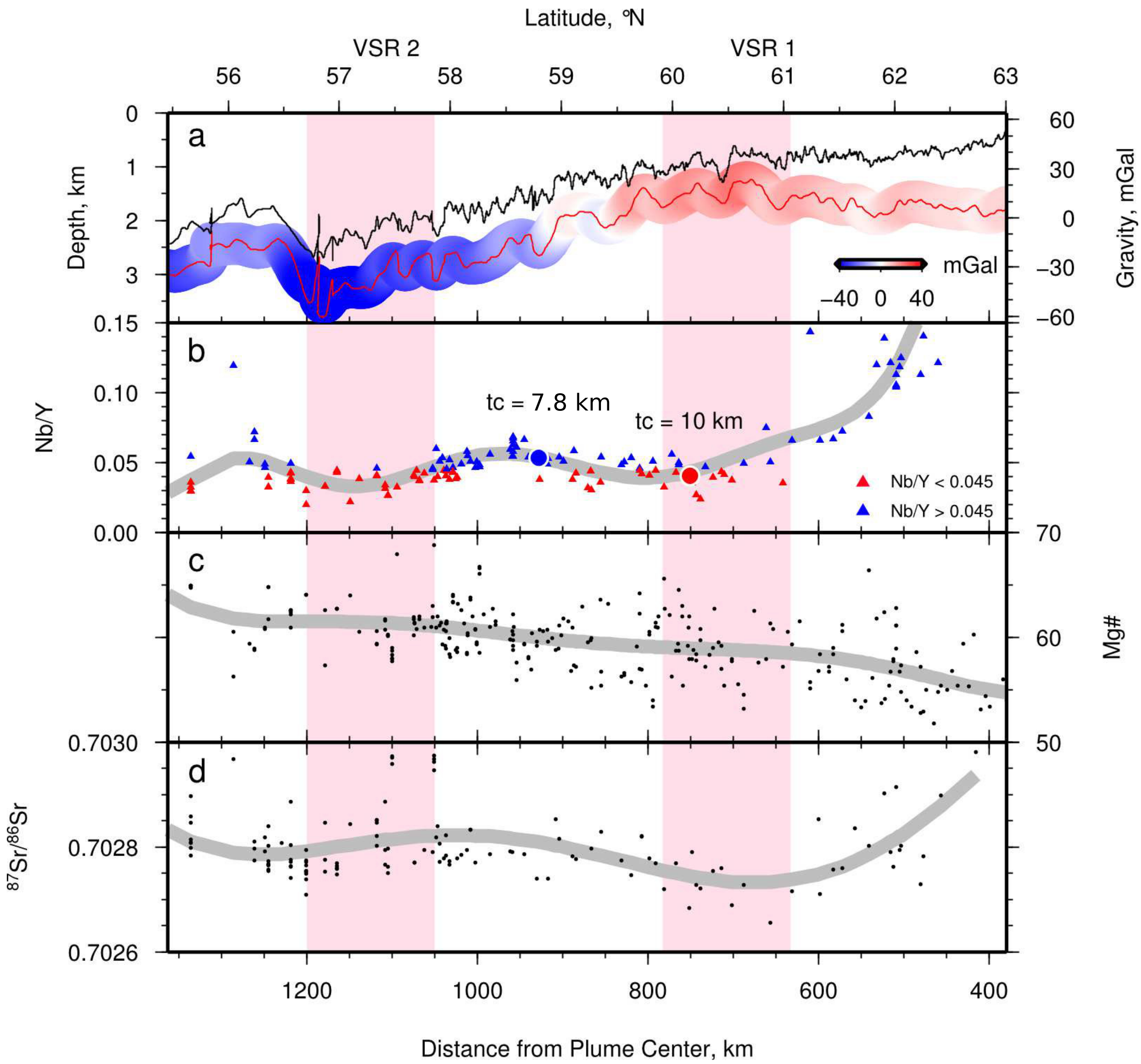

Figure 3: Geochemical data from dredged basalts along Reykjanes Ridge from 55° to 63°N[28,37]. Pink bands delineate regions where VSRs intersect ridge, width of VSR 1. (a) Black line is bathymetry; red/blue shaded line shows short wavelength gravity anomaly. (b) Nb/Y. Red/blue triangles colored by Nb/Y; gray curve is best fitting polynomial; red/blue circles show projected location of crustal thickness measurements[39]. (c) Mg#. (d) $^{87}Sr/^{86}Sr$.

for melt anomalies[45–48]. In this scenario, a sequence of propagating rifts and transform faults have led to asymmetric accretion at the ridge axis, explaining formation of VSRs and VSTs, thought to represent pseudofault scarps. A second hypothesis, where shallow buoyant mantle upwelling instabilities propagate along axis to form the observed crustal structure has been recently suggested, avoiding the requirement for rapid mantle plume flow[49]. Here, we propose to test these ideas for the origins of the VSRs, and explore the relationships between mantle convection, plate tectonics, and climate.

2 Scientific Objectives

Objective 1: Crustal Accretion and Mantle Plume Behavior

We will use the composition of basaltic samples to understand crustal formation south of Iceland at two temporal scales. First, on ∼5–10 Ma timescales we seek to test three alternative hypotheses for the formation of VSRs (Figure 4): 1) thermal pulsing; 2) propagating rifts; and 3) buoyant mantle upwelling. Drilling will allow us to test these hypotheses, which predict differing depths, temperatures and degrees of melting between VSRs and VSTs, recorded in basalt composition. Dredged samples are restricted to the ridge axis[2,28,37,50] (Figure 2b), since deep-sea corals and sediments cover off-axis areas. Hence off-axis VSRs and VSTs can only be sampled by drilling[51].

Second, we aim to test the controls on crustal architecture over longer, ∼30–40 Ma timescales. Oceanic crust south of Iceland can be divided into two distinct structural types using gravity, magnetic and bathymetric datasets[29,52,53] (dotted lines, Figure 2b). Smooth oceanic crust contains VSRs and VSTS, but also exhibits seafloor magnetic anomalies largely unbroken by fracture zone offsets, similar to that more typical at fast-spreading ridges. Rough oceanic crust exhibits fracture zone geometry that is more typical of slow-spreading ridges, hence the seafloor here represents a microcosm of global variability in crustal structure. The shape of the boundary between smooth and rough crustal styles has shifted through time. This transgressive character may record expansion and contraction of the Iceland plume head over ∼35 Ma[52,53]. Rough oceanic crust probably forms above cooler asthenosphere, whereas smooth crust may form above relatively hot asthenosphere in the Iceland plume head[52]. Therefore in the North Atlantic Ocean, small changes in melt flux and temperature may drive regime changes in crustal architecture. Our objective of understanding how crustal formation responds to mantle temperature, degree of melting, and plume activity will be achieved by comparing the geochemistry of basalts from smooth and rough crustal domains.

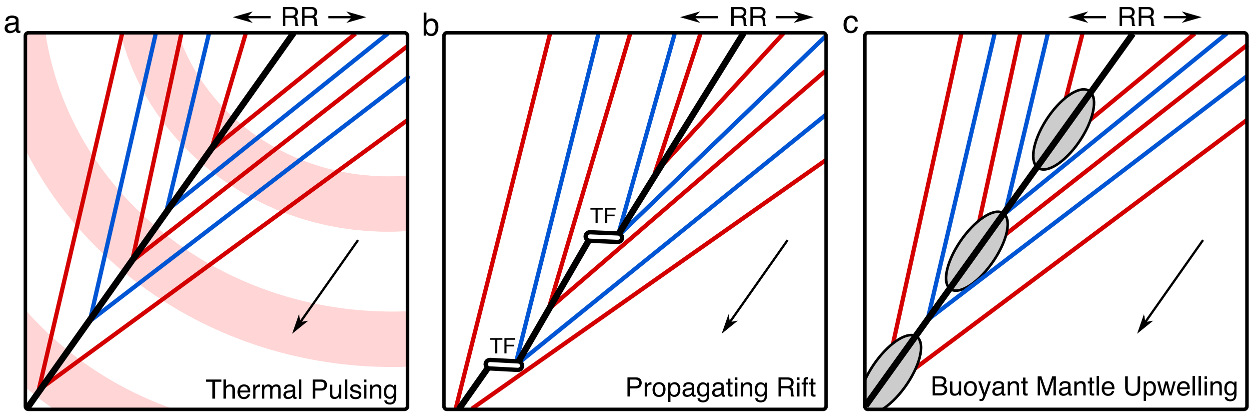

Figure 4: Schematic diagram showing three hypotheses for VSR formation. Black lines are Reykjanes Ridge (RR); short arrows indicate spreading direction; thin red lines are VSRs; blue lines are VSTs. a) Thermal pulsing[17]. Long arrow shows propagation direction of hot pulses; pink bands are thermal anomalies which advect beneath the lithosphere, generating thickened crust. b) Propagating rifts[46]. Long arrow shows propagation direction of rift; thick white lines are transform faults (TF). VSTs are considered to be pseudofaults which propagate along the axis generating relatively thin crust; VSRs are failed rifts where crust is relatively thick. c) Buoyant mantle upwelling[49]. Long arrow shows propagation direction of buoyant cell; gray blobs are buoyant upwelling cells which propagate along axis, causing enhanced upwelling and crustal thickening without a thermal anomaly.

Objective 2: Oceanic Circulation, Gateways and Sedimentation

We plan to quantify how oceanic circulation in the North Atlantic Ocean has varied since Oligocene times. Deep-water flow in the North Atlantic is dominated by two oceanic gateways, the Iceland-Faroe Ridge and Denmark Strait, which control the southwards flow of water from the Norwegian Sea and exert a major influence on global ocean circulation (Figure 5). The rate of accumulation of contourite drift sediments in the North Atlantic Ocean is primarily controlled by deep-water flow along bathymetric rises, and hence the strength and pathways of deep-water currents is recorded by these drift sediments. These deposits provide an indirect proxy for temporal variations in deep-water flow. Additionally, short-term climatic effects, relating to the location of oceanic fronts during both glacial/interglacial and (shorter) stadial/interstadial cycles, may play a role in circulation patterns on shorter timescales (thousands of years). It has been suggested that uplift and subsidence of the Iceland-Faroe Ridge and Denmark Strait is influenced by mantle upwelling beneath Iceland[12], and hence there may be an indirect connection between ocean circulation and mantle plume behavior. We plan to test the correlation between mantle plume activity and ocean circulation by using sediment accumulation rates as a first-order proxy for deep-water current strength. The oldest drilled sediments in the Iceland Basin are ~3 Ma[54], and this project will extend that record back to ~32 Ma, and allow us to investigate the relationships between mantle convection, oceanic gateway configuration and climate.

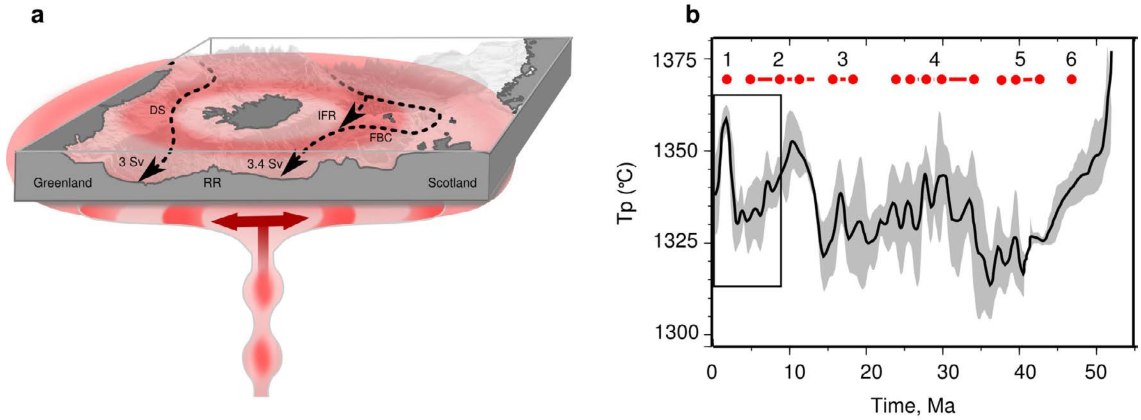

Figure 5: (a) Cartoon showing relationship between Iceland mantle plume and deep-water circulation[55]. Dashed lines are deep overflow water[56,57]; pink disk/stem is idealized extent of Iceland plume and plume head; darker pink blobs represent thermal anomalies; DS is Denmark Strait; RR is Reykjanes Ridge; IFR is Iceland-Faroe Ridge; FBC is Faroe Bank Channel. (b) Mantle potential temperature (T_p) at the Denmark Strait calculated from VSRs for past 55 Ma[34]. Numbered red circles/lines are sets of VSRs.

High sedimentation rates of contourite drift deposits in the North Atlantic ocean (12–16 cm ka^{-1}) have led to paleomagnetic and isotopic records that are among the most detailed available[58–61]. Existing boreholes provide high-resolution climate records back to 1.7 Ma[62] (Site 983). Specifically, this program will extend the high-resolution climate record into late Pliocene times. Thus, we aim to evaluate both the millennial- and million-year scale variability in Neogene climate during important intervals when temperatures were warmer than today. For example, drilling in this region has provided new constraints on the possible causes of abrupt climate shifts in the North Atlantic region over the past four glacial cycles[61], but present observations are limited to a single site. Extending these high-resolution records beyond the range possible with current material will allow us to separate the effects of climate variability and dynamic topographic variations, which we expect to operate on contrasting time scales.

Objective 3: Time-Dependent Hydrothermal Alteration of Oceanic Crust

We will investigate the nature, extent, timing and duration of hydrothermal alteration within the Reykjanes Ridge flank. Hydrothermal circulation along mid-ocean ridges and across their flanks is responsible for one-third of the heat loss through the ocean crust. It influences tectonic, magmatic and microbial process on a global scale, and is a fundamental component of global biogeochemical cycles. There is also growing evidence that the long-term carbon cycle is influenced by the reaction of seawater with the oceanic crust in low-temperature, off-axis hydrothermal systems, perhaps representing an important mechanism for carbon draw-down[63,64]. The relative contribution of this process remains controversial, since we don't know how much low temperature alteration takes place off-axis. Although the nature of the individual hydrothermal fluid rock reactions are generally understood, the magnitude and distribution of chemical exchange remain poorly quantified, as is the partitioning between high and low temperature exchange with crustal age. Consequently the role of the production, hydrothermal alteration and subsequent subduction of ocean crust in key global geochemical cycles remains uncertain. Drilled sections of hydrothermally-altered crust from the Reykjanes Ridge flank will provide time-integrated records of geochemical exchange between crust and seawater, along an age transect from 2.8 to 32.4 Ma. These sections will enable us to quantify the timing and extent of hydrothermal fluid-rock exchange across the Reykjanes Ridge flank, and to assess the hydrothermal contributions of a rapidly sedimented slow-spreading ridge flank to global geochemical budgets.

3 Relationship to IODP Science Plan 2013-2023

We consider fundamental problems under the two main themes of Climate and Ocean Change and Earth Connections side by side. This integrated approach should appeal to a broad community of geochemists, petrologists, climate scientists, geophysicists and geodynamicists.

Challenge 1. How does Earth's climate system respond to elevated levels of atmospheric CO_2?

Subsidence and uplift of the Denmark Strait and Iceland-Faroe Ridge controls the deep-water exchange between the Arctic Ocean, Nordic Seas and Atlantic Ocean (Figure 5). Thus the histories of these gateways, and their associated deep-water flow, are central to our understanding of Northern Hemisphere climate and its interaction with global thermohaline circulation. Sediments at our proposed drilling sites accumulated at high rates (>10 cm ka^{-1}), thus provide a millennial-scale paleoclimate record since Early Neogene times. Our proposed extended record will span the critical middle Pliocene intervals when global mean surface temperatures were 2–3 °C warmer than today, beyond those available today (Figure 6). We will be able to test the sensitivity of ocean circulation to changes in gateway conditions, that will provide constraints for the sensitivity of climate models to changes in atmospheric CO_2. Finally, the record of crustal alteration will allow us to examine the the role of seafloor weathering in drawdown in CO_2 over the past 32 Ma..

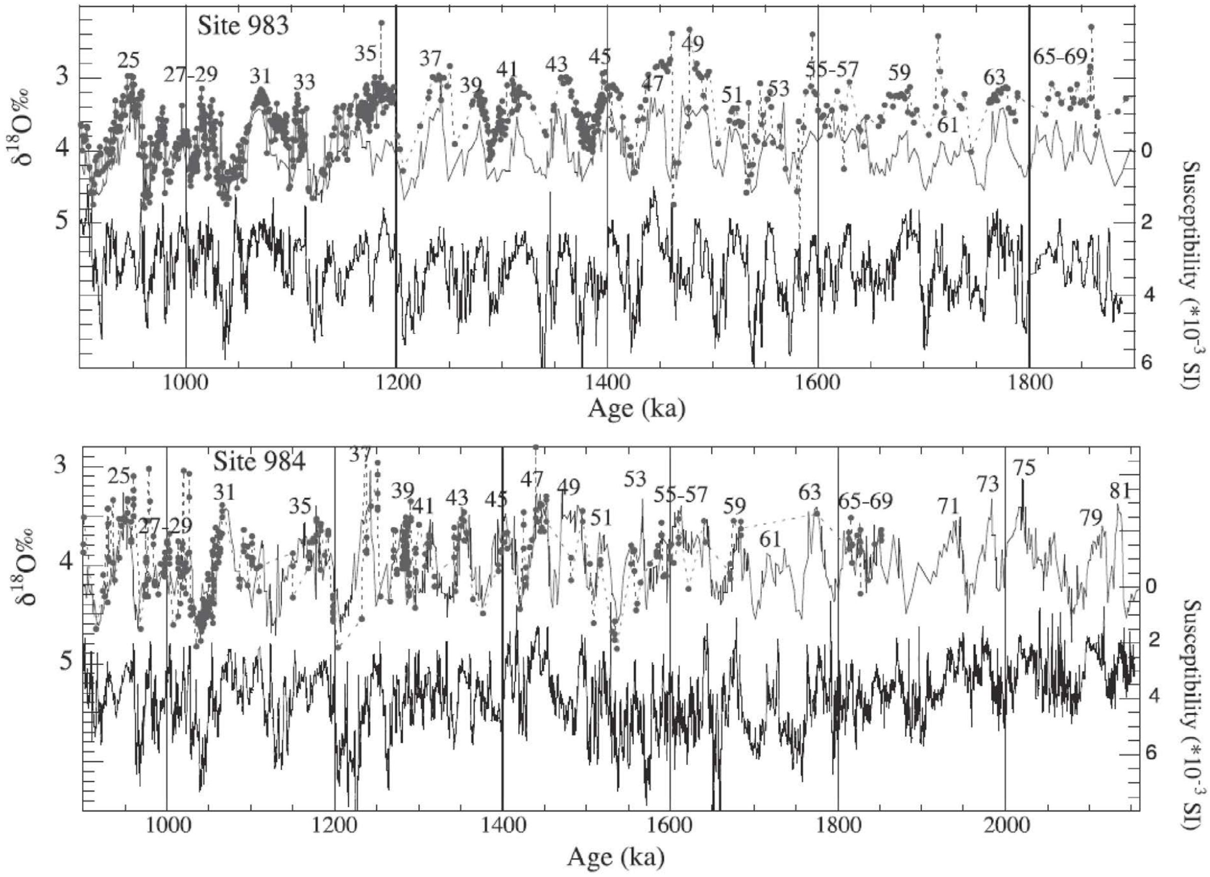

Figure 6: Benthic δ^{18}O and magnetic susceptibility data from Sites 983 and 984 in Iceland Basin[59]. Dots are δ^{18}O; gray lines show reference δ^{18}O from ODP Site 677[65]; black lines are volume magnetic susceptibility.

Challenge 8: What are the composition, structure, and dynamics of Earth's upper mantle?

The coincidence of the Reykjanes Ridge with the Iceland plume provides an opportunity to observe the composition and behavior of Earth's interior. Basalts recovered by dredging at spreading centers provide us with a modern-day snapshot of the spatial patterns in mantle heterogeneity, however by recovering off-axis samples, this proposal will provide an opportunity to constrain temporal variability. Major, rare earth and trace element concentrations of basalts will be compared between sites, and used as inputs to models of mantle melting[28,33].

Challenge 9: How are seafloor spreading and mantle melting linked to ocean crustal architecture?

Crustal architecture south of Iceland is dominated by two main features. First, the diachronous VSRs that straddle the Reykjanes Ridge and second, the transition from smooth to rough oceanic crust that took place at ∼35 Ma. These features may have been formed due to the interaction between time-dependent mantle convection and plate spreading[17,18,31,39], or alternatively due to a series of propagating rifts[46], or patches of buoyant mantle upwelling[49]. Drilling of oceanic crust south of Iceland will allow us to unravel the origins of this architecture, with implications for our understanding of the relationships between mantle melting, rifting and plate spreading.

Challenge 10: What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater?

This Challenge requires a series of ocean-basin-wide transects that extend from 0-100 Ma crust across ridge flanks that have experienced different sedimentation or hydrogeologic histories. The proposed drill sites comprise a crustal flow line transect across the western flank of the Reykjanes Ridge. The recovered cores will sample the uppermost 200 m of lavas produced 2.8, 5.2, 12.4, 14.2 and 32.4 million years ago at the slow spreading Reykjanes Ridge, providing a uniqye opportunity to quantify the timing and extent of hydrothermal fluid-rock exchange within a slow spreading ridge flank that experienced rapid sedimentation and variations in tectonic architecture.

4 Scientific Justification

4.1 Crustal Accretion and Mantle Convection

We aim to evaluate the three hypotheses for the origins of VSRs: 1) that thermal pulses advect away from the Iceland mantle plume beneath the lithosphere, forming VSRs[17,18,31,39]; 2) that VSRs are formed as a result of pseudofaults generated by rift propagation[45–48]; and 3) that buoyant mantle upwelling instabilities propagate along axis to form locally increased crustal thickness[49]. The geochemistry of drilled basalts will be used to differentiate between these three models.

4.1.1 Hypothesis 1: Thermal Pulsing

Melting models show that mantle temperature anomalies of $T_p = \pm 25°$C can explain both the crustal thickness variations and the geochemistry of dredged basalt samples associated with the youngest VSRs and VSTs[33] (Figure 3b). Constraints on T_p were extended back from the present to ∼50 Ma using seismic reflection profiles from Cruise JC50, which also reveal VSRs beneath thick sedimentary cover[34]. These images were used to estimate residual depth, a proxy for crustal thickness and hence an approximation for T_p (Figure 7a). Estimates of T_p obtained in this way correlate favorably with short-wavelength gravity anomalies (Figure 7b). These observations for older VSR cycles remain unconstrained by geochemical observations, which can only be obtained by drilling.

The thermal pulsing hypothesis predicts inverse correlation between incompatible trace element concentrations and crustal thickness, with a cyclical geochemical pattern expected between V-shaped ridge and trough pairs. Melting anomalies are expected to be temperature driven, with VSRs produced by increased melt production, leading to the prediction that melting should initiate at greater depths (i.e., at a higher mean pressure of melting). This hypothesis also suggests that pulsing activity of the plume causes changes in regional dynamic support, leading to variations in deep-water flow across the Iceland-Faroe Ridge and Denmark Strait. Hence a positive correlation between VSR compositional enrichment and Northern Component Water strength (%NCW) is predicted, which can only be tested by sampling off-axis basalts.

On timescales of 30–40 Ma, the thermal pulsing hypothesis predicts overall trend of lower incompatible trace element ratios on smooth crust where VSRs are present, in comparison to fractured crust, where higher incompatible trace element ratios due to overall lower mantle temperatures are predicted. Basalt from the region of fractured crust will contain a baseline composition for North Atlantic mantle, produced in an environment free from the influence of the Iceland plume. Samples from this location will therefore represent an important end-member for our understanding of plume influence on mantle melting processes.

4.1.2 Hypothesis 2: Propagating Rifts

There is evidence for asymmetric accretion along the Reykjanes Ridge, and it has been suggested that this asymmetry is caused by a series of propagating rifts[46,47]. Bathymetric and gravity anomaly lows, or VSTs, are interpreted to be pseudofault scarps, which converge in a series of propagating rift tips at the ridge axis. VSTs can be explained by reduced melting at propagating rift tips, thus producing relatively thin crust without the requirement for thermal pulses[46,66].

Rift propagation predicts geochemical variations in the erupted basalts. Melting is expected to be both deeper and less extensive at young propagating rifts than at established rifts, since the rift propagates into cooler, thickened lithosphere. The juxtaposition of the young spreading center with cold lithosphere leads to rapid cooling and a deepening of the top of the melting column[66–68]. Consequently, melt at the tips of propagating rifts and fracture zones is expected to be more enriched in trace elements[69]. A nearby example of this process is at the tip of the

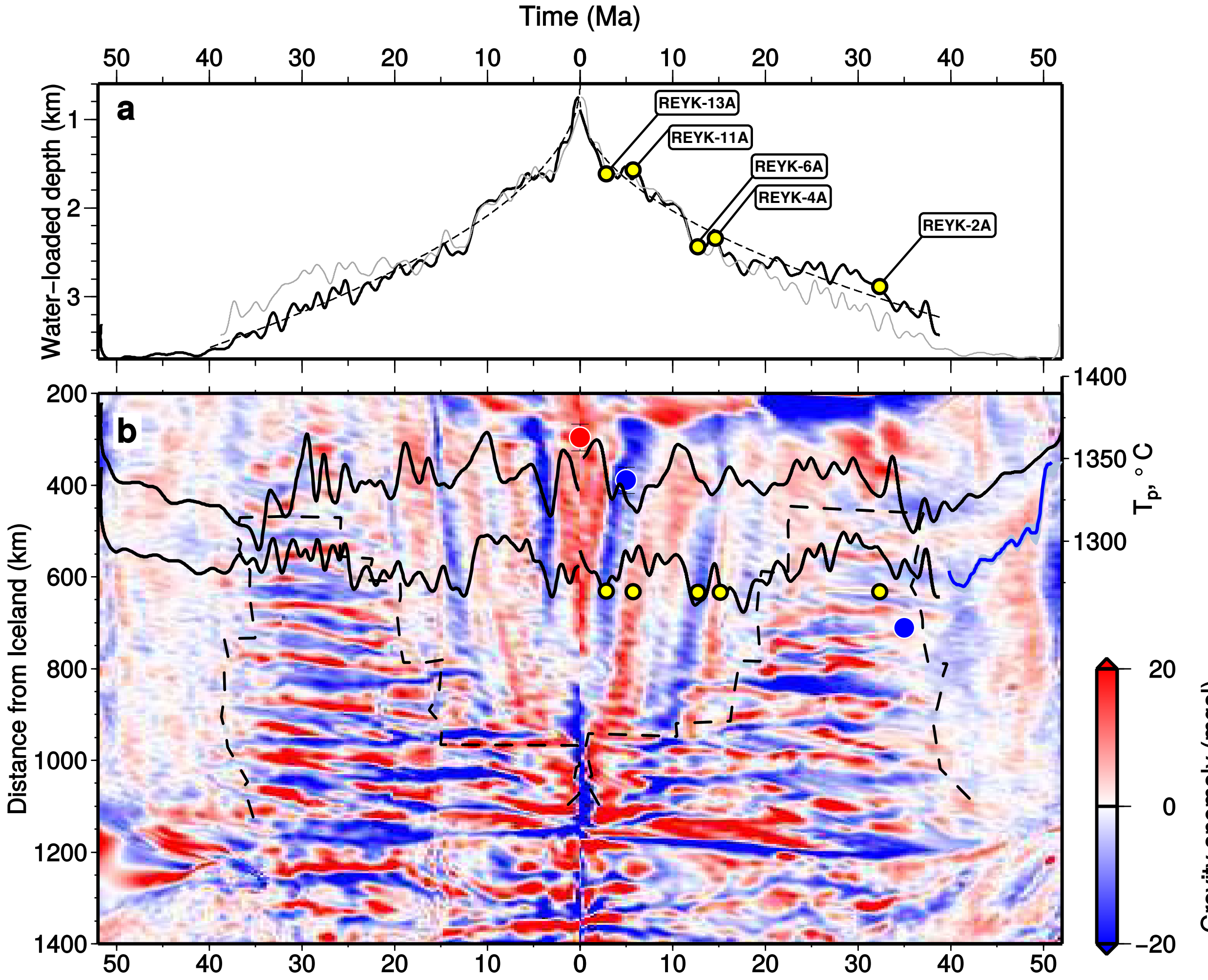

Figure 7: VSR chronology. a) Water-loaded depth to basement for JC50-1, location in Figure 2. Solid black lines are water-loaded depth to basement[34]; gray lines are water-loaded depth to basement mirrored about spreading axis; dashed line is best-fit age-depth relationship describing subsidence of oceanic crust; yellow circles are primary drilling sites. b) Gravity anomaly as function of crustal age and distance from plume center (63.95°N, 17.4°W[42]). Black lines are T_p calculated from residual depth profiles; blue lines with band is T_p from wide-angle seismic refraction data[41]; red/blue circles are crust-derived T_p[39,40]; black dashed line is smooth-rough transition from magnetic picks[34].

southward-propagating Eastern Volcanic Zone on Iceland, where basalts are trace element enriched and less primitive than those from the main neovolanic zones[70]. The propagating rift hypothesis therefore predicts trace element enrichment at the propagating rift, corresponding to where a new pseudofault intersects the ridge axis, i.e. where a new VST is being formed and crust is thinned. Geochemical observations of basalts dredged from the Reykjanes Ridge and crustal thickness agree with this prediction, since enriched trace element compositions coincide with relatively thin crust at VSTs[28,33,37]. Drilling VSTs will allow this hypothesis to be tested, and to assess the relative importance of the propagating rift mechanism through time.

The propagating rift process is expected to be restricted to the ridge axis, and does not involve the mantle plume head. Propagating rifts are therefore not expected to generate vertical motions at the Iceland-Faroe Ridge and Denmark Strait hundreds of kilometers away, and hence predict no correlation between %NCW and either VSR composition. Joint analysis of the crustal and sedimentary samples obtained in this program will allow us to test this prediction.

4.1.3 Hypothesis 3: Buoyant Mantle Upwelling

An alternative model proposes that the variations in mantle melting are generated by changes in mantle upwelling rather than temperature[49]. In this model, buoyancy-driven shallow mantle upwelling instabilities propagate along axis to form the observed crustal structure of the Reykjanes Ridge. Away from hotspots, ridge segmentation and correlating along-axis variations in crustal production have been proposed to result from small-scale convective cells, with higher rates of mantle upwelling near segment centers leading to increased melting and crustal production as compared to ridge offsets. In the propagating rift model, these buoyant mantle upwellings are proposed to initiate near Iceland and propagate southwards along the Reykjanes Ridge, driven by gradients in mantle properties (viscosity/composition), producing a wake of increased crustal thickness (VSRs). By changing the pattern of mantle advection, the gradual elimination of ridge segmentation increases melt production and crustal thickness without changes in T_p. As the shape of the buoyant melting regime and the streamlines of mantle flow are more focused than in the broad triangular melting regimes of passive upwelling, erupted basalts reflect greater extents of melting. Unlike increases in melting due to higher T_p, which deepens the solidus and results in a higher average pressure of melting, the increase in melting due to buoyant upwelling is likely to occur at more moderate to shallow depths in the melting column. Pressure-sensitive trace element ratios thus can be used to differentiate between these mechanisms.

In common with the propagating rift hypothesis, buoyant mantle upwelling is an axial process, and is not expected to influence regional topographic ups and downs. Therefore in this scenario, little or no correlation between deep-water flow and basalt composition is expected.

4.2 Terrestrial Constraints

The objectives of this study can only be achieved by sampling of the submarine portion of the oceanic crust. Subaerial Iceland, whilst providing an excellent picture of chemical variability in a mantle plume, does not record the geochemical or geophysical information that is obtainable from the ridge axis. The subaerial Iceland record only extends back to ∼17 Ma, representing half the duration of crustal production that will be sampled by this proposal. Significantly, the subaerial record does not contain information on the transition from smooth to fractured crust, which represents the largest regime-change in North Atlantic crustal accretion. A crucial piece of information in resolving the debate about the thermal or tectonic origin of the VSRs is the relationship between basalt chemistry and the amount of melt being supplied. Whilst it is possible to reconstruct a geochemical stratigraphy on Iceland by examining two-dimensional sections of old stacked lavas that flowed off of the main rift-axis, obtaining the corresponding volumes of these flows is nearly impossible given their limited exposure in glacially-carved valleys. Additionally, the preserved basalt record on subaerial Iceland is heavily biased in favor of large volume eruptions that have escaped burial at the neovolcanic zone by subsequent eruptions[71]. Thus, the one part of the record we can obtain on land, the geochemical stratigraphy, is compromised in a way that drilled sections of oceanic crust are not. Finally, the record from subaerial Iceland does not provide insight into the submarine hydrothermal processes outlined in Objective 3.

4.3 Limitations of Dredging

Testing the alternative hypotheses that the VSRs are formed by variations in temperature, mantle melting, or tectonic processes, requires geochemical samples from off-axis VSRs and VSTs. Obtaining information about VSTs by drilling is crucial, since it is not possible to sample these features by dredging. *Celtic Explorer* cruise CE0806 (2008) was designed to complement IODP proposal 646-Full and was partly funded by UK-IODP. A primary aim was to determine whether drilling is required to retrieve basalt samples from off-axis sites. Results confirm that drilling will be necessary to achieve the scientific goals of this IODP proposal[51]. Dredging was attempted at locations west of Reykjanes Ridge along VSR-1 (9 sites) and along the younger edge of VSR-2 (Figure 2b; 20 sites). Basement outcrops were not encountered in VSTs, and off-axis dredge return rates were significantly lower than for on-axis dredges. Extinct off-axis volcanic ridges and fault scarps are covered with abundant coral growth, and dredging these regions resulted in poor return or loss of the dredge. In many cases, the minor amounts of basalt recovered were contaminated by basaltic dropstones sourced from Iceland and Greenland. The risk of dredge loss, ratio of dropstones to primary basalt, and difficulty in distinguishing primary basalt from dropstones all increase with distance away from the spreading axis. Furthermore, dredging can only sample surface flows erupted when magmatism was waning. Our scientific goals require multiple samples of basalt produced during steady-state melt production, on older crust which can only be accessed by drilling.

4.4 Hydrothermal Ageing of Oceanic Crust

The formation of new ocean crust along mid-ocean ridges is a key component of the plate tectonic cycle, which repaves two thirds of Earth's surface every 200 Ma as crust spreads towards subduction zones. Thermally-driven reactions between seawater and cooling oceanic crust are a fundamental component of global biogeochemical cycles. The chemical and isotopic composition of seawater reflect the balance between inputs to the oceans from rivers draining the continents, the burial of material in marine sediments, and hydrothermal exchanges between the oceans and oceanic crust. Knowledge of the rates and magnitudes of hydrothermal exchanges would therefore help us to decipher the changes in global conditions responsible for variations in seawater chemistry. The most dramatic manifestation of hydrothermal circulation occurs along the mid-ocean ridges, where high temperature (up to ∼400 °C) fluids are vented. However, conductive heat flow deficits and pore water studies indicate that seawater-basalt exchange persists at lower temperatures (<100°C) on the ridge flanks to 65 Ma on average[72]. The magnitude and distribution of hydrothermal exchanges across ridge flanks remain poorly quantified, due to the lack of drill sites along flowline transects, and a lack of sites in 20–100 Ma in-tact in-situ crust[73]. Drilling investigation of hydrothermal processes along a crustal flow line is restricted to young (<3.6 Ma) intermediate-spreading (29 mm/yr half-rate) crust on the Juan de Fuca Ridge[74–76].

The intensity of seawater-basalt exchange depends on crustal architecture, its thermal, tectonic and sedimentation history, and spreading rate. The extent to which hydrothermal circulation has buffered ocean chemistry therefore depends on the global length of slow, intermediate and fast spreading ridges and the age-area distribution of the ridge flanks, which have varied significantly throughout the Phanerozoic. To assess the impact of these variations on past hydrothermal contributions to global geochemical cycles, we need to recover upper crustal sections along age transects through crust produced at different spreading rates and with differing sedimentation histories. The proposed drilling provides an opportunity to quantify the magnitude and distribution of hydrothermal exchanges within rapidly sedimented slow-spreading rate crust, as it ages from 3 to 32 Ma.

4.5 Ocean Circulation and Mantle Convection

Coupled oceanic-atmospheric numerical experiments have shown that the depth of oceanic gateways has a significant influence upon deep-water circulation[13]. The topographic step between smooth and rough seafloor along the Reykjanes Ridge, proposed to indicate the extent of plume-influenced uplift, is ∼300 m, and has been used as an estimate for the depth difference between the modern-day and Mid-Pliocene Greenland-Scotland Ridge (GSR)[13,18]. A deepening of the GSR of this magnitude has been shown by model experiments to explain observed increases in Arctic sea surface temperature and Mid-Pliocene deepwater production[13].

In Neogene times, vertical motions at this oceanic gateway may have moderated flux of Iceland-Scotland Overflow Water into the North Atlantic Ocean[12,33,77]. Two independent studies have demonstrated that there is a negative correlation between %NCW and vertical motion of the Greenland-Iceland-Scotland Ridge[12,77] (Figure 8). There is a reasonable correspondence between the record of potential temperature, T_p, which plays a role in controlling regional dynamic support, %NCW overflow and sedimentation rates at Bjorn and Gardar Drifts[55] (Figure 8). Between 6 Ma and 2.5 Ma, the plume was relatively cool with T_p of $\sim$ 1335°C. During this period, %NCW was elevated which suggests that the Greenland-Iceland-Scotland Ridge was deeper. Between 2.5 and 0.5 Ma, T_p increased to $\sim$ 1355°C and dynamic support beneath these two oceanic gateways was greater by $\sim$ 200 m. During this period, %NCW and sedimentation rates were reduced, which suggests that uplift of gateways inhibited deep-water flow into the North Atlantic Ocean. Over the last 0.5 Ma, T_p has decreased and %NCW and sedimentation rates have increased, consistent with renewed deep-water overflow.

We plan to use sediment accumulation rates as a first-order proxy for deep-water current strength. Accumulation rates will be estimated with sedimentary age determinations obtained from paleomagnetism, calcareous nannofossils, diatoms, silicoflagellates, and planktonic foraminifera. We will also test the success of our approach using the Sortable Silt grainsize proxy for bottom current speed[84], as applied to Site 983[85]. By recovering core throughout the sedimentary section, we intend to extend the record back to ∼32 Ma. This extended record of sedimentation rates, and hence deep-water current flow, will enable us to test the connection between plume-driven dynamic support, and oceanic circulation since Oligocene times. This will also provide an additional test for the alternative non-pulsing plume hypotheses, which do not predict any correlation between VSR formation and oceanic circulation.

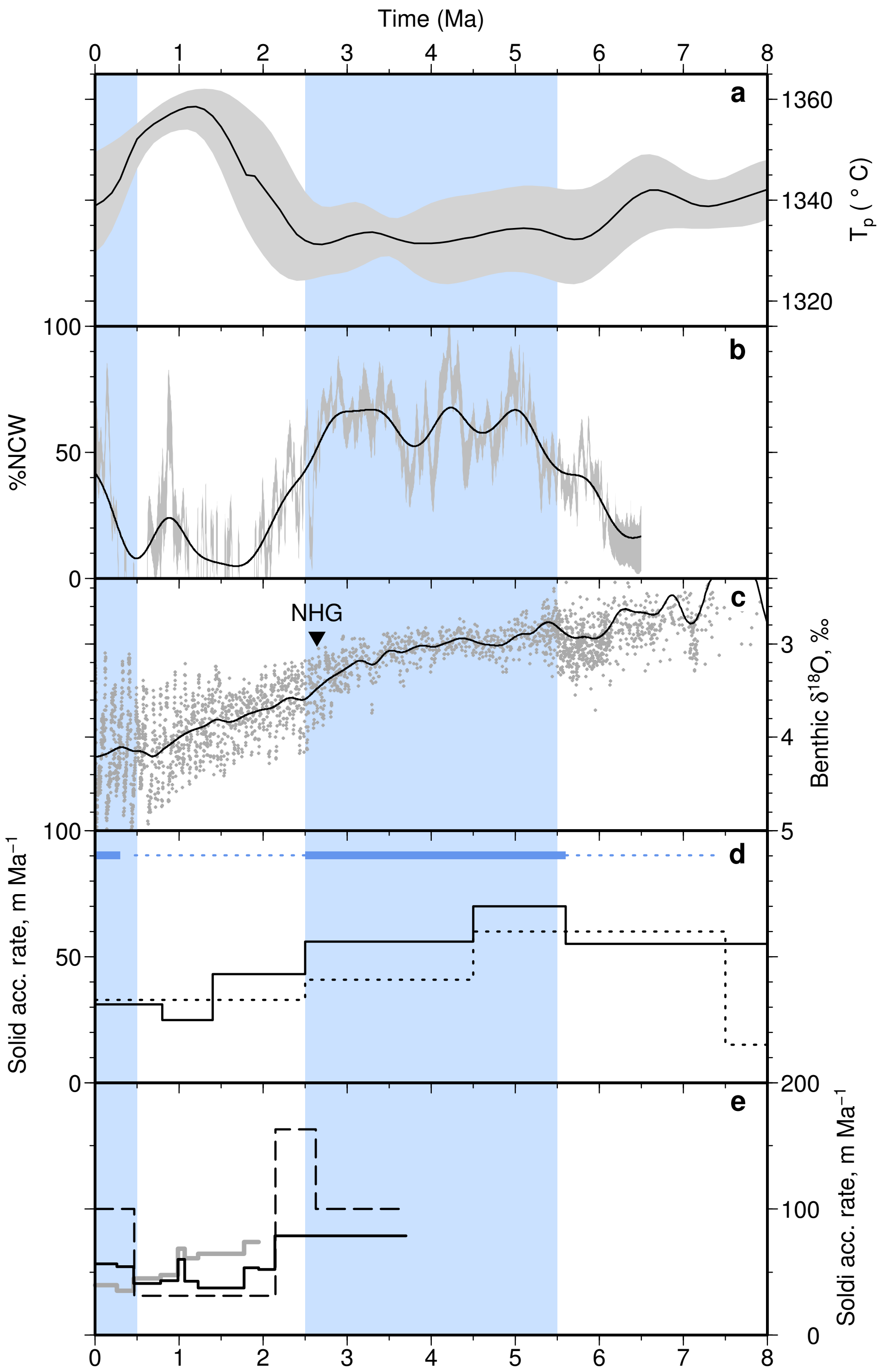

Figure 8: Calculated mantle potential temperature (T_p), Northern Component Water overflow (%NCW) and drift accumulation through time. Blue bands are periods when Iceland plume was cooler. (a) Black line with error band is T_p at Denmark Strait[34]. (b) %NCW with error band[77]. (c) Gray points are stacked deep-sea oxygen isotope record[78,79]; black line is smoothed with 0.5 Ma width Gaussian filter; triangle shows onset of Northern Hemisphere Glaciation (NHG)[80]. (d) Solid sedimentation rate of Eirik Drift. Dotted black line is rate from near Cape Farewell[81]; dashed line is rate from profile JC050-1; thick/dotted blue lines are strong/weak bottom currents[82]; (e) Solid sedimentation rate of Björn drift. Black/gray lines are rates at ODP Sites 984 and 983, respectively[83]; dashed line is rate calculated from seismic profiles JC50-1 and -2.

4.6 Millennial-scale and Abrupt Climate Change

Abrupt climate change is a ubiquitous feature of the Late Pleistocene epoch[86]. The sequence of repeated transitions between warm interstadial and cold stadial conditions, as recorded by ice cores in Greenland, are thought to be linked to changes in the mode of overturning circulation in the Atlantic Ocean[87,88]. North Atlantic cold events seem to correspond with increased iceberg calving and dispersal from ice sheets surrounding the North Atlantic. This observation has inspired many ocean and climate modelling studies that make use of freshwater forcing scenarios to simulate abrupt change across the North Atlantic region and beyond[89–91]. On the other hand, previous studies identified an apparent lag between North Atlantic cooling events and the appearance of ice-rafted debris (IRD) over the last glacial cycle, leading to the hypothesis that iceberg discharge may be a consequence of stadial conditions rather than the cause[92]. The region south of Iceland is ideally positioned to detect ice-rafting events in their earliest stages. This relationship was established using data from a single ODP site, 983[61], where a systematic delay between pronounced surface cooling and the arrival of ice-rafted debris at a site southwest of Iceland over the past four glacial cycles was demonstrated. Other studies on material from site 983 provide evidence for millennial-scale activity during the early Pleistocene and suggest a persistent link between abrupt changes in surface ocean conditions and ocean circulation[58,84]. The material collected here will allow us to test for similar relationships during much earlier periods. Furthermore, by exploiting sediments from different water depths we will be able to trace vertical movements in the main axis of ISOW not possible using a single core site[93].

Fluctuations in surface ocean temperature and the delivery of IRD at each site will be investigated at a centennial scale. This objective will be achieved by counting the relative proportion of polar planktonic foraminifers (e.g. *Neogloboquadrina pachyderma*) within the total assemblage, and the number of lithogenic/terrigenous grains >150 μm per gram dry sediment (IRD per gram). Therefore the transect of sites proposed here provide an opportunity to track changes in IRD, and thus the association between ice rafting and high-latitude temperature variability over the last four glacial cycles with unprecedented detail.

4.7 Northern Hemisphere Glaciation

Onset of Northern Hemisphere Glaciation took place during late Pliocene times (i.e. 3 Ma)[94,95]. Progressively increasing amounts of ice-rafted debris and synchronous ice sheet development in Greenland, Fennoscandia and North America have been documented at 2.72–2.75 Ma[80]. This intensification corresponds to a major increasing trend within the oxygen isotope record[78] (Figure 8c). General circulation modeling has suggested that climatic shifts associated with closure of the Panamanian seaway, with termination of a permanent El Niño state, or with regional uplift, do not account for significant growth of the Greenland icesheet[96]. Decreasing atmospheric CO_2, from elevated mid-Pliocene values to lower Quaternary values are conceivably responsible for significant increase in Greenland glaciation[96]. The reasons for this decrease in atmospheric CO_2 are unclear[97]. We wish to test the notion that restriction of deep-water flow, caused by transient uplift of the Denmark Strait and the Iceland-Faroe Ridge due to increased plume support, may have played a role in reducing the vigor of AMOC and inhibiting production of NCW throughout Neogene times. This inhibition could have pre-conditioned a coupled ocean-climate system, with full glaciation triggered by variations in Earth's orbital cycles along with a decreasing trend in atmospheric CO_2.

4.8 Oligocene–Miocene Climate

Extreme events, such as the abrupt warming and carbon-cycle dynamics during the Middle Miocene Climatic Optimum (15–17 Ma), are central for our understanding of Earth's climatic system[79,98]. Considerable gaps exist in our knowledge of the paleoceanography and paleoclimate during Oligo-Miocene times. In particular, there is a persistent lack in recovery of high-resolution records of Oligo-Miocene sediments from the North Atlantic Ocean. This time period holds useful information about evolution of the cryosphere, Northern Hemisphere ecosystem structure and the history of oceanic productivity. As a result, this interval has been recently identified as a strategically important objective for future scientific drilling[99]. Rapidly accumulated sediments at Gardar Drift provide an opportunity to obtain a high-resolution Oligo-Miocene climate record in the North Atlantic Ocean. Gardar Drift has been drilled previously during Site 983 and U1314, where the maximum depths of recovery were 271 and 279 m, respectively[62,100]. The oldest sediments recovered at these sites are late Pliocene in age. Our proposed drilling program provides an opportunity to extend this record back to Oligo-Miocene times and to establish a comprehensive history of climatic events in the North Atlantic Ocean.

4.9 Relationship to Previous Drilling Expeditions

ODP Leg 162 drilled four sites on sediment drifts south of Iceland (Figure 2). Continuous sedimentary sequences recovered in these cores provided a groundbreaking insight into climatic variability on sub-Milankovitch timescales, over millions of years[58,59,61,83,84,101,102]. The oldest sediments recovered were middle Pliocene (3.7 Ma) in age. DSDP Leg 49 recovered basalts at three sites along a transect along the western flank of the Reykjanes Ridge, on oceanic crust 36, 20 and 2.4 Ma in age (Sites 407, 408 and 409, respectively). A total basalt thickness of 453 m was penetrated at these three sites with an average core recovery rate of 40%[103]. The results of Leg 49 provided a breakthrough in our understanding of the nature and scale of mantle heterogeneity and the behavior of mantle plumes[103,104].

Given the successes of Legs 49 and 162, why is additional drilling required adjacent to the Reykjanes Ridge? First, the basalts recovered during Leg 49 were exclusively located on basement highs, i.e. VSRs (Figure 2b). In order to test the hypotheses set out here, basalts samples are required from VSTs. Secondly, basalt has not been recovered from rough oceanic crust influenced by fracture zone faulting. The composition of basalts erupted during this phase of crustal accretion is key to understanding the long-term behavior of the Iceland mantle plume and tectonic re-organization. Thirdly, drilling is required to constrain variations in climate and ocean circulation beyond middle Pliocene times, when the record from the Leg 162 sites ends. Understanding the variation in climate proxies, current strength and sedimentation rate throughout Neogene times is central to satisfying the objectives of this proposal.

5 Site Survey Data

An extensive suite of geophysical survey and dredge sample data are available in support of this drilling proposal. Here, we describe the principal datasets.

5.1 Geophysical Data

During Cruise JC50 in July–August 2010, over $\sim$ 2400 km of high resolution 2-dimensional (2D) multi-channel reflection seismic data were acquired (Figures 2 and 9). This cruise was funded as a site survey by UK-IODP, following positive reviews from proposal 646-Full[1]. The survey consisted of two basin-spanning regional profiles, oriented parallel to plate-spreading flowlines, and a series of 19 shorter perpendicular crossing lines (Figures 2, 9 and 10). 2D seismic reflection data were recorded on a 132-channel hydrophone streamer with 12.5 m group spacing. The seismic source comprised a single generator-injector airgun (250 cu.in primary pulse, 105 cu.in injector pulse) fired with a pressure of 3000 psi at 15 second intervals. Nominal ship speed of 5.0 knots ($\sim$9.3 km/hr) yielded a shot spacing of ∼40 m, and a fold of ∼21. These multichannel data are of sufficient quality to identify the sediment-basement interface, as well as potential drilling hazards such as faults, gas accumulations and stratigraphic discontinuities.

Multibeam bathymetric data were acquired during Cruise JC50 at each site using a hull-mounted Kongsberg EM120 multibeam echosounder. At depths of 1 km (typical at the Reykjanes Ridge), resolution is ∼30 m. Additional legacy bathymetric surveys, carried out on RV *Maurice Ewing* Cruise EW9008 and RRS *Charles Darwin* Cruises CD81 and C87, provide coverage near to the Reykjanes Ridge[105,106].

5.2 Dredged Geologic Samples

Over 200 dredged basalt samples were recovered during Cruises CD80 and CE0806[28,37] (1994 and 2008, respectively). The combined dataset extends from 57° to 63°N along Reykjanes Ridge axis, while a subset of samples from CE0806 are located on VSR-2 and VST-2 (Figure 2b). Analysis of these samples has revealed systematic patterns in the geochemistry of basalt erupted at the ridge axis (Figure 3).

5.3 Previous Drilling Expeditions

Previous drilling expeditions in the North Atlantic Ocean provide useful indications of how drilling operations will proceed. Below we summarize the relevant results.

Sites 983 and 984 of Leg 162, located 65 and 180 km from proposed site REYK-2A, respectively, were drilled in July 1995 using the *JOIDES Resolution* (Figure 2). At these sites, rapidly accumulated contourite sediments of Gardar and Björn Drifts were cored with 100% recovery rates. Coring proceeded without incident with a standard Advanced Piston Coring / Extended Core Barrel (APC/XCB) bottom hole assembly for three holes at Site 983 (A–C) until scientific target depths of 254, 251 and 260 m had been reached, respectively. At Site 984, four holes (A–D) were drilled with the APC/XCB to scientific target depths of 176, 504, 290 and 271 m, respectively. At hole 984C, liner collapse problems were encountered near the base of the hole while using the APC.

Oceanic basement was drilled at three sites on the west flank of the Reykjanes Ridge during DSDP Leg 49 in 1976 using *Glomar Challenger* (Figure 2). The deepest basement penetration was at Site 409, where 240 m of vesicular basalt was drilled with a recovery rate of ∼30%[107].

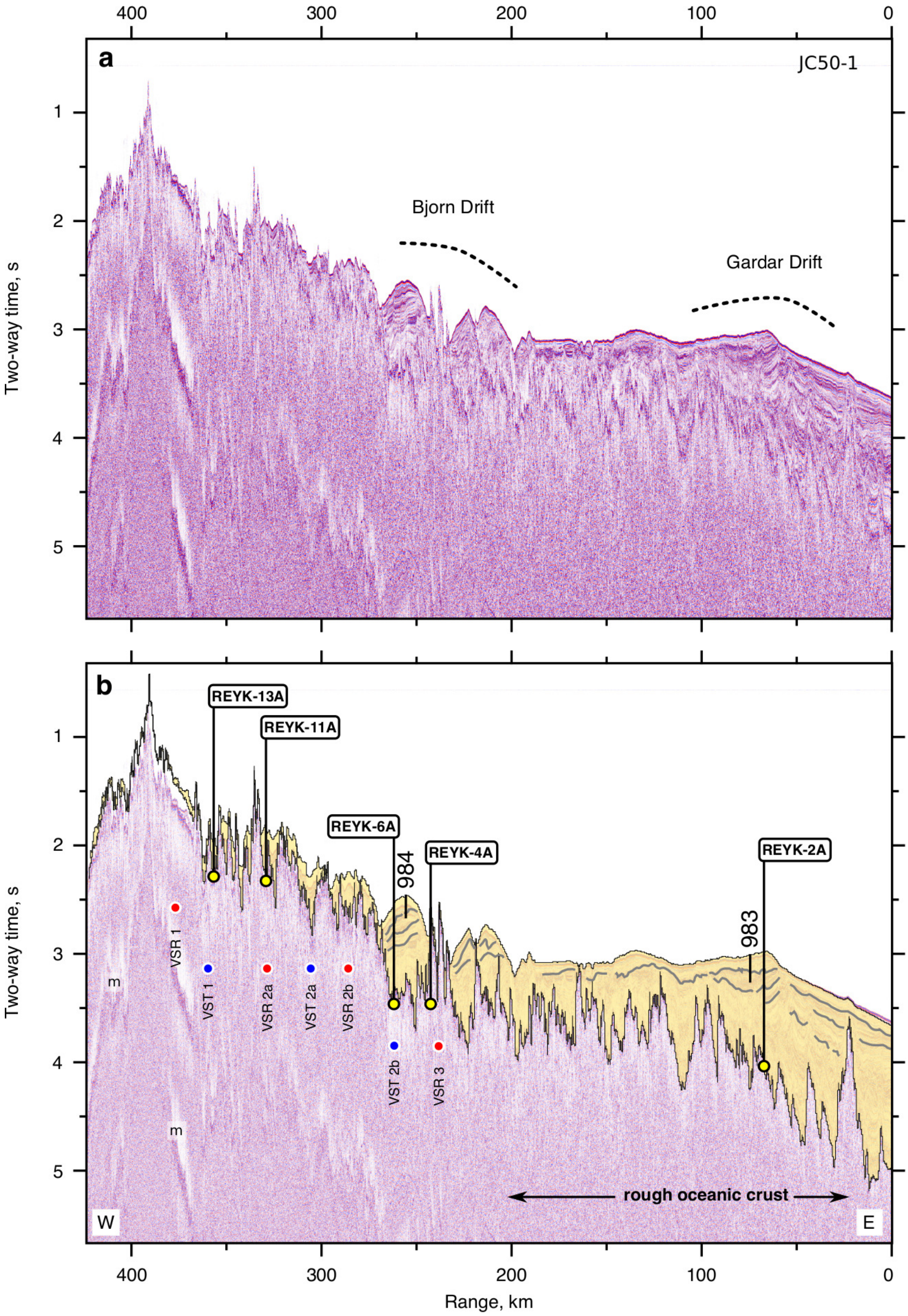

Figure 9: Portion of seismic reflection profile JC50-1 (see Figure 2 for location). (a) Uninterpreted time-migrated image. Dotted lines are sedimentary drifts. (b) Interpretation. Yellow shading and gray lines are sedimentary strata; solid line is sediment-basement interface; red/blue circles are VSRs/VSTs; yellow circles are primary drilling sites; m marks water-bottom multiple reflections; lines labeled 983/984 are projected locations of Leg 162 drilling sites.

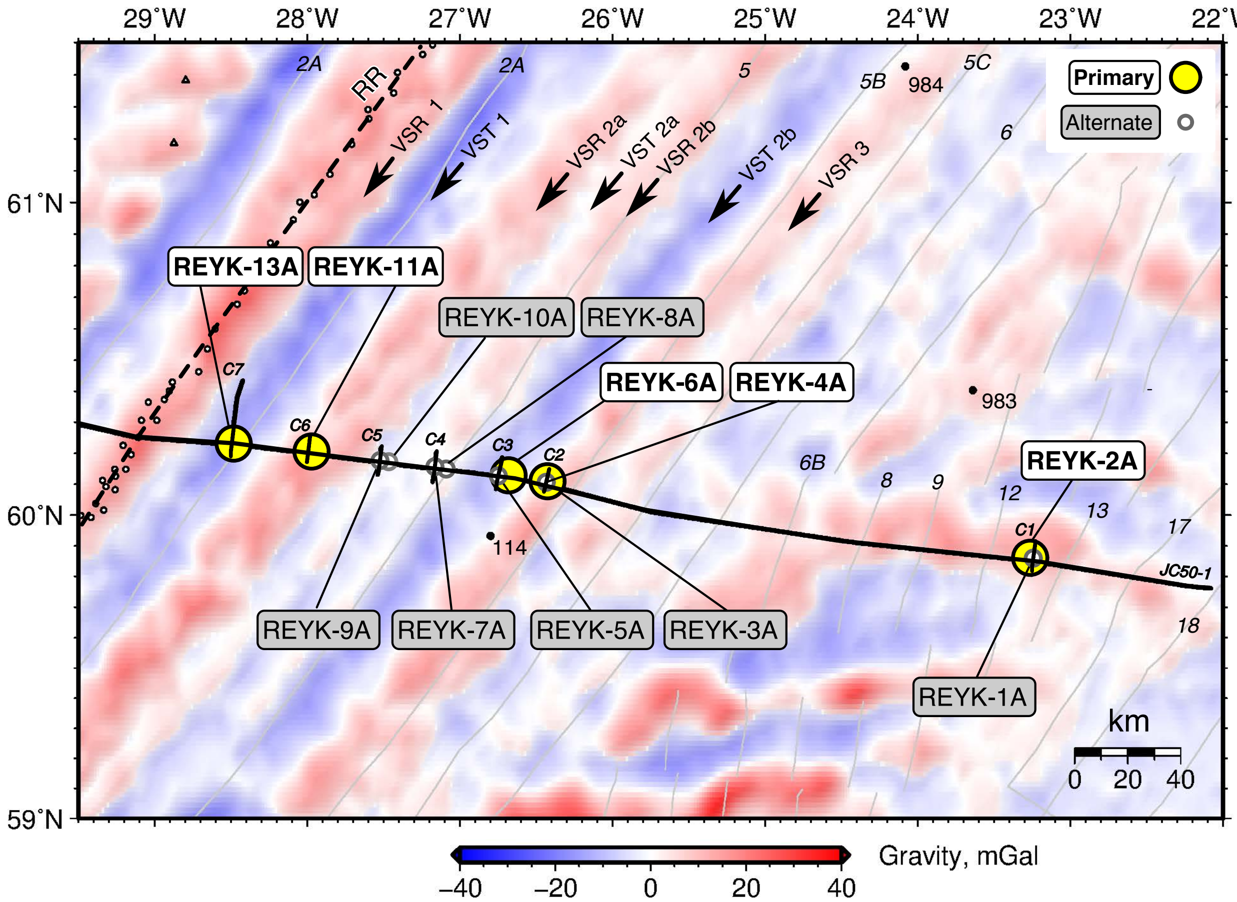

Figure 10: a) Satellite free-air gravity anomaly map[36], showing proposed drilling sites and age chrons. Yellow/gray circles are primary/alternate sites, respectively; solid black lines are seismic reflection profiles; dashed line is Reykjanes Ridge; labelled gray lines are magnetic polarity chrons[18]; labelled black dots are existing ODP/DSDP boreholes; labeled arrows are VSRs and VSTs; open circles/triangles are dredged basalt samples[28,37].

Penetration rates in the basalt section at Site 409 were 4–60 m hr^{-1}. These high penetration rates were probably due to the highly vesicular nature of the basalts, and the presence of tuffaceous or poorly consolidated debris. At this site, basalt was continuously cored with a single bit, which upon recovery was reported to be in good condition.

6 Drilling Plan

Drilling is essential for meeting our objectives, since it is the only sampling method that can provide information about off-axis crust. Since older crust is draped in sediment and corals, features such as VSTs are out of reach for other sampling techniques such as dredging[51]. Our first objective is to acquire geochemical information about the crustal rocks formed under the influence of the Iceland plume over the past 35 Ma. Our second objective is to obtain a continuous record of climate and

Site	Target	Number of holes	Latitude, N	Longitude, W	Crustal age, Ma	Water depth, m	Basement depth, mbsf	Depth into basement, m	Category
REYK-13A	VST 1	1	60.2282	28.5004	2.8	1520	210	200	Primary
REYK-11A	VSR 2a	1	60.1999	28.0000	5.2	1415	340	200	Primary
REYK-6A	VST 2b; Bjorn Drift	3	60.1251	26.7016	12.7	1871	705	200	Primary
REYK-4A	VSR 3	1	60.0992	26.4435	14.2	2110	185	200	Primary
REYK-2A	Fractured basement; Gardar Drift	3	59.8506	23.2664	32.3	2206	970	200	Primary
REYK-7A	VSR 2b; Bjorn Drift	1	60.1507	27.1698	9.8	1735	330	200	Alternate
REYK-9A	VST 2a; Bjorn Drift	1	60.1702	27.5299	7.7	1701	310	200	Alternate
REYK-1A	Fractured basement; Gardar Drift	3	59.8496	23.2473	32.4	2209	955	200	Alternate
REYK-3A	VSR 3	1	60.0989	26.4404	14.2	2110	205	200	Alternate
REYK-5A	VST 2b; Bjorn Drift	3	60.1264	26.7516	12.4	1894	675	200	Alternate
REYK-8A	VSR 2b; Bjorn Drift	1	60.1491	27.1370	10.0	1695	320	200	Alternate
REYK-10A	VST 2a	1	60.1667	27.4726	8.1	1689	155	200	Alternate

Table 1: Summary of proposed drilling sites.

deep-water current flow from sedimentary samples. This requirement has led us to select sites east of the Reykjanes Ridge, where thick sedimentary accumulations are visible on seismic reflection profiles. Sediments are thin and discontinuous west of the Reykjanes Ridge. All sites have been chosen to lie on seismic profile JC50-1, which is oriented parallel to a plate-spreading flowline[39]. This flowline orientation means that lavas were located at the same distance from the Iceland plume when erupted, thus avoiding spatial variations in composition.

We propose to drill into oceanic crust at four sites where VSRs and VSTs can be identified, and a fifth site characterized by fractured oceanic crust devoid of V-shaped features (Table 1). Basement penetration is 200 m for all sites. Each site is expected to consist of a sequence of fine-grained sediments of thickness 180–1200 m lying above basaltic crust. Sediments will be cored with a combination of APC, XCB and Rotary Core Barrel (RCB) in order to achieve our paleoceanographic objectives. Sediments are expected to be similar in composition to those recovered at ODP Sites 983 and 984. Dominant lithologies at Sites 983/984 are silty clay, clay, clayey nannofossil mixed sediment and nannofossil ooze[54,62].

Table 2 summarizes the transit, drilling and logging times for the five primary and seven alternate sites. We anticipate a total of 48 operational days and total of 53 expedition days, assuming Reykjavik, Iceland as port of departure. We assume sediment penetration rates during APC and XCB operations of ∼10 m/hr, consistent with those reported at Sites 983 and 984. Penetration rates of 15 m/hr are assumed when using the RCB. Basalt penetration rates of 2–4.5 m/hr dependent on drill depth are assumed, consistent with those achieved during Legs 49 and

Site	Location Lat N Long W	Water Depth (m)	Target	Holes	Operations Description	Transit (days)	Coring (days)	Logging (days)	On site (days)
Primary Sites									
Reykjavik, Iceland					5.0 days in port				
					Transit 298 nmi to Site REYK-13A at 10.5 kt	1.2			
REYK-13A	60.228183 28.500401	1520	VST 1	1	Hole 1: APC to basement (210 m). RCB to 410 m, two bit trips Logging: triple combo, FMS-sonic		5.9	0.8	**6.7**
					Transit 15 nmi to Site REYK-11A at 10.5 kt	0.1			
REYK-11A	60.19994 28.00000	1415	VSR 2a	1	Hole 1: APC/XCB to basement (340 m). RCB to 540 m, two bit trips Logging: triple combo, FMS-sonic		6.5	0.8	**7.2**
					Transit 39 nmi to Site REYK-6A at 10.5 kt	0.15			
REYK-6A	60.12510 26.70160	1871	VST 2b Bjorn Drift	3	Holes 1 & 2: APC to refusal Hole 3: APC/XCB to refusal, RCB to 905 m, two bit trips Logging: triple combo, FMS-sonic		10.2	1.0	**11.2**
					Transit 8 nmi to Site REYK-4A at 10.5 kt	0.03			
REYK-4A	60.099163 26.443547	2110	VSR 3	1	Hole 1: APC to basement (185 m). RCB to 385 m, two bit trips Logging: triple combo, FMS-sonic		5.3	0.8	**6.1**
					Transit 97 nmi to Site REYK-2A at 10.5 kt	0.4			
REYK-2A	59.850611 23.26643	2206	Fractured basement Gardar Drift	3	Holes 1 & 2: APC to refusal Hole 3: APC/XCB to refusal, RCB to 1170 m, two bit trips Logging: triple combo, FMS-sonic		13.0	1.0	**14.0**
					Transit 260 nmi to Reykjavik at 10.5 kt	1.0			
Reykjavik, Iceland					**Subtotals**	**2.8**	**35.7**	**3.5**	**45.3**
					Total on-site days	**45.3**			
					Total operational days	**48.1**			
					Port call days	**5.0**			
					Total expedition days	**53.1**			
Alternate Sites									
REYK-7A *time permitting*	60.15074 27.169766	1735	VSR 2b Bjorn Drift	1	Hole 1: APC to refusal, XCB to 380 m. RCB to 580 m, two bit trips Logging: triple combo, FMS-sonic		6.7	0.8	**7.4**
REYK-9A *time permting*	60.170192 27.529939	1701	VST 2a	1	Hole 1: APC/XCB to basement (310 m). RCB to 510 m, two bit trips Logging: triple combo, FMS-sonic		6.5	0.8	**7.2**
REYK-1A *alt for REYK-2A*	59.84961 23.247259	2209	Fractured Basement Gardar Drift	3	Holes 1 & 2: APC to refusal Hole 3: APC/XCB to refusal, RCB to 1155 m, two bit trips Logging: triple combo, FMS-sonic		13.7	1.0	**14.7**
REYK-3A *alt for REYK-4A*	60.098856 26.440356	2110	VSR 3	1	Hole 1: APC to basement (205 m). RCB to 405 m, two bit trips Logging: triple combo, FMS-sonic		6.4	0.8	**7.1**
REYK-5A *alt for REYK-6A*	60.126412 26.751562	1894	VST 2b Bjorn Drift	3	Holes 1 & 2: APC to refusal Hole 3: APC/XCB to refusal, RCB to 875 m, two bit trips Logging: triple combo, FMS-sonic		11.4	1.0	**12.4**
REYK-8A *alt for REYK-7A*	60.149127 27.136992	1695	VSR 2b Bjorn Drift	1	Hole 1: APC/XCB to refusal. RCB to 520 m, two bit trips Logging: triple combo, FMS-sonic		6.5	0.8	**7.3**
REYK-10A *alt for REYK-9A*	60.166682 27.472573	1689	VST 2a	1	Hole 1: APC to basement (155 m). RCB to 355 m, two bit trips Logging: triple combo, FMS-sonic		5.8	0.8	**6.6**

Table 2: Operations summary for proposed drilling sites.

197[103,108]. We assume two bit trips will be required at all sites as we expect to use two RCB bits to reach the target basement depth. The first trip will change from APC/XCB to RCB, the second trip will replace an expended RCB drill bit. We assume that free-fall funnels will be used for re-entries. However, there is a risk that a collapsed borehole may not be able to be located and re-entered.

The number of lava flow units encountered during drilling will determine whether 200 m is sufficient basement penetration. In order to obtain a geochemically meaningful sample, >20 basaltic flows need to be encountered. At Site 409, 58 flow units were encountered over a 240 m basalt section[107]. We anticipate similar flow unit thicknesses to those found at Site 409. The required depth of basalt penetration will be determined during the course of drilling operations. Following the recommendations of a recent IODP workshop[109], we propose to use real-time monitoring of geochemical and petrological data to distinguish eruptive units. For example, flow units may be defined by changes in drilling rate, vesicularity, phenocryst mineralogy, magnetic inclination and occurrence of chilled margins[107]. This approach will allow us to determine an appropriate termination depth and maximize the number of sites sampled during the expedition. We plan to use a standard suite of logging tools, including Triple Combo (density, porosity, resistivity, gamma ray, magnetic susceptibility) and FMS-Sonic tools. Data acquired using these tools are critical in identifying both sedimentary and volcanic units, as well as establishing structural dip and tilting of lava flows.

7 Site Descriptions and Selection Criteria

We propose five primary sites that will allow us to achieve our objectives within a single leg (Figure 10). We have suggested seven alternate sites, two of which which would yield additional results (REYK-7A and REYK-9A), the remaining sites provide options to avoid sedimentary disturbances and faults identified at primary sites, or are located at the intersection of crossing seismic lines.

7.1 Primary Sites

Two primary sites are at the crests of VSRs 2a and 3 (Figure 10; REYK-11A and REYK-4A, respectively), and two sites are at the base of VSTs 1 and 2b (REYK-13A and REYK-6A, respectively). One site overlies fractured oceanic crust (REYK-2A) where V-shaped features appear to be absent. Two of these sites have been optimally located to obtain a continuous, undisturbed sedimentary record from Björn and Gardar Drifts (REYK-6A and REYK-2A, respectively). At these sites, three holes will be drilled within the sedimentary section in order to obtain a complete stratigraphic record. Single holes will be drilled elsewhere in order to maximize drilling time (REYK-13A, REYK-11A and REYK-4A).

REYK-13A: VST 1. Located within VST 1, on basement 2.8 Ma in age, at the intersection of seismic profiles JC50-1 and JC50-C7. Represents the youngest oceanic crust to be sampled, which lies beneath a local sediment high which is ∼210 m thick. Sediments consist of a series of closely spaced reflections, with no evidence for erosional discontinuities or faulting. The sediment–basement interface is a bright, laterally continuous, approximately horizontal reflecton. Single hole.

REYK-11A: VSR 2a. Located at the crest of VSR 2a, on crust 5.7 Ma in age, and at the intersection between seismic profiles JC50-1 and JC50-C6. Sediment here is ∼340 m thick, and characterized by a continuous sequence of reflections. The sedimentary sequence at this site provides an opportunity to obtain a continuous climatic record. The sediment–basement interface is a bright reflection that is low in dip. Single hole.

REYK-6A: VST 2b and Björn Drift. Located at the crest of Björn Drift and over VST 2b, our major basement and sedimentary objectives will be addressed here. This site is shifted 2.8 km east of the intersection between seismic profiles JC50-1 and JC50-C3, in order to avoid a sediment discontinuity which can be identified at seismic crossing location. Three holes will be drilled to APC refusal to obtain a continuous stratigraphic section. The third hole will be extended 200 m into igneous crust. Basement, 12.7 Ma in age, lies beneath ∼705 m-thick contourite sediments here. The site is located at a localized basement high, which has shallow dip and is laterally continuous. Three holes.

REYK-4A: VSR 3. Located at the crest of VSR 3, on crust 14.2 Ma in age. This site is shifted 200 m west of the intersection between seismic profiles JC50-1 and JC50-C2,to avoid the possible basement fault just to the west of the crossing seismic lines. A thin (∼185 m) sediment pond sits above the basement. Single hole.

REYK-2A: Rough oceanic crust and Gardar Drift. Chosen to intersect Gardar Drift and the region of rough oceanic crust that is devoid of VSRs and VSTs. This site is shifted 1.1 km west of the intersection between seismic profiles JC50-1 and JC50-C1, in order to avoid some shallow faults which can be identified at seismic crossing location. Three holes will be drilled to APC/XCB refusal here to obtain a continuous stratigraphic section. The third hole will be extended 200 m into igneous crust. Contourite drift sediments here are ∼955 m thick, while oceanic basement is 32.4 Ma in age. The basement appears to be gently dipping towards the east and is an uneven, bright reflection. Three holes.

7.2 Alternate Sites

We have identified seven alternate sites, chosen to provide contingency for drilling obstacles identified on seismic profiles.

REYK-7A: VSR 2b. Located on VSR 2b and intersects a ∼380 m thick section of Björn Drift sediment, over basement 9.8 Ma in age. Placed at the intersection between JC50-1 and JC50-C4. Sediments show evidence of erosional features, while the basement reflection is bright in amplitude and may be affected by normal faults. Single hole.

REYK-9A: VST 2a. Located at VST 2a, where crust is 7.7 Ma in age, at the intersection between JC50-1 and JC50-C5. Sediments here are ∼310 m thick, and are continuous and gently dipping, apart from a slightly disturbed section at 2.45 s TWTT. The basement is a bright reflection. Single hole.

REYK-1A: Rough oceanic crust and Gardar Drift. Placed at the intersection of profiles JC50-1 and JC50-C1, in region of rough oceanic crust where VSRs are absent. The sedimentary package is disturbed by a number of small faults that extend from basement to seabed, at range 66–67 km on JC50-1 and 6.4 km on JC50-C1, hence REYK-2A is preferred. The basement appears to be gently dipping towards the east and is an uneven, bright reflection. Three holes.

REYK-3A: VSR 3. Located at the crest of VSR 3 where seismic lines cross. Situated in a local depression to the west of a basement outcrop, filled with ∼200 m thick sediments. The first basement reflection here appears at 3.04 s TWTT, appears to be dipping eastwards and shows relatively dim amplitude. The basement reflection appears twice, and this site is close to what appears to be a small fault, hence REYK-4A is preferred. Out-of plane of section noise may be responsible for this multiple reflection. Single hole.

REYK-5A: VST 2b and Björn Drift. Placed on the intersection of profiles JC50-1 and JC50-C3. A sedimentary disturbance can be seen at 3.0 s TWTT at this site, along with evidence for faulting at range 263 km on JC50-1, hence REYK-6A is preferred. Three holes.

REYK-8A: VSR 2b. Chosen to obtain a continuous sedimentary sequence and avoid erosional features at REYK-7A. Shifted 1.8 km east of the intersection between seismic profiles JC50-1 and JC50-C4, where sediment is expected to be 320 m thick. The basement reflection here is steeply dipping and bright in amplitude. Single hole.

REYK-10A: VST 2a. Located at VST 2a, shifted 3.2 km east of crossing point to minimize the sediment thickness required to drill before reaching basement, expected to be 155 m. The basement is a rugged, bright reflection. Single hole.

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IODP Site Forms

Form 1 – General Site Information

892 - Full 2

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Sample ~200 m of basalt at V-shaped trough 1. Primary site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-13A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 60.2281	Jurisdiction:	International
Longitude:	Deg: -28.5004	Distance to Land: (km)	140
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☑ Alternate: ☐	Water Depth (m):	1520

Generated: 2017-04-13T00:09:30+00:00

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	210	200
	Total Sediment Thickness (m) 210	
		Total Penetration (m): 410
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

APC to basement or refusal, RCB to target depth ~200 m within oceanic crustal basement.

APC ☑ XCB ☑ RCB ☑ Re-entry ☐ PCS ☐

Wireline Logging Plan:

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

Other Measurements:

Estimated Days:

Drilling/Coring:	Logging:	Total On-site:
5.9	0.8	6.7

Observatory Plan:

Longterm Borehole Observation Plan/Re-entry Plan

N/A

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_2S	☐	High Dip Angle	☐	Ice Conditions	☐
CO_2	☐				

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

Preferred weather window: Summer required as North Atlantic weather poor in Winter

Other:

Proposal #: 892 - Full 2	Site #: REYK-13A	Date Form Submitted: 2017-04-03 15:37:51

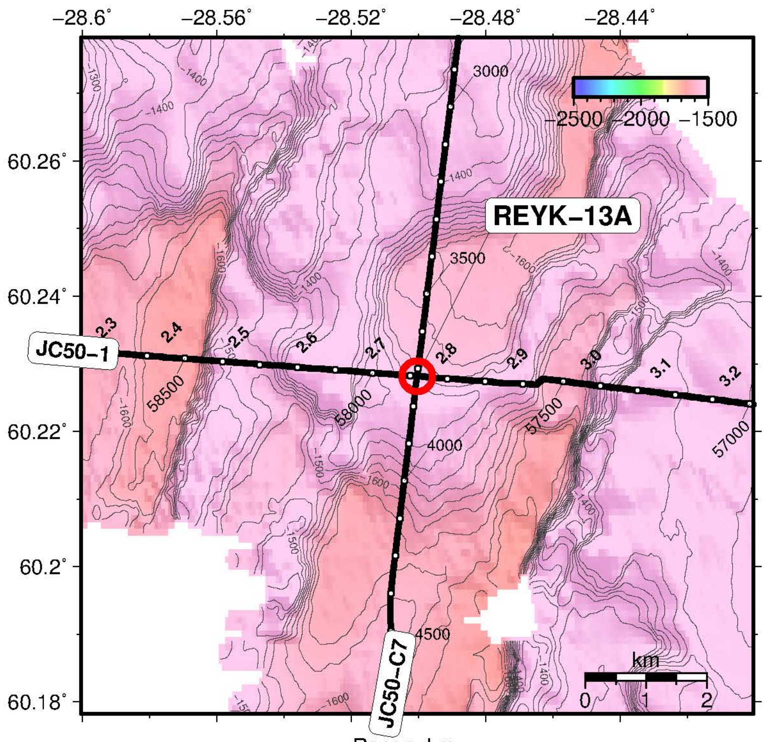
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 57881
1b High resolution seismic seismic reflection (crossing)	yes	Line: Profile JC50-C7 Position: 3720
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 cruise navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-13A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Single APC to basement at 250 m. RCB 200 m into basement, log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-13A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 125	Seabed to reflection B2	0.47	1.55	Nannofossil clay	Pelagic	266	Age based upon reflection R2 at Site 984
125 - 210	Reflection B2 to basement	less than 2.8 Ma	1.63	Silty clay	Pelagic	36	Age and lithology based on results from Site 983
210 - 210	Acoustic basement	2.8 and older	2.7	Vesicular basalt	Pelagic	NA	



Site Summary Figure: Proposal P892-Full Site REYK-13A

Location: -28.50040 W, 60.22818 N

CMP 57881 on JC50-1; CMP 3720 on JC50-C7

Water depth: 1520 m / 2.053 s TWTT

Basement depth: 210 mbsf / 2.318 s TWTT

Target depth: 410 mbsf / 2.466 s TWTT

Basement age: 2.80 Ma

Figures and supporting data in SSDB:

Location map: REYK-13A_site_sum_fig_map.pdf

Seismic images: REYK-13A_site_sum_fig_JC50-1.pdf &

REYK-13A_site_sum_fig_JC50-C7.pdf

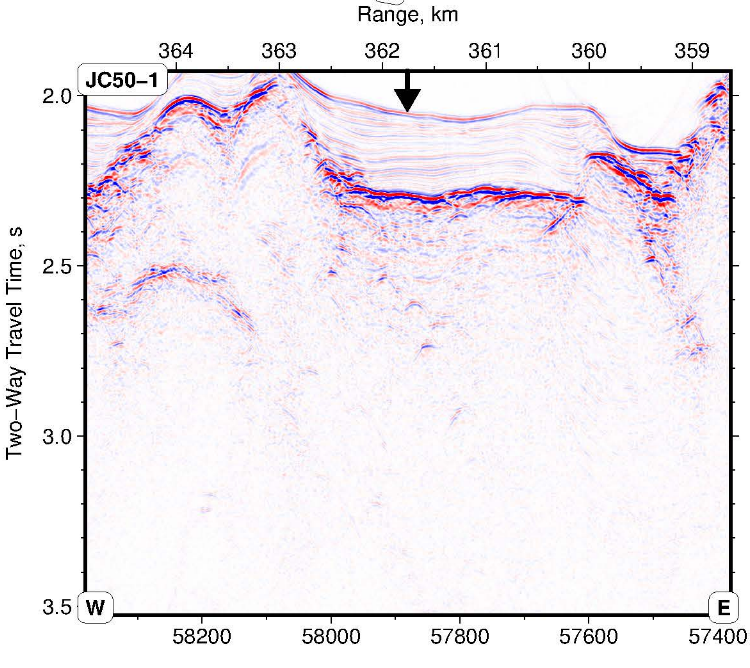
SEGY data / Navigation: JC50-1_stolt_trbal.segy / JC50-1.xy &

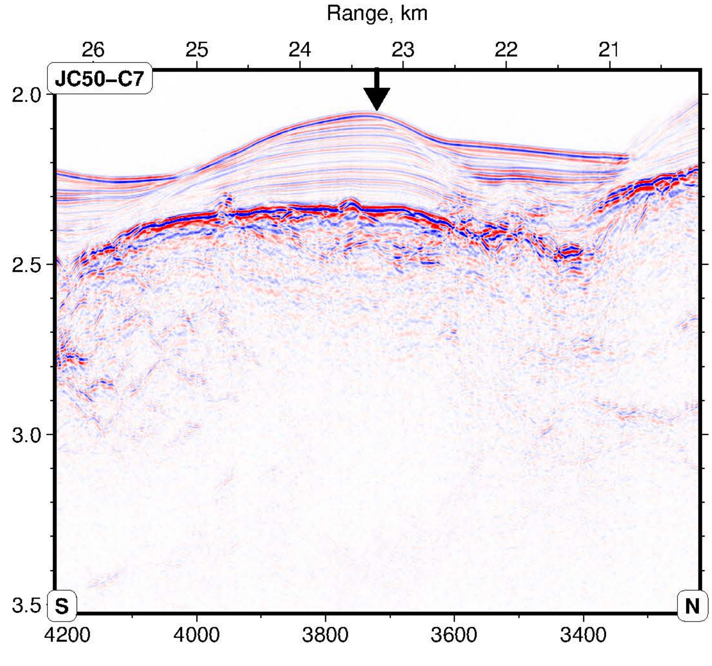
JC50-C7_stolt_trbal.segy / JC50-C7.xy

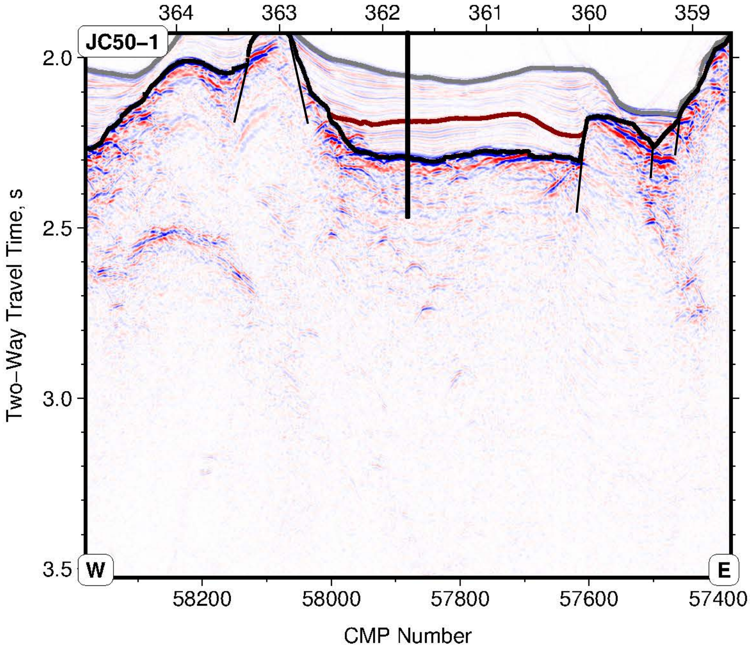
Interpretation:

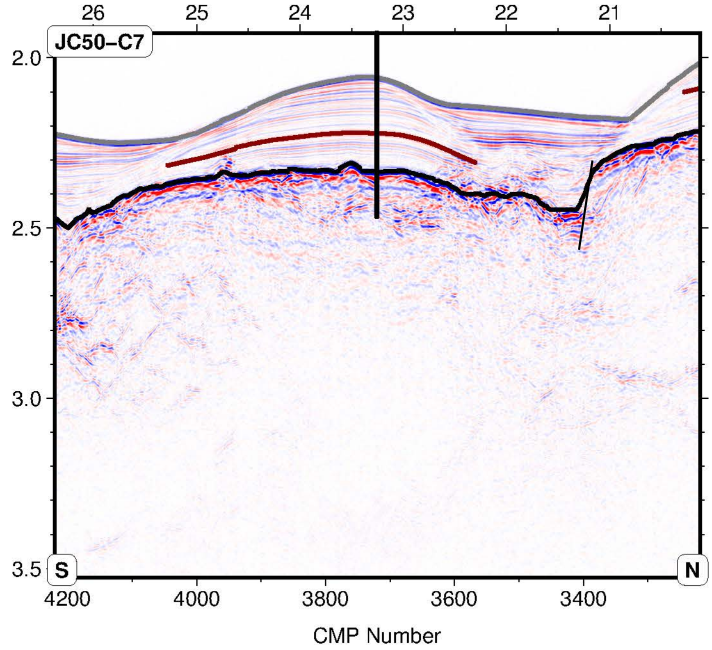
Gray = seabed ; red = B2 (0.47 Ma); green = B3 (2.15 Ma);

blue = B4 (2.63 Ma); orange = B5 (3.7 Ma); black = basement









IODP Site Forms

Form 1 – General Site Information

892 - Full 2

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Sample ~200 m of basalt at V-shaped ridge 2a. Primary site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-11A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 60.2000	Jurisdiction:	International
Longitude:	Deg: -28.0000	Distance to Land: (km)	157
Coordinate System:	WGS 84		
Priority of Site:	Primary: ✔ Alternate: ☐	Water Depth (m):	1415

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	340	200
	Total Sediment Thickness (m) 340	
		Total Penetration (m): 540
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

APC/XCB to refusal, RCB to target depth ~200 m within oceanic crustal basement.

- 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:

Other Measurements:

Estimated Days:	Drilling/Coring: 6.5	Logging: 0.8	Total On-site: 7.3

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) ☐
- H_2S ☐
- CO_2 ☐
- Complicated Seabed Condition ☐
- Soft Seabed ☑
- Currents ☑
- Fracture Zone ☐
- Fault ☐
- High Dip Angle ☐
- Hydrothermal Activity ☐
- Landslide and Turbidity Current ☐
- Gas Hydrate ☐
- Diapir and Mud Volcano ☐
- High Temperature ☐
- Ice Conditions ☐

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

Preferred weather window: Summer required as North Atlantic weather poor during winder

Other:

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Proposal #: 892 - Full 2	Site #: REYK-11A	Date Form Submitted: 2017-04-03 15:37:51

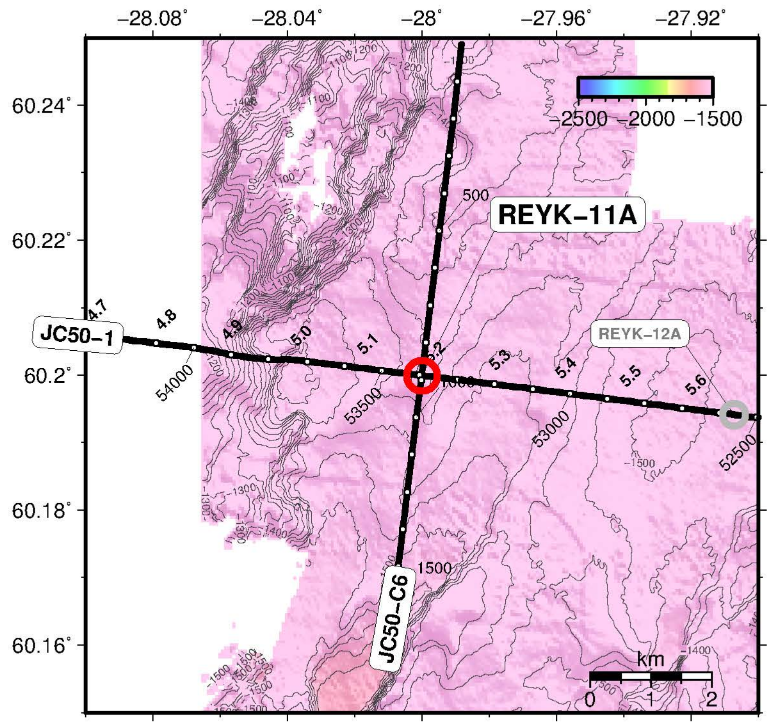
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: JC50-1 Position: 53393
1b High resolution seismic seismic reflection (crossing)	yes	Line: JC50-C6 Position: 888
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	JC50 EM120 multibeam survey
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 cruise navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-11A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Single APC/XCB to basement at 340 m. RCB 200 m into basement, log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-11A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 75	Seabed to reflection B2	0.47	1.55	Nannofossil clay	Pelagic	160	Age based upon reflection R2 at Site 984
75 - 340	Reflection B2 to basement	less than 5.2 Ma	1.63	Silty clay	Pelagic	56	Age and lithology based on results from Site 984
340 - 340	Acoustic basement	5.2 and older	2.7	Vesicular basalt	Pelagic	NA	

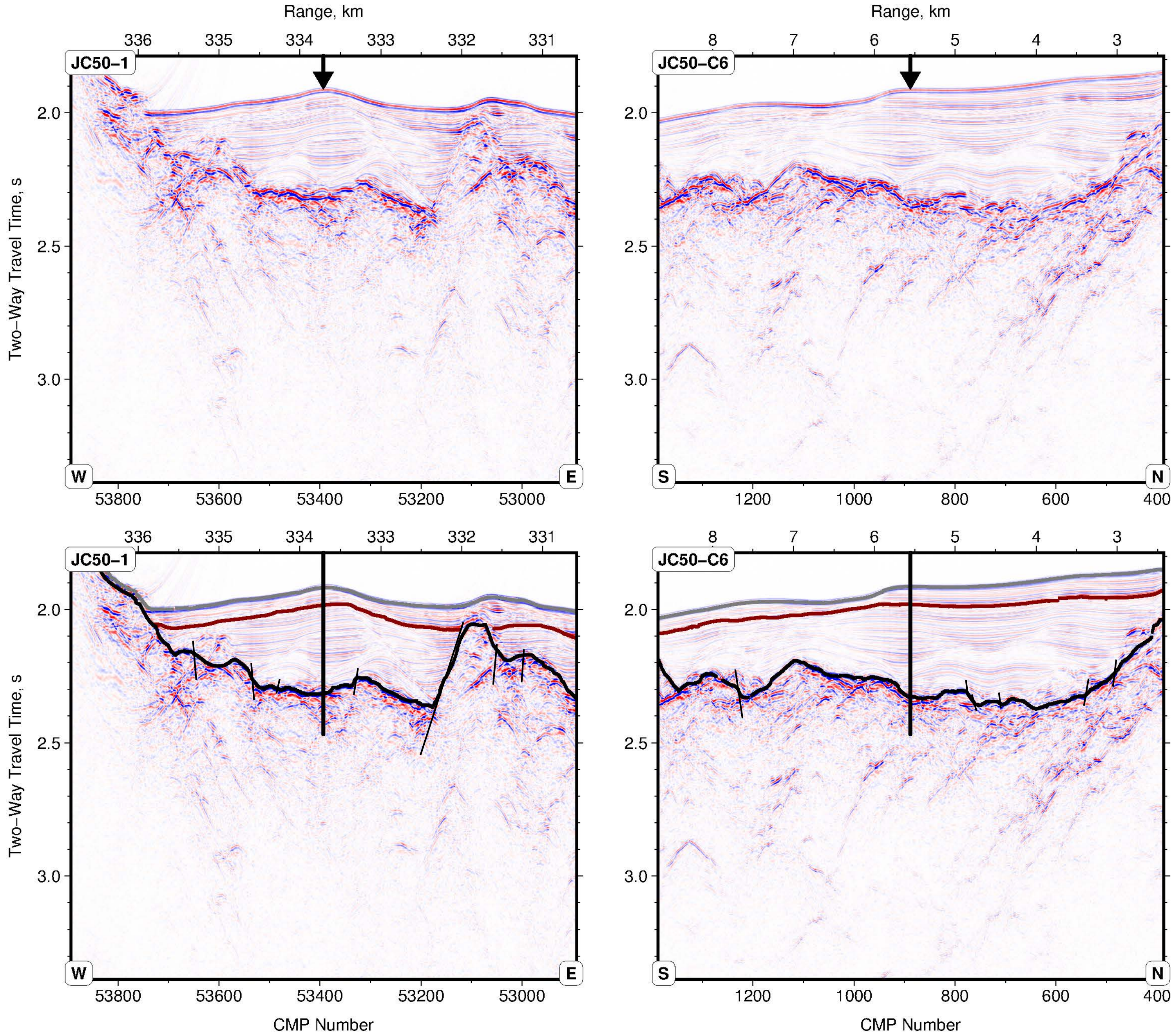


Site Summary Figure: Proposal P892−Full Site REYK−11A

Location: −28.00000 W, 60.19994 N
CMP 53393 on JC50−1; CMP 888 on JC50−C6
Water depth: 1415 m / 1.918 s TWTT
Basement depth: 340 mbsf / 2.319 s TWTT
Target depth: 540 mbsf / 2.467 s TWTT
Basement age: 5.23 Ma

Figures and supporting data in SSDB:
Location map: REYK−11A_site_sum_fig_map.pdf
Seismic images: REYK−11A_site_sum_fig_JC50−1.pdf & REYK−11A_site_sum_fig_JC50−C6.pdf
SEGY data / Navigation: JC50−1_stolt_trbal.segy / JC50−1.xy & JC50−C6_stolt_trbal.segy / JC50−C6.xy

Interpretation:
Gray = seabed ; red = B2 (0.47 Ma); green = B3 (2.15 Ma); blue = B4 (2.63 Ma); orange = B5 (3.7 Ma); black = basement



IODP Site Forms

Form 1 – General Site Information

892 - Full 2

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Obtain continuous stratigraphic section through Bjorn Drift, then sample ~200 m of basaltic crust at V-shaped trough 2b. Primary site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-6A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 60.1251	Jurisdiction:	International
Longitude:	Deg: -26.7016	Distance to Land: (km)	149
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☑ Alternate: ☐	Water Depth (m):	1871

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	705	200
	Total Sediment Thickness (m) 705	
		Total Penetration (m): 905
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

Triple APC to refusal, third hole continue XCB/RCB to target depth ~200 m within oceanic crustal basement.

APC ☑ XCB ☑ RCB ☑ Re-entry ☑ PCS ☐

Wireline Logging Plan:

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

Other Measurements:

Estimated Days:		
Drilling/Coring: 10.2	Logging: 1	Total On-site: 11.2

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_2S	☐	High Dip Angle	☐	Ice Conditions	☐
CO_2	☐				

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

Preferred weather window: Summer required as North Atlantic weather poor during winter

Other:

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Proposal #: 892 - Full 2	Site #: REYK-6A	Date Form Submitted: 2017-04-03 15:37:51

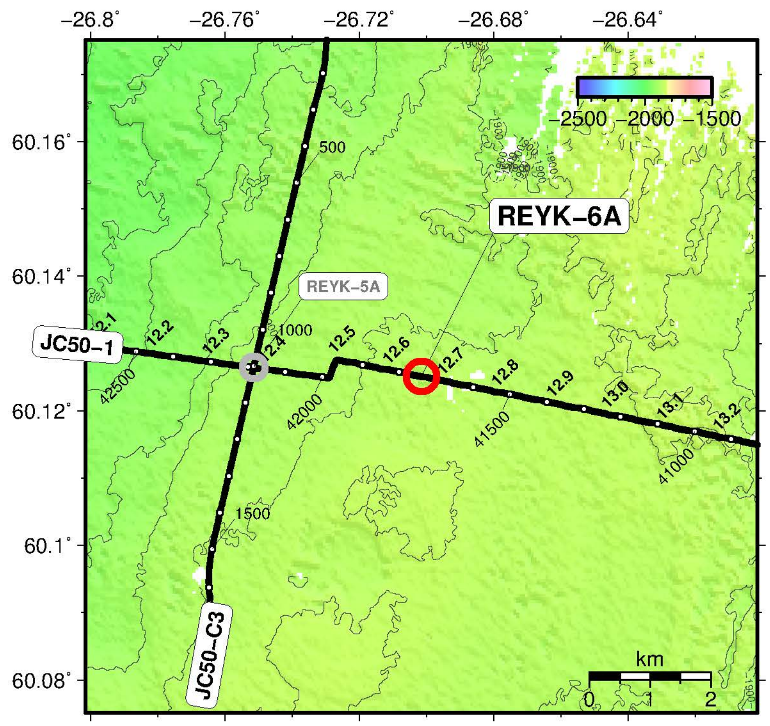
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 41740
1b High resolution seismic seismic reflection (crossing)		Line: Profile JC50-C3 Position: 1005 Site located 2.8 km east of crossing point in order to avoid a possible sediment discontinuity
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 Cruise navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-6A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Triple APC to refusal, on final hole XCB/RCB to basement at 705 m. RCB 200 m into basement, log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-6A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 110	Seabed to reflection B2	0.47	1.55	Nannofossil clay	Pelagic	234	Age based upon reflection R2 at Site 984
110 - 175	Reflection B2 to reflection B3	0.47-2.15	1.63	Nannofossil clay	Pelagic	39	Age and lithology based on results from Site 984
175 - 365	Reflection B3 to reflection B4	2.15-2.63	1.76	Silty clay	Pelagic	396	
365 - 600	Reflection B4 to reflection B5	2.63-3.7	1.87	Silty clay	Pelagic	220	
600 - 705	Reflection B5 to acoustic basement	3.7-12.7	2000	Silty clay	Pelagic	12	
705 - 705	Acoustic basement	12.7 and older	2.7	Vesicular basalt	Pelagic	N/A	

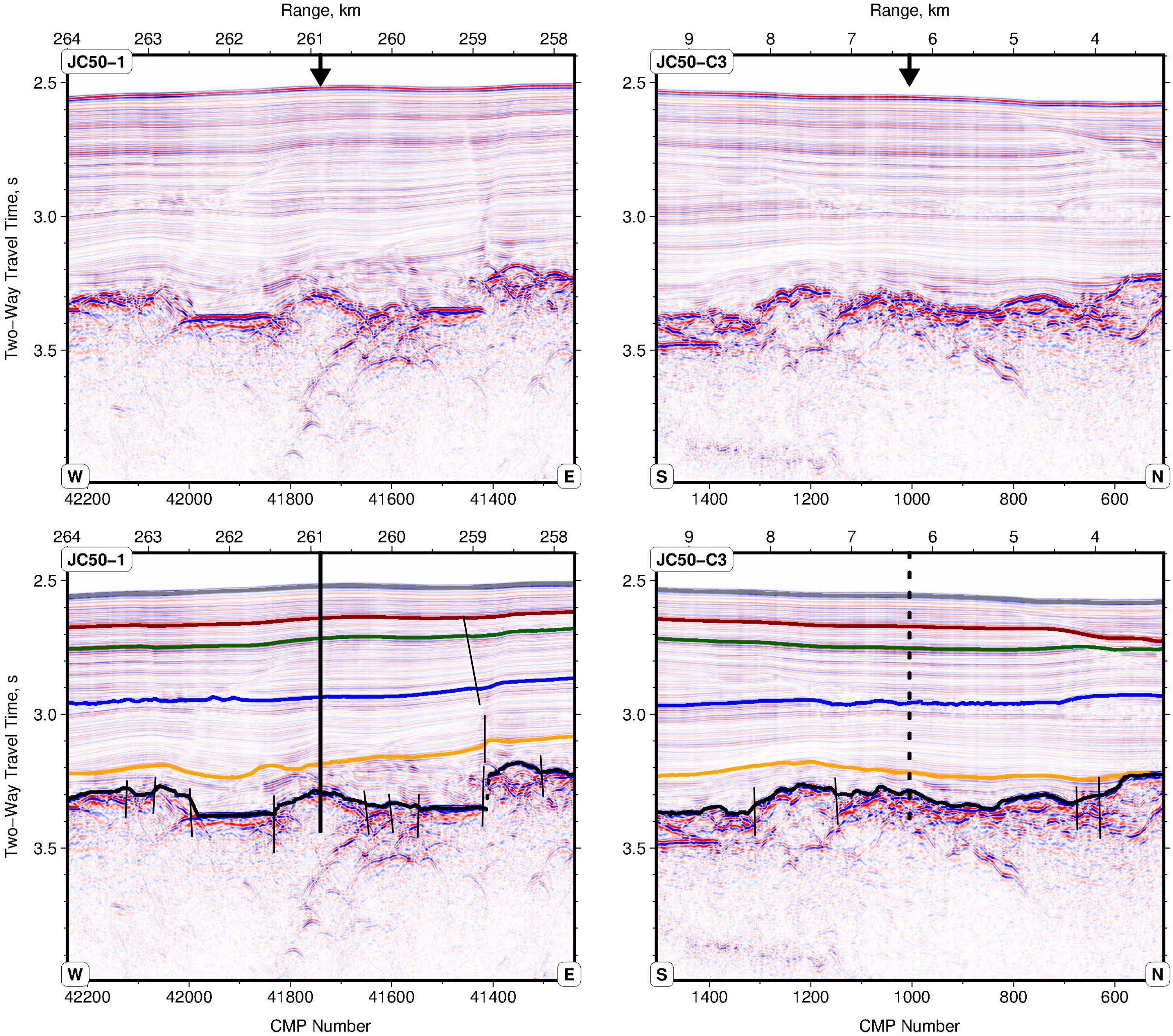


Site Summary Figure: Proposal P892−Full Site REYK−6A

Location: −26.70160 W, 60.12510 N
CMP 41740 on JC50−1; CMP 1005 on JC50−C3
Water depth: 1871 m / 2.520 s TWTT
Basement depth: 705 mbsf / 3.288 s TWTT
Target depth: 905 mbsf / 3.437 s TWTT
Basement age: 12.68 Ma

Figures and supporting data in SSDB:
Location map: REYK−6A_site_sum_fig_map.pdf
Seismic images: REYK−6A_site_sum_fig_JC50−1.pdf & REYK−6A_site_sum_fig_JC50−C3.pdf
SEGY data / Navigation: JC50−1_stolt_trbal.segy / JC50−1.xy & JC50−C3_stolt_trbal.segy / JC50−C3.xy

Interpretation:
Gray = seabed ; red = B2 (0.47 Ma); green = B3 (2.15 Ma); blue = B4 (2.63 Ma); orange = B5 (3.7 Ma); black = basement



IODP Site Forms

Form 1 – General Site Information

892 - Full 2

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Sample ~200 m of basalt at V-shaped ridge 3. Primary site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-4A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 60.0992	Jurisdiction:	International
Longitude:	Deg: -26.4436	Distance to Land: (km)	147
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☑ Alternate: ☐	Water Depth (m):	2110

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	185	200
	Total Sediment Thickness (m): 185	
		Total Penetration (m): 385
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

APC to basement or refusal, RCB to target depth ~200 m within oceanic crustal basement.

APC ☑ XCB ☑ RCB ☑ Re-entry ☐ PCS ☐

Wireline Logging Plan:

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

Other Measurements:

Estimated Days:

Drilling/Coring:	Logging:	Total On-site:
5.3	0.8	6.1

Observatory Plan:

Longterm Borehole Observation Plan/Re-entry Plan

N/A

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_2S	☐	High Dip Angle	☐	Ice Conditions	☐
CO_2	☐				

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

Preferred weather window: Summer required as North Atlantic weather poor in Winter

Other:

Proposal #: 892 - Full 2	Site #: REYK-4A	Date Form Submitted: 2017-04-03 15:37:51

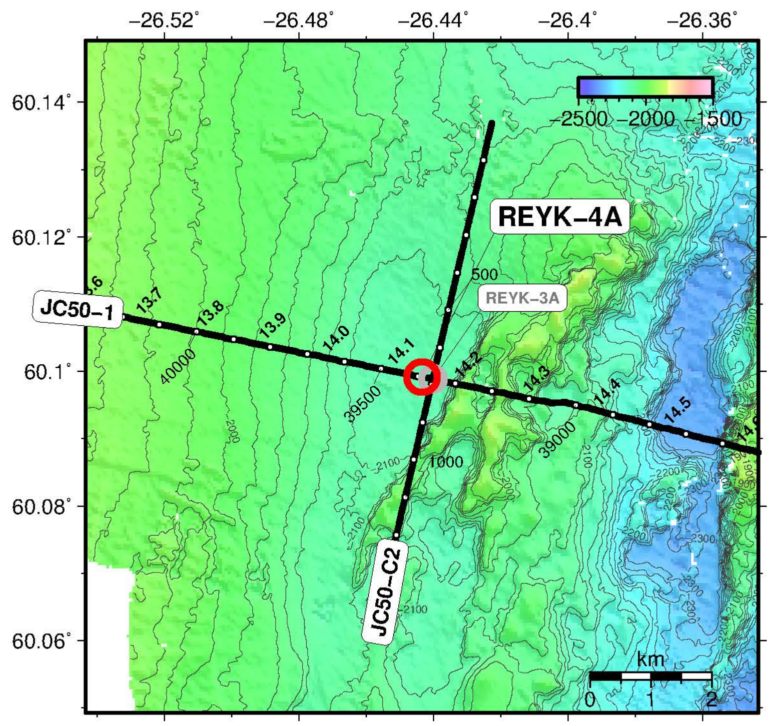
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 39390
1b High resolution seismic seismic reflection (crossing)	yes	Line: Profile JC50-C2 Position: 685 Site located 200 m west of crossing point in order to avoid possible basement fault
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 cruise navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-4A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Single APC to basement at 185 m. RCB 200 m into basement, log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-4A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 65	Seabed to reflection B2	0.47	1.55	Nannofossil clay	Pelagic	138	Age based upon reflection R2 at Site 984
65 - 135	Reflection B2 to reflection B5	0.47-3.7	1.63	Silty clay	Pelagic	22	Age and lithology based on results from Site 984
135 - 185	Reflection B5 to acoustic basement	3.7-14.2	1.76	Silty clay	Pelagic	5	
205 - 205	Acoustic basement	14.2 and older	2.7	Vesicular basalt	Pelagic	NA	

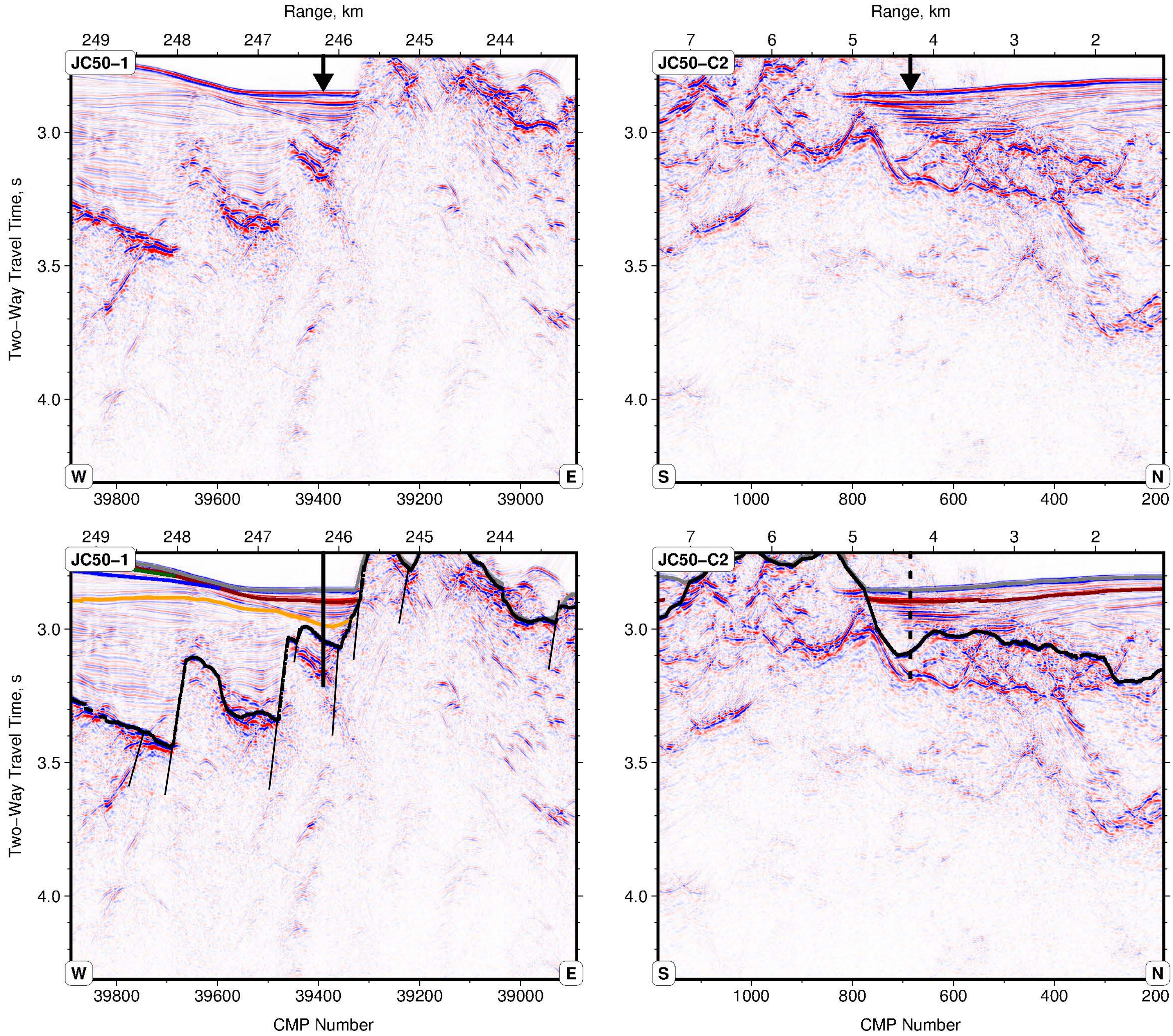


Site Summary Figure: Proposal P892-Full Site REYK-4A

Location: -26.44355 W, 60.09916 N
CMP 39390 on JC50-1; CMP 685 on JC50-C2
Water depth: 2110 m / 2.853 s TWTT
Basement depth: 185 mbsf / 3.063 s TWTT
Target depth: 385 mbsf / 3.211 s TWTT
Basement age: 14.17 Ma

Figures and supporting data in SSDB:
Location map: REYK-4A_site_sum_fig_map.pdf
Seismic images: REYK-4A_site_sum_fig_JC50-1.pdf & REYK-4A_site_sum_fig_JC50-C2.pdf
SEGY data / Navigation: JC50-1_stolt_trbal.segy / JC50-1.xy & JC50-C2_stolt_trbal.segy / JC50-C2.xy

Interpretation:
Gray = seabed ; red = B2 (0.47 Ma); green = B3 (2.15 Ma); blue = B4 (2.63 Ma); orange = B5 (3.7 Ma); black = basement



IODP Site Forms

892 - Full 2

Form 1 – General Site Information

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Obtain continuous stratigraphic section through Gardar Drift, then sample ~200 m of basaltic rocks from the rough crustal domain. Primary site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-2A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 59.8506	Jurisdiction:	International
Longitude:	Deg: -23.2664	Distance to Land: (km)	140
Coordinate System:	WGS 84		
Priority of Site:	Primary: ✔ Alternate: ☐	Water Depth (m):	2206

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Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	970	200
	Total Sediment Thickness (m): 970	
		Total Penetration (m): 1170
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

Triple APC to refusal, third hole continue XCB/RCB to target depth ~200 m within oceanic crustal basement.

APC ☑ XCB ☑ RCB ☑ Re-entry ☑ PCS ☐

Wireline Logging Plan:

Standard Measurements		Special Tools		Other tools
WL	☑	Magnetic Susceptibility	☑	
Porosity	☑	Borehole Temperature	☐	
Density	☑	Formation Image (Acoustic)	☐	
Gamma Ray	☑	VSP (walkaway)	☐	
Resistivity	☑	LWD	☐	
Sonic (Δt)	☑			
Formation Image (Res)	☑			
VSP (zero offset)	☐			
Formation Temperature & Pressure	☐			

Other Measurements:

Estimated Days:

Drilling/Coring:	Logging:	Total On-site:
13	1	14

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_2S	☐	High Dip Angle	☐	Ice Conditions	☐
CO_2	☐				

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

Preferred weather window: Summer required as North Atlantic weather poor during Winter

Other:

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Proposal #: 892 - Full 2	Site #: REYK-2A	Date Form Submitted: 2017-04-03 15:37:51

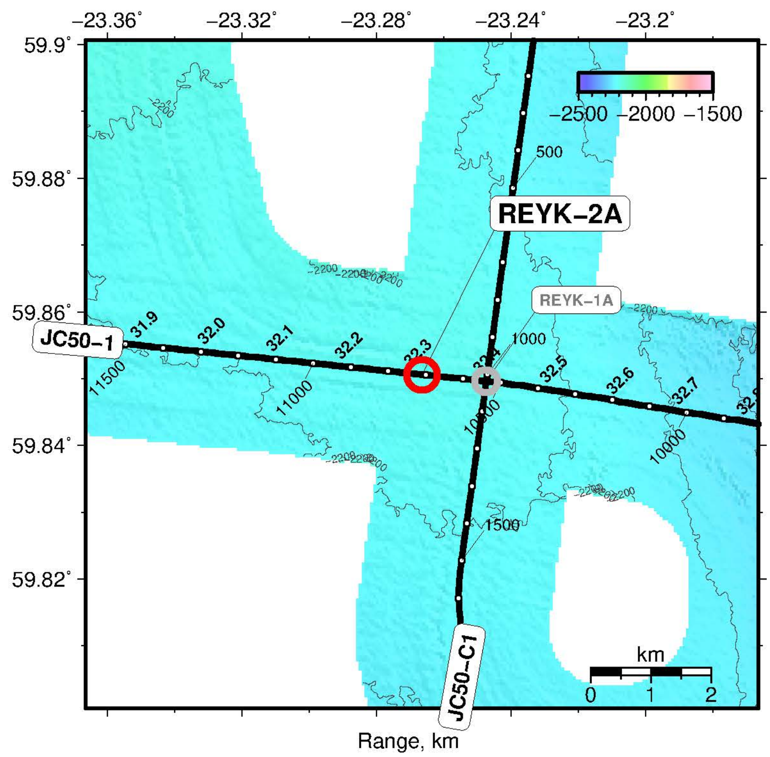
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 10710
1b High resolution seismic seismic reflection (crossing)	yes	Line: Profile JC50-C1 Position: 1019 Site located 1.1 km west of crossing point in order to avoid shallow faults
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 site survey navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-2A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Triple APC to refusal, on final hole XCB/RCB to basement at 955 m. RCB 200 m into basement, log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-2A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 145	Seabed to reflection G2	1.0	1.55	Nannofossil clay	Pelagic	145	Age based upon reflection R2 at Site 983
145 - 195	Reflection G2 to reflection G3	1.0-1.25	1.63	Nannofossil clay	Pelagic	200	Age and lithology based on results from Site 983
195 - 355	Reflection G3 to reflection G4	older than 1.25	1.76	Silty clay	Pelagic	unknown	Ages unknown between reflection G3 and acoustic basement
355 - 615	Reflection G4 to reflection G5	older than 1.25	1.87	Silty clay	Pelagic	unknown	Ages unknown between reflection G3 and acoustic basement
615 - 970	Reflection G5 to acoustic basement	1.25 - 32.3	2000	Silty clay	Pelagic	unknown	Ages unknown between reflection G3 and acoustic basement
970 - 970	Acoustic basement	32.3 and older	2.7	Vesicular basalt	Pelagic	N/A	

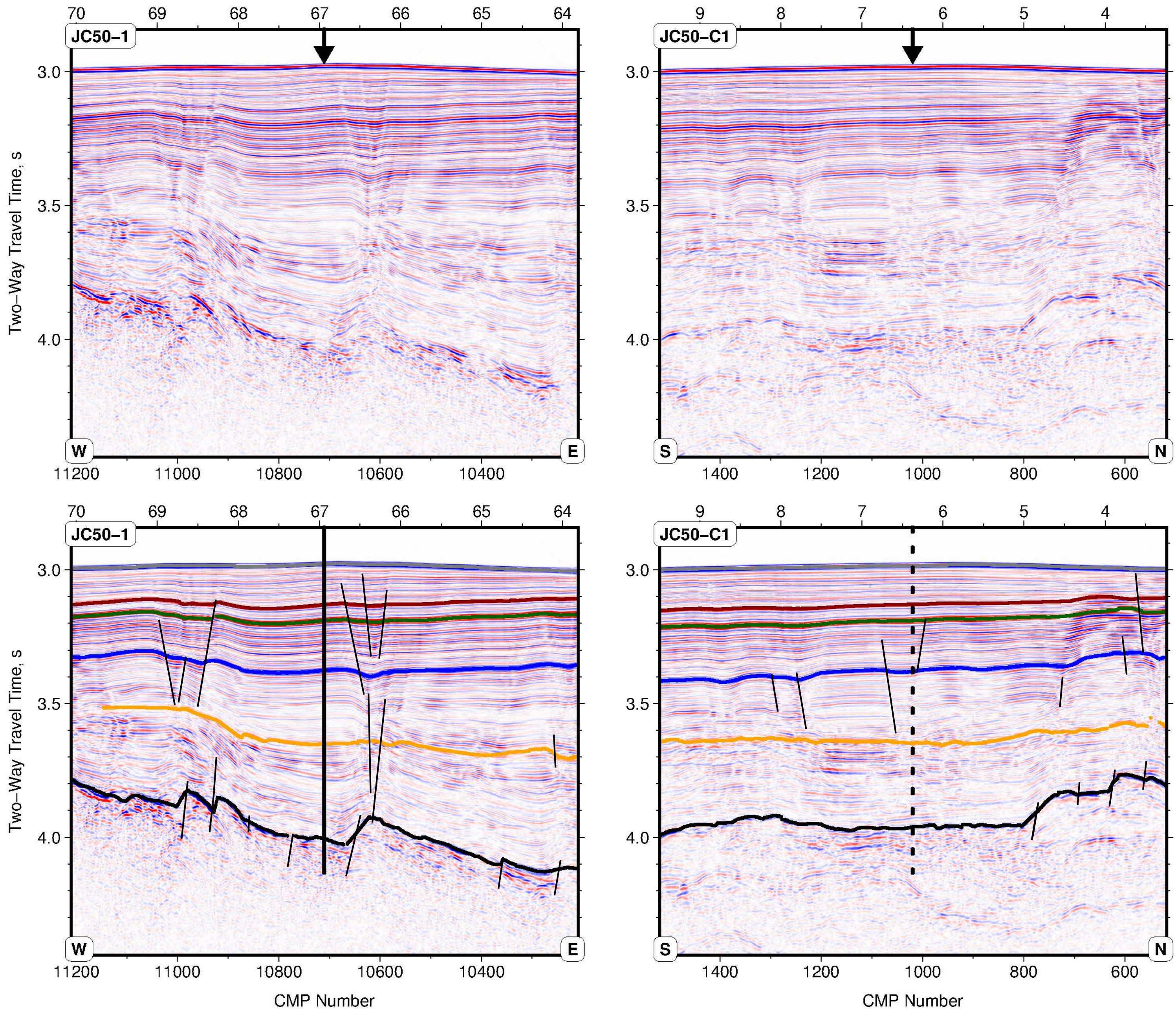


Site Summary Figure: Proposal P892−Full Site REYK−2A

Location: −23.26643 W, 59.85061 N
CMP 10710 on JC50−1; CMP 1019 on JC50−C1
Water depth: 2206 m / 2.977 s TWTT
Basement depth: 970 mbsf / 3.983 s TWTT
Target depth: 1170 mbsf / 4.132 s TWTT
Basement age: 32.35 Ma

Figures and supporting data in SSDB:
Location map: REYK−2A_site_sum_fig_map.pdf
Seismic images: REYK−2A_site_sum_fig_JC50−1.pdf & REYK−2A_site_sum_fig_JC50−C1.pdf
SEGY data / Navigation: JC50−1_stolt_trbal.segy / JC50−1.xy & JC50−C1_stolt_trbal.segy / JC50−C1.xy

Interpretation:
Gray = seabed ; red = G2 (1.0 Ma); green = G3 (1.25 Ma); blue = G4; orange = G5; black = basement



IODP Site Forms

Form 1 – General Site Information

892 - Full 2

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Sample ~200 m of basalt at V-shaped ridge 2b. Alternate site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-7A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 60.1507	Jurisdiction:	International
Longitude:	Deg: -27.1698	Distance to Land: (km)	151
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☐ Alternate: ☑	Water Depth (m):	1735

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	330	200
	Total Sediment Thickness (m) 330	
		Total Penetration (m): 530
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

APC to basement or refusal, RCB to target depth ~200 m within oceanic crustal basement.

APC ☑ XCB ☑ RCB ☑ Re-entry ☐ PCS ☐

Wireline Logging Plan:

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

Other Measurements:

Estimated Days: Drilling/Coring: 6.7 Logging: 0.8 Total On-site: 7.5

Observatory Plan:

Longterm Borehole Observation Plan/Re-entry Plan

N/A

Potential Hazards/ Weather:

						Preferred weather window
Shallow Gas	☐	Complicated Seabed Condition	☐	Hydrothermal Activity	☐	Summer required as North Atlantic weather poor in Winter
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_2S	☐	High Dip Angle	☐	Ice Conditions	☐	
CO_2	☐					
Sensitive marine habitat (e.g., reefs, vents)						

Other:

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Proposal #: 892 - Full 2	Site #: REYK-7A	Date Form Submitted: 2017-04-03 15:37:51

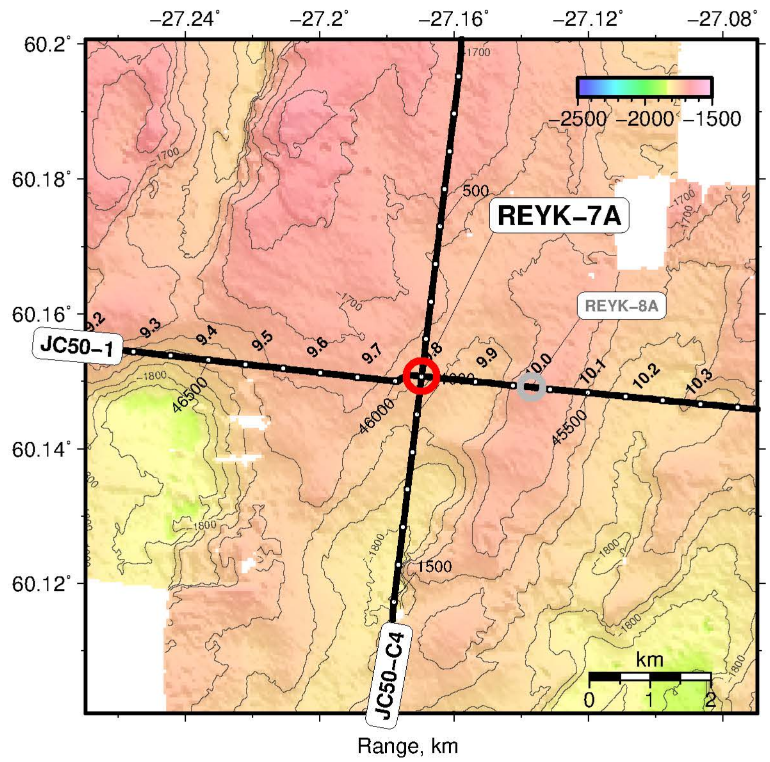
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 45944
1b High resolution seismic seismic reflection (crossing)	yes	Line: Profile JC50-C4 Position: 899
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 cruise navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-7A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Single APC to refusal. XCB/RCB to basement at 380 m, penetrate 200 m into basement and log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-7A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 115	Seabed to reflection B2	0.47	1.55	Nannofossil clay	Pelagic	245	Age based upon reflection R2 at Site 984
115 - 180	Reflection B2 to reflection B3	0.47-2.15	1.63	Silty clay	Pelagic	39	Age and lithology based on results from Site 984
180 - 330	Reflection B3 to acoustic basement	2.15-9.8	1.76	Silty clay	Pelagic	20	
330 - 330	Acoustic basement	9.8 and older	2.7	Vesicular basalt	Pelagic	NA	



Site Summary Figure: Proposal P892-Full Site REYK-7A

Location: -27.16977 W, 60.15074 N

CMP 45944 on JC50-1; CMP 899 on JC50-C4

Water depth: 1735 m / 2.343 s TWTT

Basement depth: 330 mbsf / 2.715 s TWTT

Target depth: 530 mbsf / 2.863 s TWTT

Basement age: 9.82 Ma

Figures and supporting data in SSDB:

Location map: REYK-7A_site_sum_fig_map.pdf

Seismic images: REYK-7A_site_sum_fig_JC50-1.pdf &

REYK-7A_site_sum_fig_JC50-C4.pdf

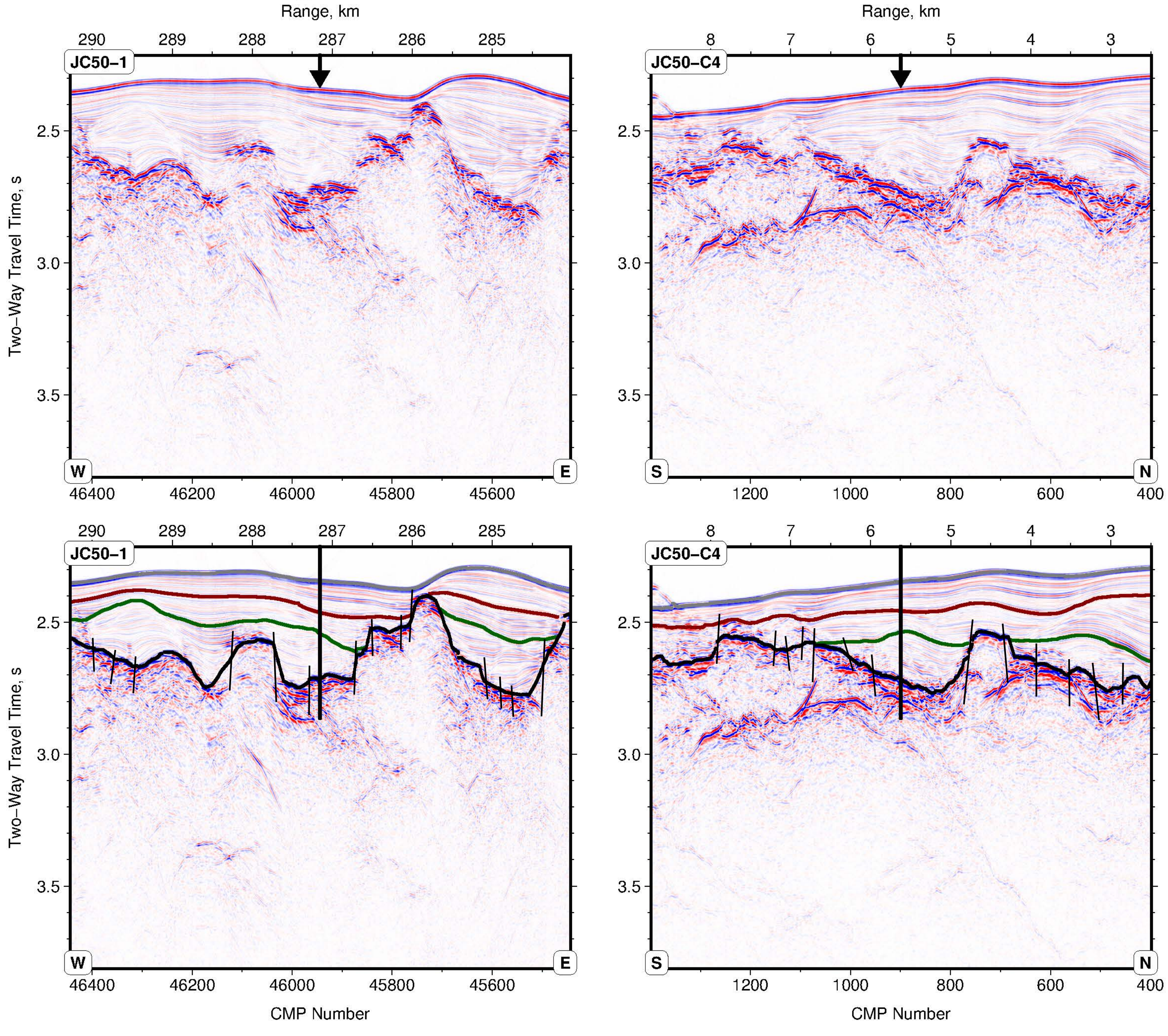
SEGY data / Navigation: JC50-1_stolt_trbal.segy / JC50-1.xy &

JC50-C4_stolt_trbal.segy / JC50-C4.xy

Interpretation:

Gray = seabed ; red = B2 (0.47 Ma); green = B3 (2.15 Ma);

blue = B4 (2.63 Ma); orange = B5 (3.7 Ma); black = basement



IODP Site Forms

892 - Full 2

Form 1 – General Site Information

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Sample ~200 m of basalt at V-shaped trough 2a. Alternate site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-9A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 60.1702	Jurisdiction:	International
Longitude:	Deg: -27.5310	Distance to Land: (km)	154
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☐ Alternate: ☑	Water Depth (m):	1701

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	310	200
	Total Sediment Thickness (m): 310	
		Total Penetration (m): 510
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

APC/XCB to basement at 310 m, RCB to target depth ~200 m within oceanic crustal basement.

- APC ☑
- XCB ☑
- RCB ☑
- Re-entry ☐
- PCS ☐

Wireline Logging Plan:

Standard Measurements		Special Tools	
WL	☑	Magnetic Susceptibility	☑
Porosity	☑	Borehole Temperature	☐
Density	☑	Formation Image (Acoustic)	☐
Gamma Ray	☑	VSP (walkaway)	☐
Resistivity	☑	LWD	☐
Sonic (Δt)	☑		
Formation Image (Res)	☑		
VSP (zero offset)	☐		
Formation Temperature & Pressure	☐		

Other tools:

Other Measurements:

Estimated Days: Drilling/Coring: 6.5 | Logging: 0.8 | Total On-site: 7.3

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

N/A

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_2S	☐	High Dip Angle	☐	Ice Conditions	☐
CO_2	☐				

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

Preferred weather window: Summer required as North Atlantic weather poor in Winter

Other:

Generated: 2017-04-13T00:09:35+00:00

Proposal #: 892 - Full 2	Site #: REYK-9A	Date Form Submitted: 2017-04-03 15:37:51

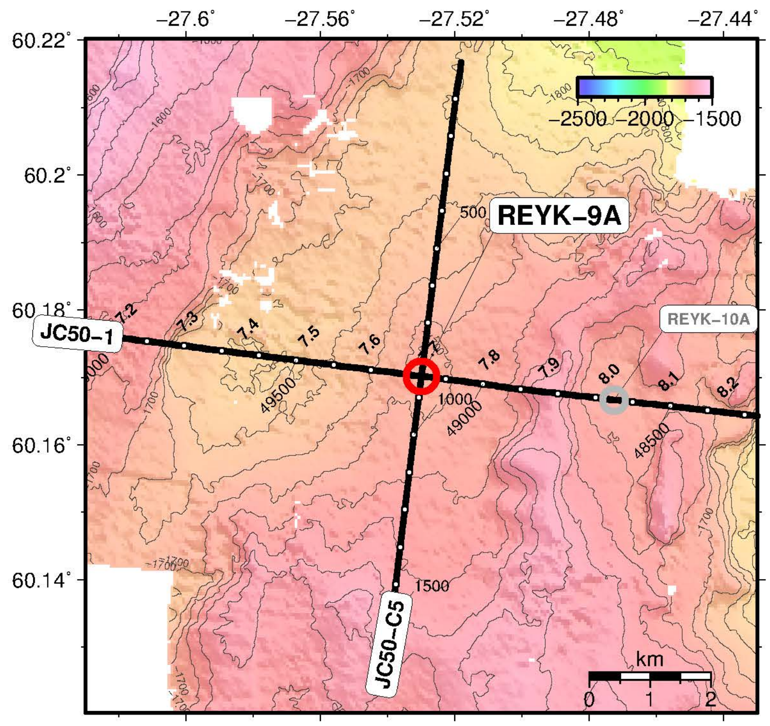
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 49165
1b High resolution seismic seismic reflection (crossing)	yes	Line: Profile JC50-C5 Position: 843
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 cruise navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-9A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Single APC/XCB to basement at 310 m, penetrate 200 m into basement and log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-9A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 125	Seabed to reflection B2	0.47	1.55	Nannofossil clay	Pelagic	266	Age based upon reflection R2 at Site 984
125 - 310	Reflection B2 to acoustic basement	0.47-7.7	1.76	Silty clay	Pelagic	26	
310 - 310	Acoustic basement	7.7 and older	2.7	Vesicular basalt	Pelagic	NA	

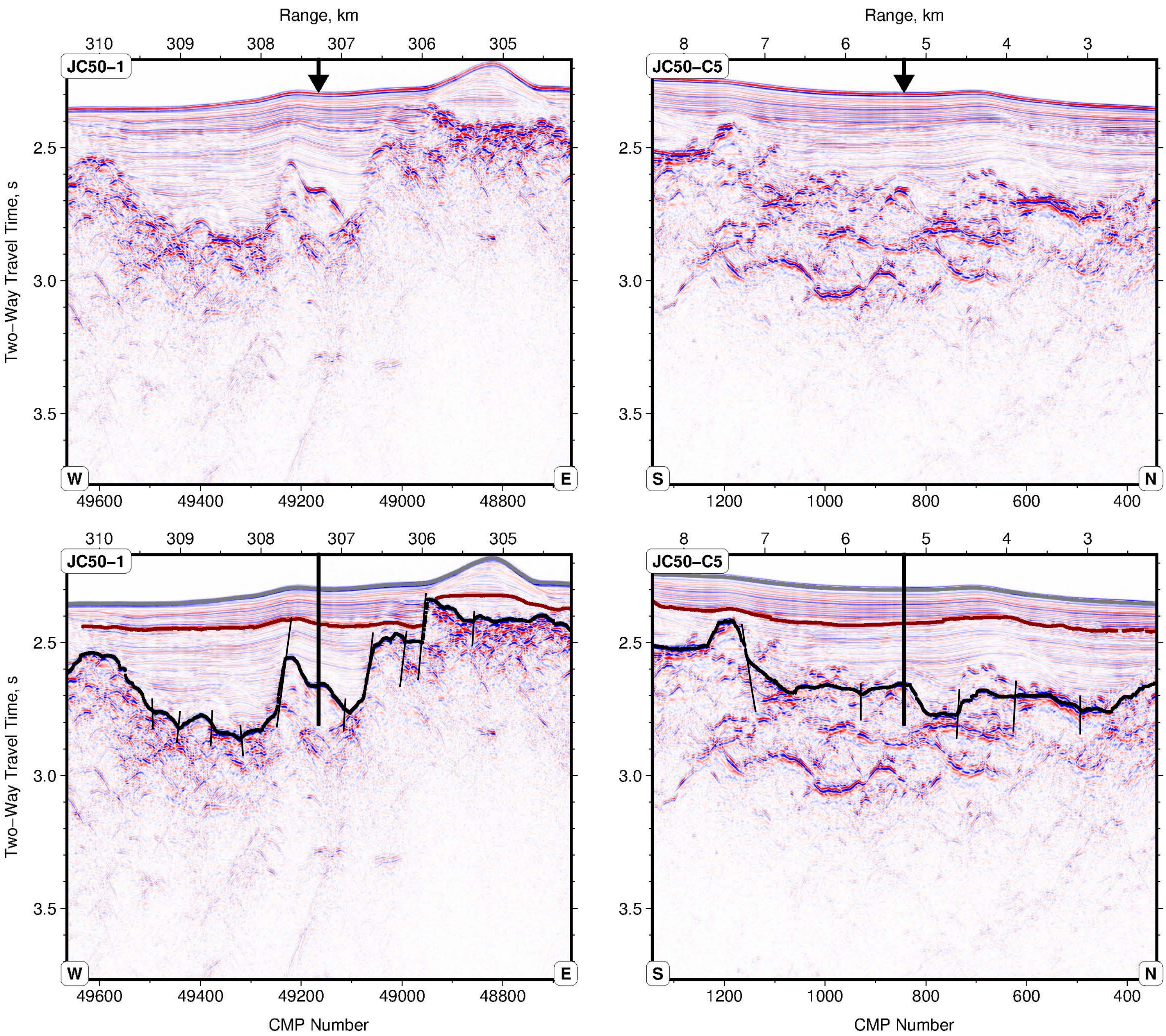


Site Summary Figure: Proposal P892−Full Site REYK−9A

Location: −27.52994 W, 60.17019 N
CMP 49165 on JC50−1; CMP 843 on JC50−C5
Water depth: 1701 m / 2.297 s TWTT
Basement depth: 310 mbsf / 2.658 s TWTT
Target depth: 510 mbsf / 2.806 s TWTT
Basement age: 7.73 Ma

Figures and supporting data in SSDB:
Location map: REYK−9A_site_sum_fig_map.pdf
Seismic images: REYK−9A_site_sum_fig_JC50−1.pdf & REYK−9A_site_sum_fig_JC50−C5.pdf
SEGY data / Navigation: JC50−1_stolt_trbal.segy / JC50−1.xy & JC50−C5_stolt_trbal.segy / JC50−C5.xy

Interpretation:
Gray = seabed ; red = B2 (0.47 Ma); green = B3 (2.15 Ma); blue = B4 (2.63 Ma); orange = B5 (3.7 Ma); black = basement



IODP Site Forms

Form 1 – General Site Information

892 - Full 2

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Obtain continuous stratigraphic section through Gardar Drift, then sample ~200 m of basaltic rocks from the fractured crustal domain. Alternate site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-1A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 59.8496	Jurisdiction:	International
Longitude:	Deg: -23.2473	Distance to Land: (km)	140
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☐ Alternate: ☑	Water Depth (m):	2209

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	955	200
	Total Sediment Thickness (m): 955	
		Total Penetration (m): 1155
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

Triple APC to refusal, third hole continue XCB/RCB to target depth ~200 m within oceanic crustal basement.

APC ☑ XCB ☑ RCB ☑ Re-entry ☑ PCS ☐

Wireline Logging Plan:

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

Other Measurements:

Estimated Days:

Drilling/Coring:	Logging:	Total On-site:
13.7	1	14.7

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

Potential Hazards/ Weather:

						Preferred weather window
Shallow Gas	☐	Complicated Seabed Condition	☐	Hydrothermal Activity	☐	Summer required as North Atlantic weather poor during Winter
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_2S	☐	High Dip Angle	☐	Ice Conditions	☐	
CO_2	☐					

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

Other:

Proposal #: 892 - Full 2	Site #: REYK-1A	Date Form Submitted: 2017-04-03 15:37:51

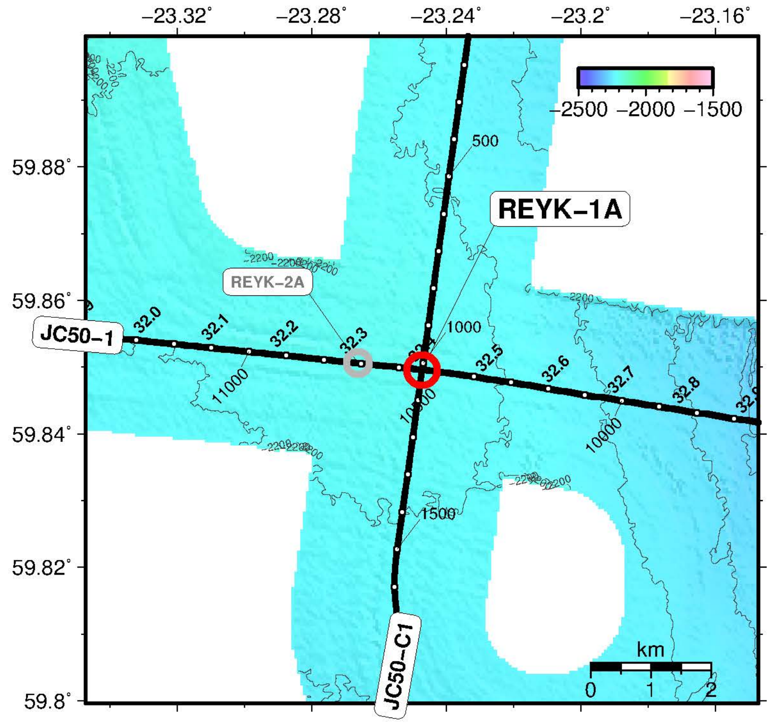
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 10538 The sedimentary package is disturbed by a number of small faults that extend from basement to seabed, at range 66–67 km on JC50-1 and 6.4 km on JC50-C1, hence primary site REYK-2A is preferred,
1b High resolution seismic seismic reflection (crossing)	yes	Line: Profile JC50-C3 Position: 1019
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 site survey navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-1A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Triple APC to refusal, on final hole XCB/RCB to basement at 955 m. RCB 200 m into basement, log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-1A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 140	Seabed to reflection G2	1.0	1.55	Nannofossil clay	Pelagic	140	Age based upon reflection R2 at Site 983
140 - 190	Reflection G2 to reflection G3	1.0-1.25	1.63	Nannofossil clay	Pelagic	200	Age and lithology based on results from Site 983
190 - 355	Reflection G3 to reflection G4	older than 1.25	1.76	Silty clay	Pelagic	unknown	Ages unknown between reflection G3 and acoustic basement
355 - 610	Reflection G4 to reflection G5	older than 1.25	1.87	Silty clay	Pelagic	unknown	Ages unknown between reflection G3 and acoustic basement
610 - 955	Reflection G5 to acoustic basement	1.25 - 32.3	2000	Silty clay	Pelagic	unknown	Ages unknown between reflection G3 and acoustic basement
955 - 955	Acoustic basement	32.3 and older	2.7	Vesicular basalt	Pelagic	N/A	

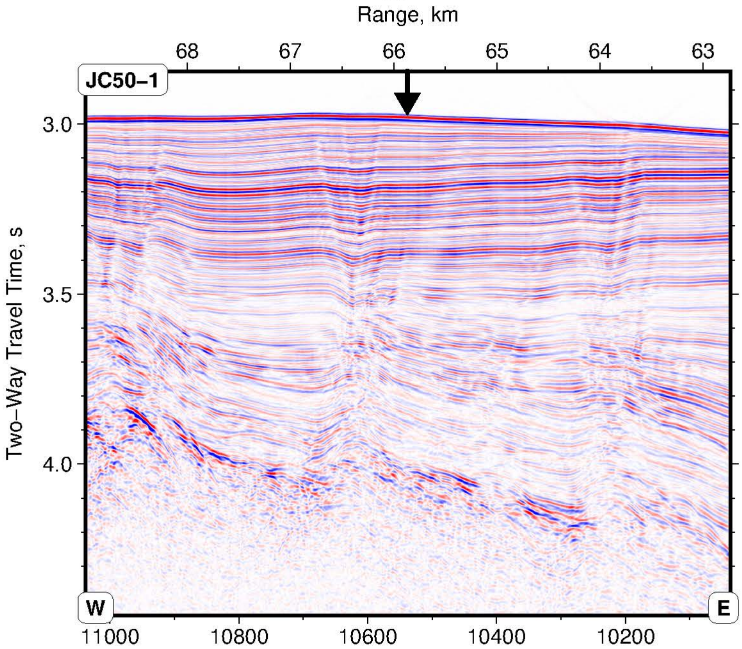


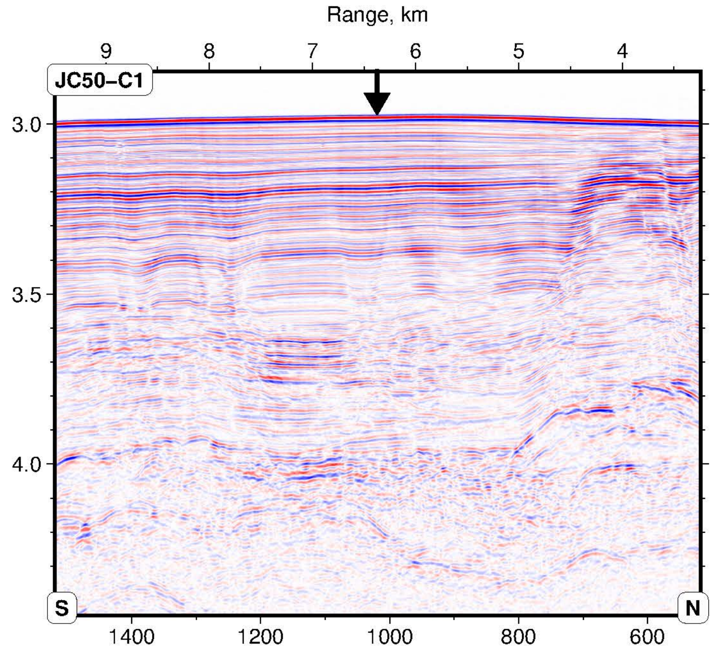
Site Summary Figure: Proposal P892−Full Site REYK−1A

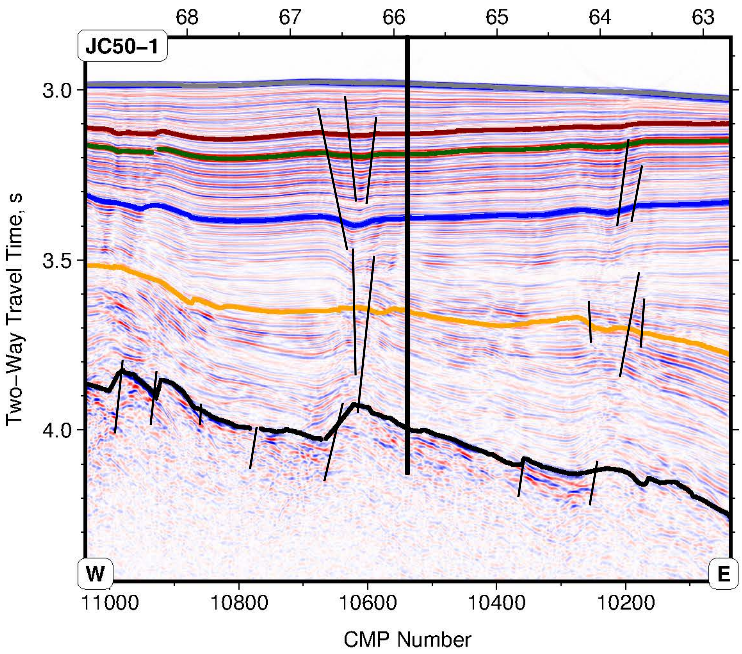
Location: −23.24726 W, 59.84961 N
CMP 10538 on JC50−1; CMP 1019 on JC50−C1
Water depth: 2209 m / 2.980 s TWTT
Basement depth: 955 mbsf / 3.978 s TWTT
Target depth: 1155 mbsf / 4.126 s TWTT
Basement age: 32.44 Ma

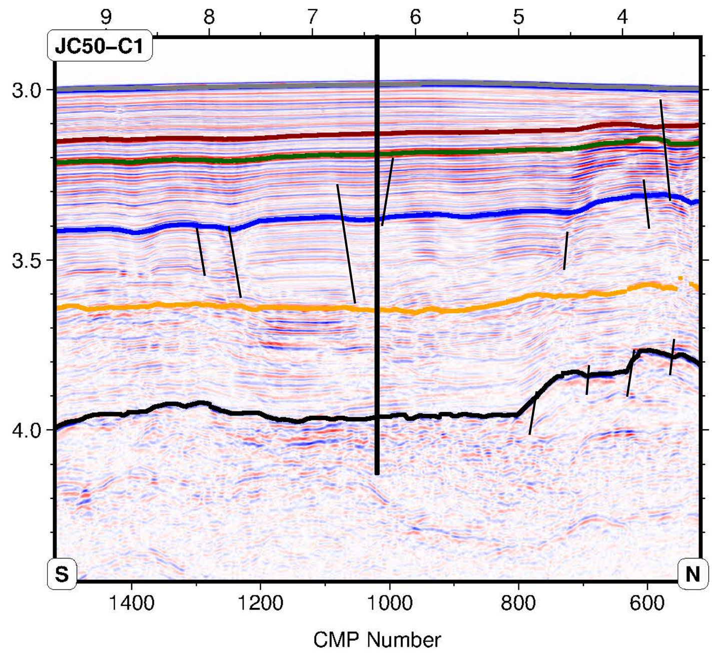
Figures and supporting data in SSDB:
Location map: REYK−1A_site_sum_fig_map.pdf
Seismic images: REYK−1A_site_sum_fig_JC50−1.pdf & REYK−1A_site_sum_fig_JC50−C1.pdf
SEGY data / Navigation: JC50−1_stolt_trbal.segy / JC50−1.xy & JC50−C1_stolt_trbal.segy / JC50−C1.xy

Interpretation:
Gray = seabed ; red = G2 (1.0 Ma); green = G3 (1.25 Ma); blue = G4; orange = G5; black = basement









IODP Site Forms

Form 1 – General Site Information

892 - Full 2

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Sample ~200 m of basalt at V-shaped ridge 3. Alternate site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-3A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 60.0989	Jurisdiction:	International
Longitude:	Deg: -26.4404	Distance to Land: (km)	147
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☐ Alternate: ☑	Water Depth (m):	2110

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	205	200
	Total Sediment Thickness (m) 205	
		Total Penetration (m): 405
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

APC to basement or refusal, RCB to target depth ~200 m within oceanic crustal basement.

APC ☑ XCB ☑ RCB ☑ Re-entry ☐ PCS ☐

Wireline Logging Plan:

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

Other Measurements:

Estimated Days: Drilling/Coring: 6.4 Logging: 0.8 Total On-site: 7.2

Observatory Plan:

Longterm Borehole Observation Plan/Re-entry Plan

N/A

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_2S	☐	High Dip Angle	☐	Ice Conditions	☐
CO_2	☐				

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

Preferred weather window: Summer required as North Atlantic weather poor in Winter

Other:

Generated: 2017-04-13T00:09:36+00:00

Proposal #: 892 - Full 2	Site #: REYK-3A	Date Form Submitted: 2017-04-03 15:37:51

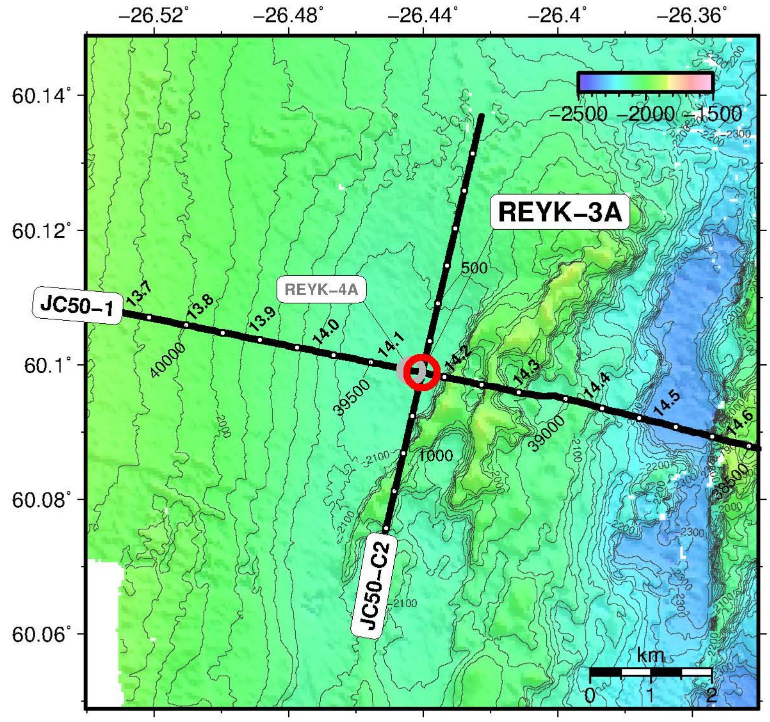
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 39361 Crossing point is close to a basement fault near range 246 km, which is avoided by shifting location 200 m west to REYK-4A
1b High resolution seismic seismic reflection (crossing)	yes	Line: Profile JC50-C2 Position: 685
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 cruise navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-3A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Single APC to basement at 205 m. RCB 200 m into basement, log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-3A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 65	Seabed to reflection B2	0.47	1.55	Nannofossil clay	Pelagic	138	Age based upon reflection R2 at Site 984
65 - 135	Reflection B2 to reflection B5	0.47-3.7	1.63	Silty clay	Pelagic	22	Age and lithology based on results from Site 984
135 - 205	Reflection B5 to acoustic basement	3.7-14.2	1.76	Silty clay	Pelagic	7	
205 - 205	Acoustic basement	14.2 and older	2.7	Vesicular basalt	Pelagic	NA	

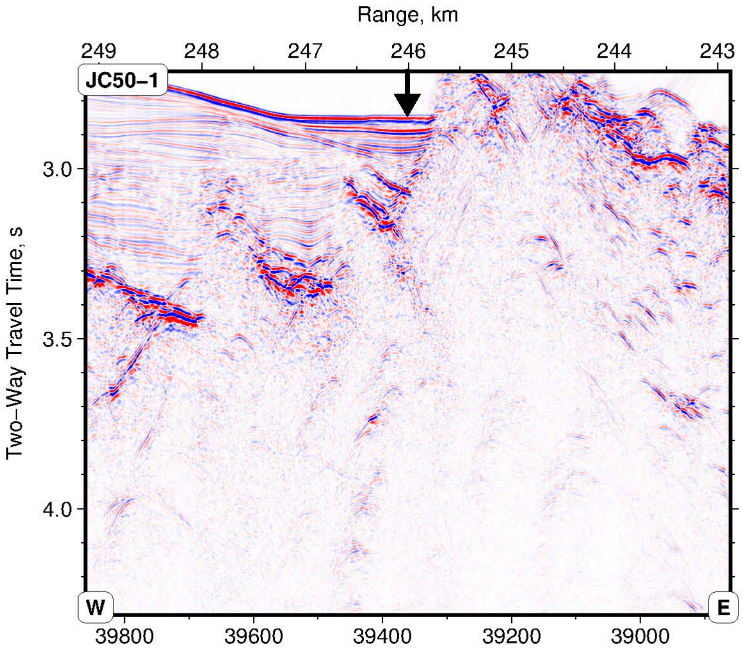


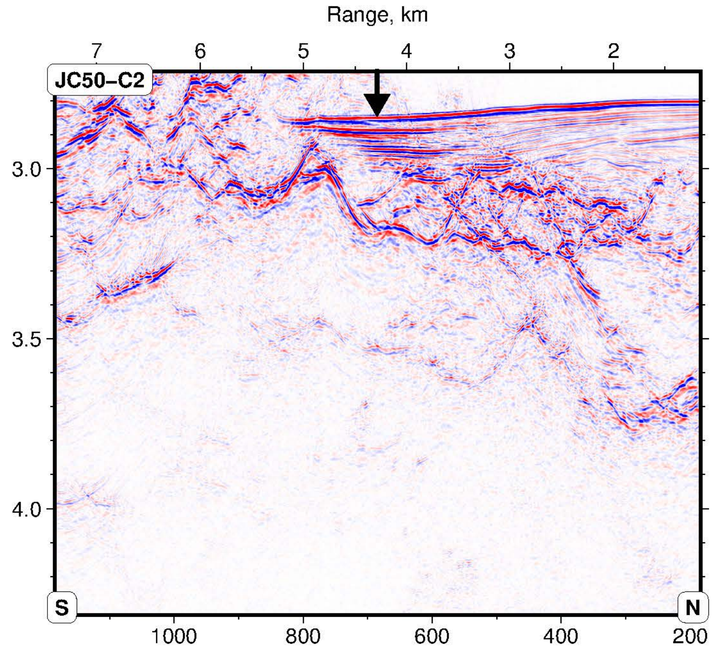
Site Summary Figure: Proposal P892−Full Site REYK−3A

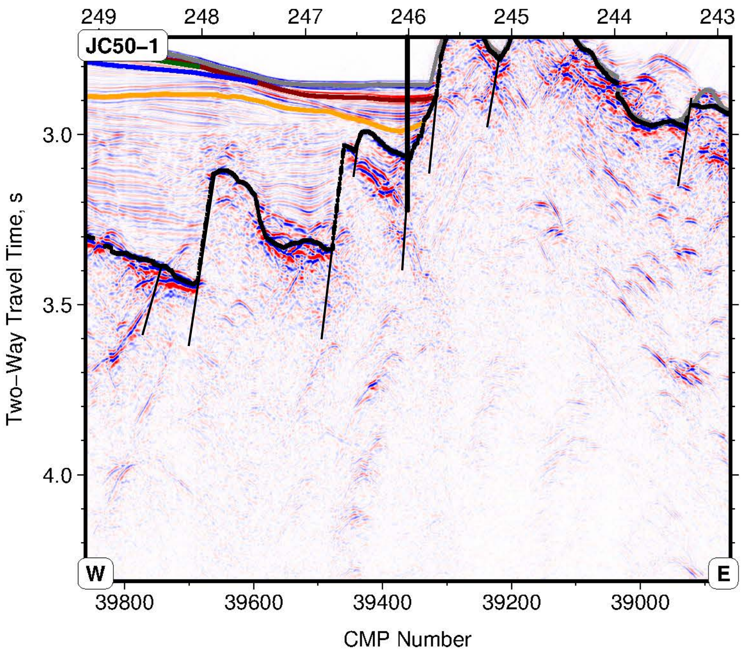
Location: −26.44036 W, 60.09886 N
CMP 39361 on JC50−1; CMP 685 on JC50−C2
Water depth: 2110 m / 2.853 s TWTT
Basement depth: 205 mbsf / 3.074 s TWTT
Target depth: 405 mbsf / 3.222 s TWTT
Basement age: 14.19 Ma

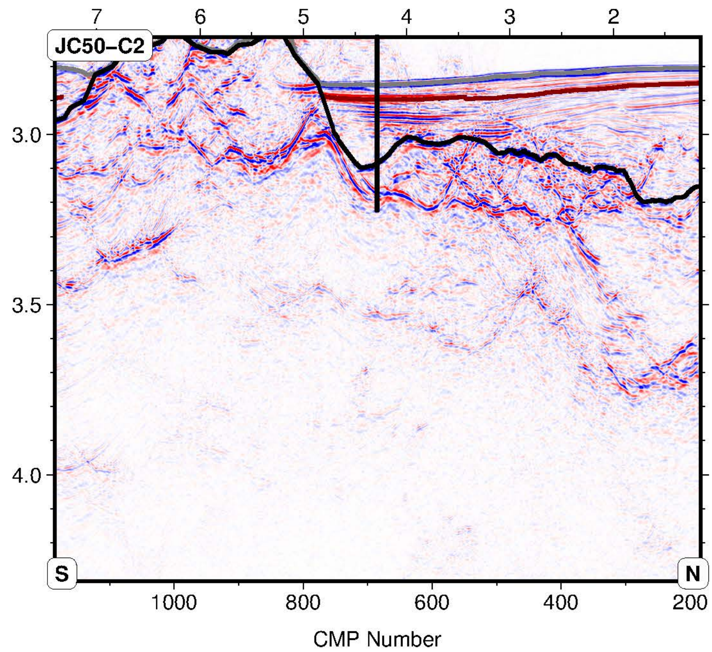
Figures and supporting data in SSDB:
Location map: REYK−3A_site_sum_fig_map.pdf
Seismic images: REYK−3A_site_sum_fig_JC50−1.pdf &
REYK−3A_site_sum_fig_JC50−C2.pdf
SEGY data / Navigation: JC50−1_stolt_trbal.segy / JC50−1.xy &
JC50−C2_stolt_trbal.segy / JC50−C2.xy

Interpretation:
Gray = seabed ; red = B2 (0.47 Ma); green = B3 (2.15 Ma);
blue = B4 (2.63 Ma); orange = B5 (3.7 Ma); black = basement









IODP Site Forms

Form 1 – General Site Information

892 - Full 2

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Obtain continuous stratigraphic section through Bjorn Drift, then sample ~200 m of basaltic crust at V-shaped trough 2b. Alternate site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-5A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 60.1264	Jurisdiction:	International
Longitude:	Deg: -26.7516	Distance to Land: (km)	149
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☐ Alternate: ☑	Water Depth (m):	1894

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	675	200
	Total Sediment Thickness (m) 675	
		Total Penetration (m): 875
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

Triple APC to refusal, third hole continue XCB/RCB to target depth ~200 m within oceanic crustal basement.

APC ☑ XCB ☑ RCB ☑ Re-entry ☑ PCS ☐

Wireline Logging Plan:

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

Other Measurements:

Estimated Days:

Drilling/Coring:	Logging:	Total On-site:
11.4	1	12.4

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	☐
H_2S	☐	High Dip Angle	☐	Ice Conditions	☐
CO_2	☐				

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

Preferred weather window

Summer required as North Atlantic weather poor during winter

Other:

Generated: 2017-04-13T00:09:37+00:00

Proposal #: 892 - Full 2	Site #: REYK-5A	Date Form Submitted: 2017-04-03 15:37:51

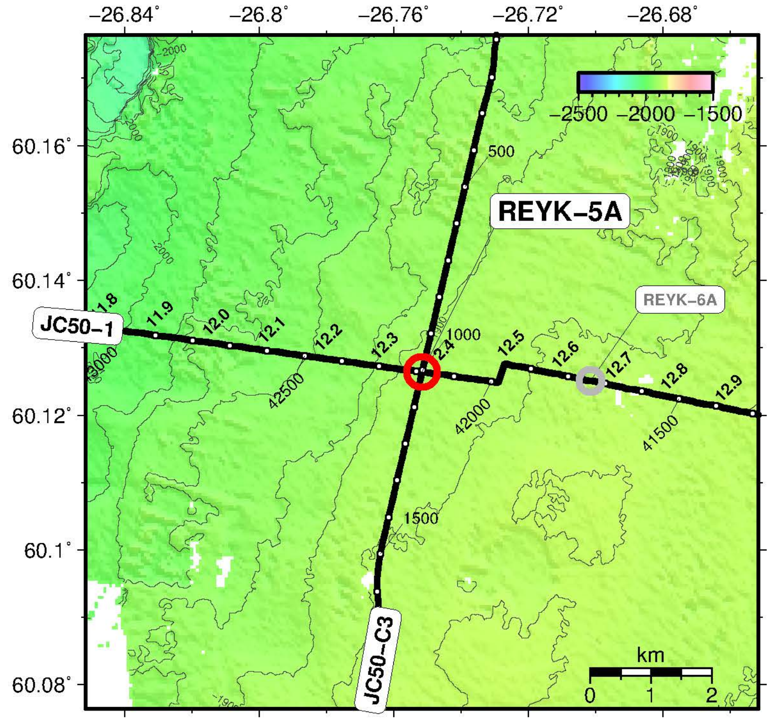
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 42185 A sedimentary disturbance can be seen at 3.0 s TWTT at this site, along with evidence for faulting at CMP 42100 (range 263 km) on JC50-1, thus primary site REYK-6A is preferred.
1b High resolution seismic seismic reflection (crossing)	yes	Line: Profile JC50-C3 Position: 1005
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-5A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Triple APC to refusal, on final hole XCB/RCB to basement at 875 m. RCB 200 m into basement, log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-5A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 110	Seabed to reflection B2	0.47	1.55	Nannofossil clay	Pelagic	234	Age based upon reflection R2 at Site 984
110 - 175	Reflection B2 to reflection B3	0.47-2.15	1.63	Nannofossil clay	Pelagic	39	Age and lithology based on results from Site 984
175 - 360	Reflection B3 to reflection B4	2.15-2.63	1.76	Silty clay	Pelagic	385	
360 - 600	Reflection B4 to reflection B5	2.63-3.7	1.87	Silty clay	Pelagic	224	
600 - 675	Reflection B5 to acoustic basement	3.7-12.4	2000	Silty clay	Pelagic	10	
675 - 675	Acoustic basement	12.4 and older	2.7	Vesicular basalt	Pelagic	N/A	

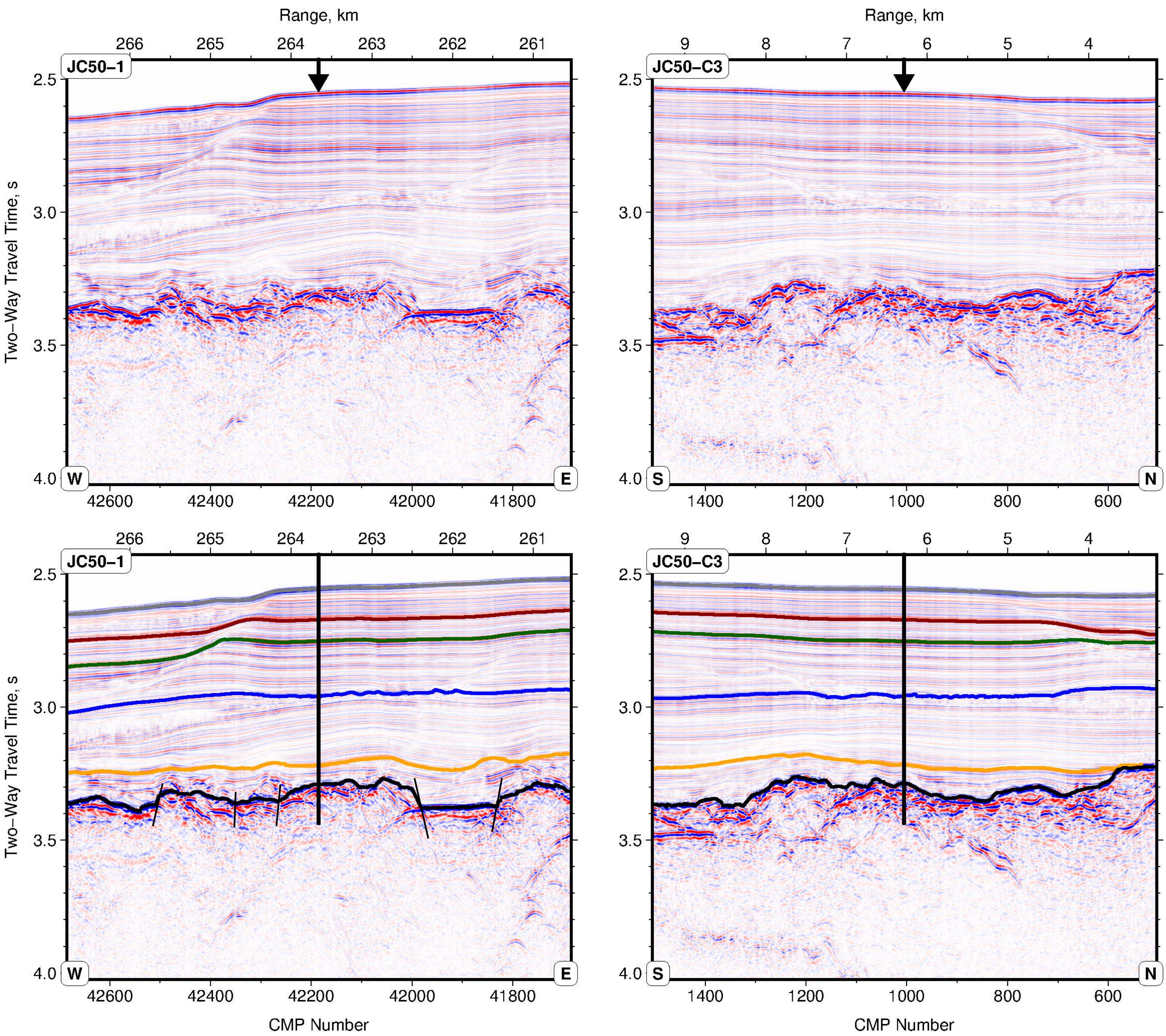


Site Summary Figure: Proposal P892−Full Site REYK−5A

Location: −26.75156 W, 60.12641 N
CMP 42185 on JC50−1; CMP 1005 on JC50−C3
Water depth: 1894 m / 2.553 s TWTT
Basement depth: 675 mbsf / 3.288 s TWTT
Target depth: 875 mbsf / 3.436 s TWTT
Basement age: 12.40 Ma

Figures and supporting data in SSDB:
Location map: REYK−5A_site_sum_fig_map.pdf
Seismic images: REYK−5A_site_sum_fig_JC50−1.pdf &
REYK−5A_site_sum_fig_JC50−C3.pdf
SEGY data / Navigation: JC50−1_stolt_trbal.segy / JC50−1.xy &
JC50−C3_stolt_trbal.segy / JC50−C3.xy

Interpretation:
Gray = seabed ; red = B2 (0.47 Ma); green = B3 (2.15 Ma);
blue = B4 (2.63 Ma); orange = B5 (3.7 Ma); black = basement



IODP Site Forms

Form 1 – General Site Information

892 - Full 2

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Sample ~200 m of basalt at V-shaped ridge 2b. Alternate site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-8A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 60.1491	Jurisdiction:	International
Longitude:	Deg: -27.1370	Distance to Land: (km)	151
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☐ Alternate: ☑	Water Depth (m):	1695

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	320	200
	Total Sediment Thickness (m) 320	
		Total Penetration (m): 520
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

APC to basement or refusal, RCB to target depth ~200 m within oceanic crustal basement.

APC ☑ XCB ☑ RCB ☑ Re-entry ☐ PCS ☐

Wireline Logging Plan:

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

Other Measurements:

Estimated Days: Drilling/Coring: 6.5 | Logging: 0.8 | Total On-site: 7.3

Observatory Plan:

Longterm Borehole Observation Plan/Re-entry Plan

N/A

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_2S	☐	High Dip Angle	☐	Ice Conditions	☐
CO_2	☐				

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

Preferred weather window: Summer required as North Atlantic weather poor in Winter

Other:

Proposal #: 892 - Full 2	Site #: REYK-8A	Date Form Submitted: 2017-04-03 15:37:51

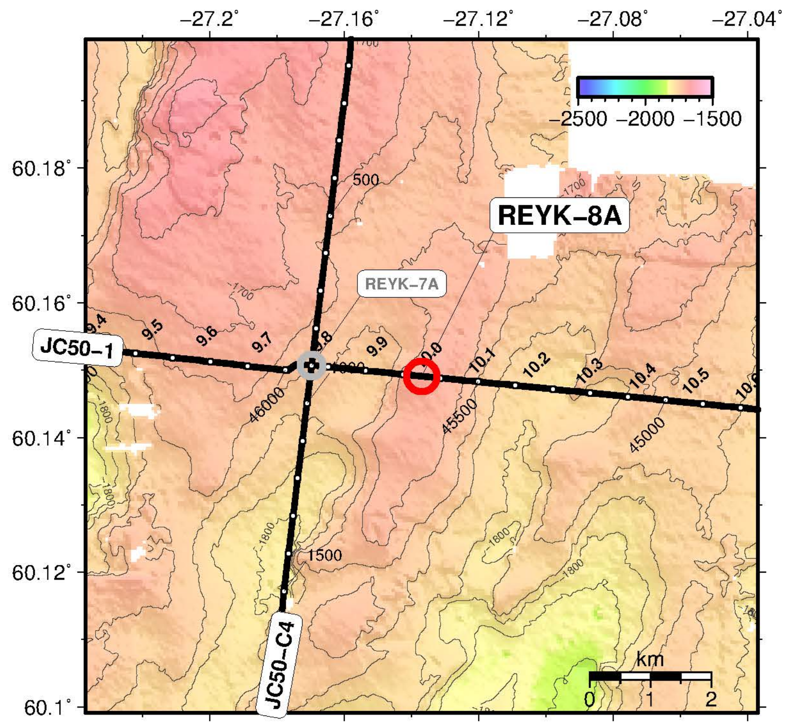
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 45650
1b High resolution seismic seismic reflection (crossing)	yes	Line: JC50-C4 Position: 899 Shifted 1.8 km east of the intersection between seismic profiles JC50-1 and JC50-C4 to obtain more complete sedimentary section
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 cruise navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-8A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Single APC to refusal. XCB/RCB to basement at 320 m, penetrate 200 m into basement and log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-8A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 115	Seabed to reflection B2	0.47	1.55	Nannofossil clay	Pelagic	245	Age based upon reflection R2 at Site 984
115 - 185	Reflection B2 to reflection B3	0.47-2.15	1.63	Silty clay	Pelagic	42	Age and lithology based on results from Site 984
185 - 320	Reflection B3 to acoustic basement	2.15-10.0	1.76	Silty clay	Pelagic	17	
330 - 330	Acoustic basement	10.0 and older	2.7	Vesicular basalt	Pelagic	NA	

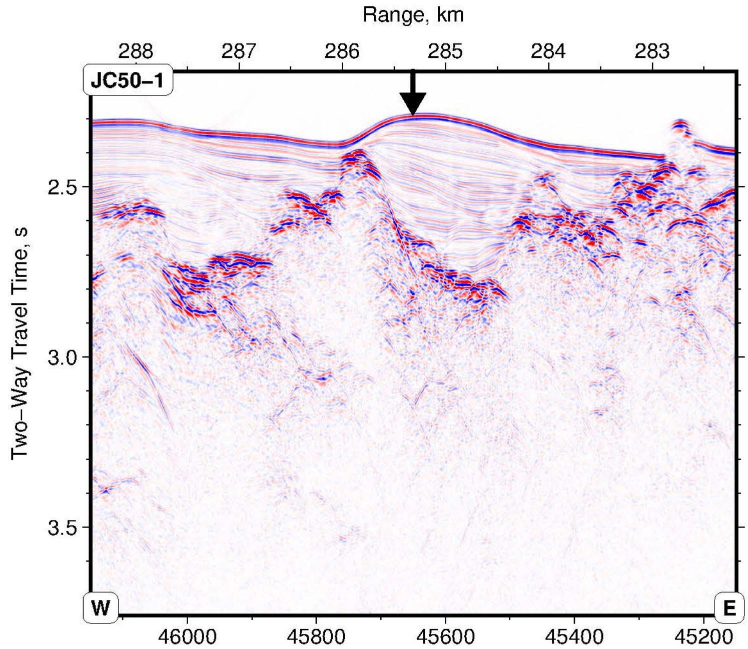


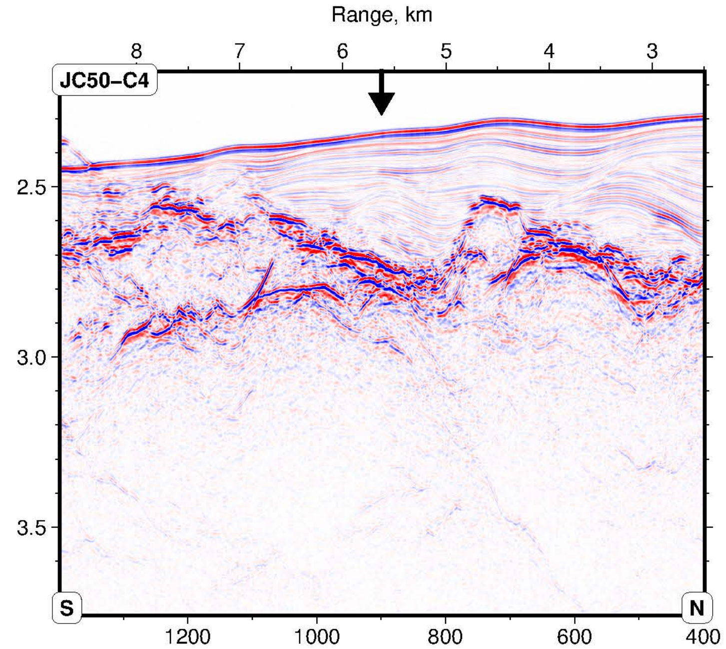
Site Summary Figure: Proposal P892−Full Site REYK−8A

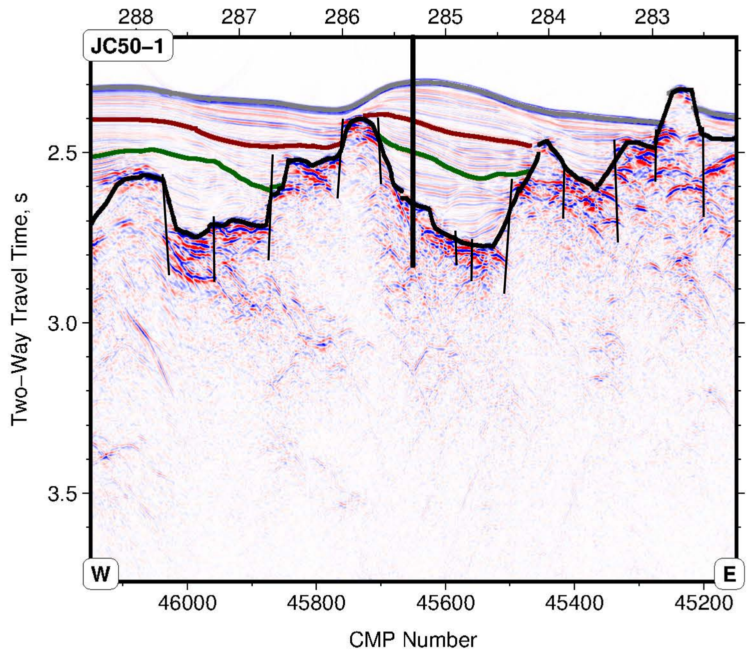
Location: −27.13699 W, 60.14913 N
CMP 45650 on JC50−1; CMP 899 on JC50−C4
Water depth: 1695 m / 2.295 s TWTT
Basement depth: 320 mbsf / 2.682 s TWTT
Target depth: 520 mbsf / 2.830 s TWTT
Basement age: 10.02 Ma

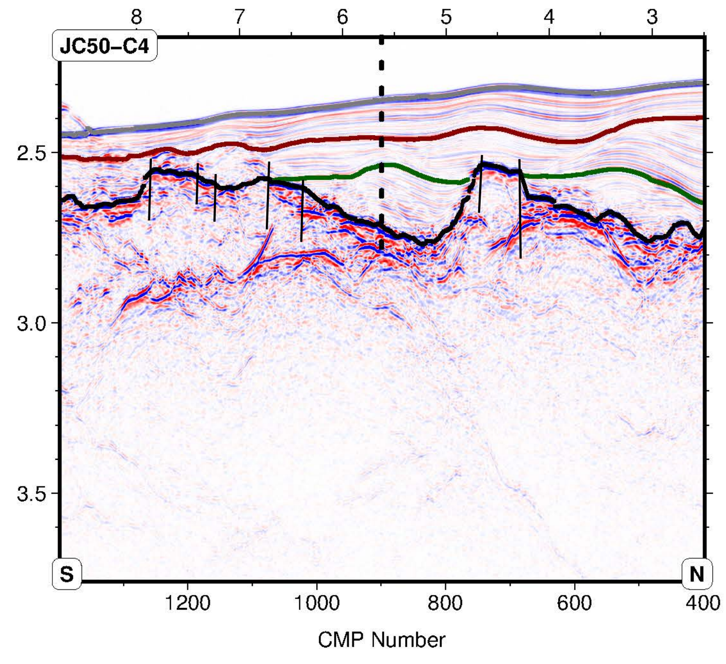
Figures and supporting data in SSDB:
Location map: REYK−8A_site_sum_fig_map.pdf
Seismic images: REYK−8A_site_sum_fig_JC50−1.pdf &
REYK−8A_site_sum_fig_JC50−C4.pdf
SEGY data / Navigation: JC50−1_stolt_trbal.segy / JC50−1.xy &
JC50−C4_stolt_trbal.segy / JC50−C4.xy

Interpretation:
Gray = seabed ; red = B2 (0.47 Ma); green = B3 (2.15 Ma);
blue = B4 (2.63 Ma); orange = B5 (3.7 Ma); black = basement









IODP Site Forms

Form 1 – General Site Information

892 - Full 2

Section A: Proposal Information

Proposal Title	Mantle Dynamics, Paleoceanography and Climate Evolution in the North Atlantic Ocean
Date Form Submitted	2017-04-03 15:37:51
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Sample ~200 m of basalt at V-shaped trough 2a. Alternate site.
List Previous Drilling in Area	Leg 162 Sites 983 and 984

Section B: General Site Information

Site Name:	REYK-10A	Area or Location:	North Atlantic Ocean
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 60.1667	Jurisdiction:	International
Longitude:	Deg: -27.4726	Distance to Land: (km)	153
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☐ Alternate: ☑	Water Depth (m):	1689

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	155	200
	Total Sediment Thickness (m) 155	
		Total Penetration (m): 355
General Lithologies:	Nannofossil ooze, clay and mud	Vesicular basalt

Coring Plan: (Specify or check)

APC/XCB to basement at 310 m, RCB to target depth ~200 m within oceanic crustal basement.

APC ☑ XCB ☑ RCB ☑ Re-entry ☐ PCS ☐

Wireline Logging Plan:

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

Other Measurements:

Estimated Days: Drilling/Coring: 5.8 Logging: 0.8 Total On-site: 6.6

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

N/A

Potential Hazards/ Weather:

Shallow Gas	☐	Complicated Seabed Condition	☐	Hydrothermal Activity	☐	Preferred weather window: Summer required as North Atlantic weather poor in Winter
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_2S	☐	High Dip Angle	☐	Ice Conditions	☐	
CO_2	☐					

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

Other:

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Proposal #: 892 - Full 2	Site #: REYK-10A	Date Form Submitted: 2017-04-03 15:37:51

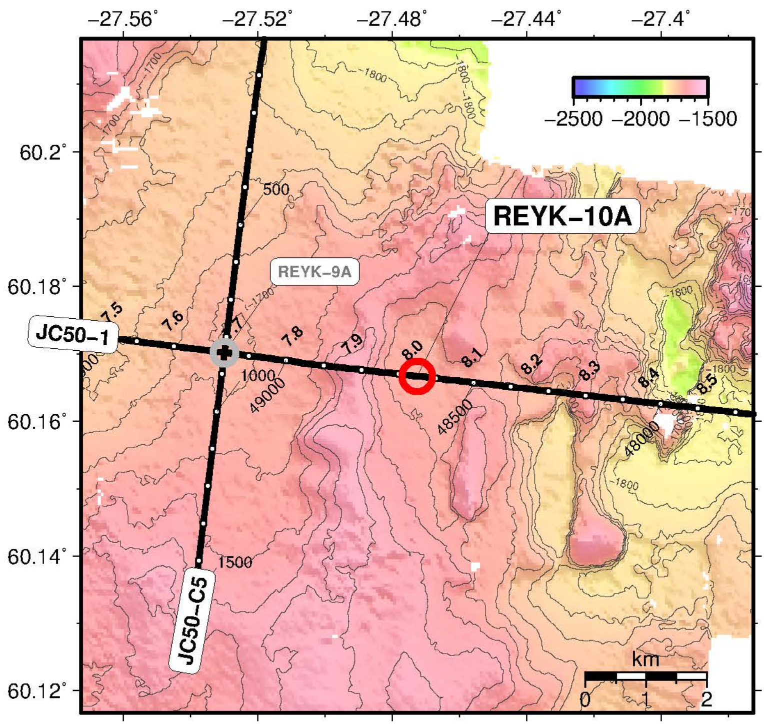
Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	yes	Line: Profile JC50-1 Position: 48650 Shifted 3.2 km east of crossing point to minimize the sediment thickness required to drill before reaching basement.
1b High resolution seismic seismic reflection (crossing)	yes	Line: JC50-C5 Position: 843
2a Deep penetration seismic reflection (primary)		
2b Deep penetration seismic reflection (crossing)		
3 Seismic Velocity	yes	
4 Seismic Grid		
5a Refraction (surface)		
5b Refraction (bottom)		
6 3.5 kHz		
7 Swath bathymetry	yes	Cruise JC50 EM120 multibeam survey
8a Side looking sonar (surface)		
8b Side looking sonar (bottom)		
9 Photography or video		
10 Heat Flow		
11a Magnetics	yes	Regional magnetic data compilation and chron interpretation
11b Gravity	yes	Satellite free-air gravity anomaly
12 Sediment cores		
13 Rock sampling		
14a Water current data		
14b Ice Conditions		
15 OBS microseismicity		
16 Navigation	yes	JC50 cruise navigation
17 Other		

Proposal #: 892 - Full 2	Site #: REYK-10A	Date Form Submitted: 2017-04-03 15:37:51

Pollution & Safety Hazard	Comment
1. Summary of operations at site	Single APC/XCB to basement at 155 m, penetrate 200 m into basement and log as shown on form 3
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	None
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	None
4. Indications of gas hydrates at this location	None
5. Are there reasons to expect hydrocarbon accumulations at this site?	None
6. What "special" precautions will be taken during drilling?	None
7. What abandonment procedures need to be followed?	Not applicable
8. Natural or manmade hazards which may affect ship's operations	None
9. Summary: What do you consider the major risks in drilling at this site?	Poor weather

Proposal #: 892 - Full 2	Site #: REYK-10A	Date Form Submitted: 2017-04-03 15:37:51

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 95	Seabed to reflection B2	0.47	1.55	Nannofossil clay	Pelagic	202	Age based upon reflection R2 at Site 984
95 - 155	Reflection B2 to acoustic basement	0.47-8.1	1.76	Silty clay	Pelagic	8	
155 - 155	Acoustic basement	8.1 and older	2.7	Vesicular basalt	Pelagic	NA	



Site Summary Figure: Proposal P892−Full Site REYK−10A

Location: −27.47257 W, 60.16668 N
CMP 48650 on JC50−1; CMP 843 on JC50−C5
Water depth: 1689 m / 2.281 s TWTT
Basement depth: 155 mbsf / 2.553 s TWTT
Target depth: 355 mbsf / 2.701 s TWTT
Basement age: 8.05 Ma

Figures and supporting data in SSDB:
Location map: REYK−10A_site_sum_fig_map.pdf
Seismic images: REYK−10A_site_sum_fig_JC50−1.pdf & REYK−10A_site_sum_fig_JC50−C5.pdf
SEGY data / Navigation: JC50−1_stolt_trbal.segy / JC50−1.xy & JC50−C5_stolt_trbal.segy / JC50−C5.xy

Interpretation:
Gray = seabed ; red = B2 (0.47 Ma); green = B3 (2.15 Ma); blue = B4 (2.63 Ma); orange = B5 (3.7 Ma); black = basement