IODP Proposal Cover Sheet

937 - Full 2

Deepening Hole U1309D

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Title	Accessing the Building Blocks of Life: Deepening Hole U1309D, Atlantis Massif, Mid-Atlantic Ridge
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Area	Mid-Atlantic Ridge

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Abstract

The Atlantis Massif Oceanic Core Complex (OCC) is one of the best studied locations in the ocean crust, the site of four IODP expeditions so far (304, 305, 340T and 357). It is the site of the Lost City Hydrothermal Field (LCHF), venting alkaline fluids rich in hydrogen and methane at 40-90 centigrade. IODP Hole U1309D, located 5km north of the LCHF, is the deepest (1415m) hole so far drilled in young (<2 Ma) ocean crust, sampling a primitive series of gabbroic rocks interpreted in part to be metasomatised peridotite. Gabbroic lithologies in Hole U1309D contrast with serpentinized peridotites sampled near the LCHF by seafloor coring in Exp. 357 and sampling on the south wall of the Massif. The hydrologic regime is also very different at the two locations, with deep permeability required beneath the LCHF, and a low permeability conductive regime evidenced by a linear thermal gradient deeper than 750 mbsf in Hole U1309D.

The principle aim of this proposal is to sample fluids and rocks in a stable regime with temperatures higher than ever sampled before by IODP. We hope to access temperatures above 200 centigrade, where active serpentinization is occurring in olivine-rich rocks, and where the building blocks for life (H_2, CH_4, and more complex organic compounds) may be created abiotically.

In addition we will drill a short Hole close to the Lost City Hydrothermal Field in order to gain a complete section through a detachment fault zone and address biosphere, structural and alteration objectives not completed in IODP Expedition 357 due to failure to penetrate to depths envisaged.

We will sample fluids in the existing Hole 1309D using newly developed temperature-sensitive sampling tools and leave a clean legacy hole reaching 2100 mbsf and temperatures of 220 C for future logging and fluid sampling once thermal equilibrium has returned. H_2, CH_4, other organic molecules and cations will be sampled in fluid inclusions to compare with ambient fluids. We hypothesise that concentration gradients in volatile species may exist in the Massif.

We will also study the magmatic evolution of oceanic core complexes including melt-rock reaction processes critical to the assembly and geochemistry of oceanic gabbro bodies and the relationship between plutonic rocks and MORB

Drilling to temperature regimes not previously accessed by IODP will allow the limitations of current technology to be evaluated in preparation for future deep drilling

Scientific Objectives

Our proposed drilling strategy will address a number of objectives in the Earth in Motion, Earth Connection and Biosphere Frontiers themes of the IODP Science Plan.

Objective 1: The life cycle of an oceanic core complex: Links between igneous, metamorphic, structural and fluid flow processes, and testing of geophysical and hydrothermal models. This objective addresses Science Plan Challenge 9: "How are seafloor spreading and mantle melting linked to ocean crustal architecture?" Challenge 10: What are the mechanisms, magnitude and history of chemical exchanges between the ocean crust and seawater" and Challenge 14: How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?

Objective 2: Accessing the chemical kitchen preceding the appearance of life on Earth: formation of organic molecules of prebiotic interest at high and low temperatures in the Atlantis Massif. This objective addresses Science Plan challenge 10 "What are the mechanisms, magnitude, and history of chemical exchanges between
the oceanic crust and seawater?", Challenge 13 “What properties and processes govern the flow and storage of carbon in the subseafloor”; and Challenge 14 “How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?” It will also be of great interest to the Astrobiology Community studying hydrothermal processes on Icy Worlds and Mars

Objective 3: Deep biosphere and limits for life in the Atlantis Massif: controls of lithological substrate, porosity and permeability, temperature, fluid chemistry and reactive gradients on microbiology. This objective concerns Science Plan Challenge 5 "What are the origin, composition, and global significance of deep
subseafloor communities?" and Challenge 6 "What are the limits of life in the subseafloor realm?"

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

Sampling of fluids using downhole logging tools at selected intervals, in particular using shape metal alloy sampling systems currently under development
Preserving selected samples away from atmospheric alteration and potentially at near-ambient temperature above the temperature limits of life

Proposed Sites (Total proposed sites: 3; pri: 2; alt: 1; N/S: 0)

Site Name	Position (Lat, Lon)	Water Depth (m)	Penetration (m)			Brief Site-specific Objectives
			Sed	Bsm	Total	
AMDH-01A (Primary)	30.1687 -42.1186	1656	0	660	660	(i) Sample fluids and measure temperature in existing Hole 1309D down to 1414 mbsf (expected temperature 225 centigrade). (ii) Deepen existing Hole U1309D by ~650 m and collect samples for petrology and geochemistry of abiotic organic compounds and H2; (iii) log Hole with flasked tools. (iv) Drill new 80m Hole 20-30 m north of Hole U1309D, for microbiology sampling of porous rocks, fault zones, and correlation with Holes U1309B and D. This Hole is designated "U1309-J" in the text and site form. Note that Hole 1309C with protruding casing needs to be avoided.
AMDH-02A (Primary)	30.1317 -42.1202	825	3	200	203	200mHole with re-entry. Complete section through detachment fault zone in serpentinized peridotite. Sample for deformation, alteration, igneous petrology, microbiology and organic/inorganic geochemistry. Log for temperature and other properties. Legacy Hole for sampling fluids and gases, establishing temperature profile, potential instrumentation
AMDH-03A (Alternate)	30.1389 -42.1455	1275	5	200	205	Drill through detachment fault shear zone; igneous petrology, alteration, deformation fabrics, microbiology, organic geochemistry. potential for post-detachment volcanic rocks. Temperature profile, fluid sampling, potential to provide re-entry system for legacy

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Benedicte	Menez	IPGP Paris	France	Other Lead	geomicrobiology; geochemistry
Marvin	Lilley	University of Washington	United States	Other Lead	fluid geochemistry; hydrocarbons
Geoffery	Wheat	University of Alaska, Fairbanks	United States	Other Lead	geochemistry; downhole sampling; hydrogeology
Johan	Lissenberg	Cardiff University	United Kingdom	Other Lead	igneous petrology
Benoit	Ildefonse	University of Montpellier	France	Other Lead	igneous petrology; tectonics; physical properties
Frieder	Klein	Woods Hole Oceanographic Institute	United States	Other Lead	fluid geochemistry; fluid-rock interaction
Susan	Lang	University of South Carolina	United States	Other Lead	biogeochemistry; geochemistry
William	Seyfried	University of Minnesota	United States	Other Proponent	fluid geochemistry; fluid-rock interaction
Muriel	Andreani	University of Lyon	France	Other Proponent	metamorphic petrology; geochemistry
Barbara	John	University of Wyoming	United States	Other Proponent	tectonics; petrology; geochronology
Marguerite	Godard	University of Montpellier	France	Other Proponent	petrology; geochemistry
Antony	Morris	University of Plymouth	United Kingdom	Other Proponent	Palaeomagnetism; rock magnetism; tectonics
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Christopher	MacLeod	Cardiff University	United Kingdom	Other Proponent	tectonics, petrology
Ivan	Savov	University of Leeds	United Kingdom	Other Proponent	geochemistry, volcanology, petrology
Natsue	Abe	Jamstec	Japan	Other Proponent	Igneous petrology
Yasukiko	Ohara	Hydrographic and Oceanographic Department of Japan	Japan	Other Proponent	Marine geology and tectonics

1. Introduction

1.1: Setting of Proposal

Atlantis Massif (30 °N, Mid-Atlantic Ridge) has been investigated by four IODP expeditions (304, 305, 340T and 357) and numerous other cruises (Blackman et al., 1998; Blackman and Collins, 2010; Blackman et al., 2011; Blackman et al., 2013; Canales et al., 2004; Canales et al., 2008; Cann et al., 1997; Karson et al., 2006; Kelley et al., 2001; Kelley et al., 2005). It was the first corrugated massif identified as an oceanic core complex (OCC), and hosts the Lost City Hydrothermal Field (LCHF), which has vented alkaline fluids rich in H_2 and CH_4 at temperatures of 40-90°C for >100,000 years (Kelley et al., 2005; Ludwig et al., 2011; Proskurowski et al., 2008). IODP Hole U1309D penetrated largely gabbroic rocks to 1415 mbsf (Figs. 1-4) and contrasts with the southern wall of the Massif near LCHF, which consists dominantly of serpentinized peridotite with ~20% gabbroic rocks (Fig. 2). A detachment fault zone ~100 m thick forms the surface of the Massif (Karson et al., 2006; Schroeder and John, 2004) and the uppermost few meters of this was extensively sampled in IODP Expedition 357 (Fig. 1, 4, 5) (Früh-Green et al., 2018). The fault zone comprises talc-tremolite-chlorite schists overprinting serpentinite, with fault breccias and cataclasites locally overprinting higher temperature fault rocks including amphibolites, gabbros, and syntectonic diabase dykes intruded in the fault zone (Blackman et al., 2011; McCaig et al., 2010; McCaig and Harris, 2012). The Massif was exhumed on this convex-up detachment fault bringing gabbro and peridotite onto the seafloor, with 45° rotation around a subhorizontal ridge-parallel axis below the Curie temperature (Morris et al., 2009). U1309D core can be interpreted as an inclined section plunging ≤ 45° through a previously active, moderate to steeply dipping detachment fault zone and its footwall (Fig. 2, 6). One aim of Expedition 357 was to collect 80 m long near-complete sections through the detachment fault zone close to the south wall, but the maximum penetration of 16.4 m meant that only the uppermost part was sampled.

This proposal aims to:

1. Deepen Hole U1309D into the depth/temperature range where active serpentinization reactions in olivine-bearing rocks likely to be occurring (Allen and Seyfried, 2004; Seyfried and Dibble, 1980), together with abiotic synthesis of CH_4, and other organic compounds at temperatures where microbial synthesis is not possible. Fluid sampling will be undertaken in the existing 1415 m deep Hole. *If the target of 2060m is reached, Hole U1309D will be the deepest Hole in young (<1.5 Ma) lithosphere with bottom temperatures estimated at 220 °C.*

2. Drill a new 200m deep Hole (AMDH-2A) within the footprint of Expedition 357, with added focus on collecting microbiology samples in porous, permeable horizons. In conjunction with Exp. 357 cores, this Hole will complete a section through the 100 m thick fault zone, and amplify studies of microbiology, geobiology, organic and inorganic geochemistry of pore fluids and cored rocks, petrology and structural geology.
3. Drill a new 80 m Hole at Site U1309 ("U1309-J") to collect microbiology samples in fault breccias and rocks containing reaction porosity to enable direct comparison of results from this mafic site with those obtained at ultramafic AMDH-2A.

To allow future deeper drilling, logging, fluid sampling and potentially borehole observatories, we plan to install a re-entry system in Hole AMDH-2A and leave Hole U1309D open. Legacy is a very important aspect of this proposal since some objectives require fluid sampling and temperature measurements that are only viable several years after drilling.

This proposal addresses multiple challenges within the IODP Science Plan themes Biosphere Frontiers, Earth Connections and Earth in Motion:

- *Challenge 5: What are the origin, composition and global significance of deep subseafloor communities?*
- *Challenge 6: What are the limits of life in the subseafloor realm?*
- *Challenge 9: How are seafloor spreading and mantle melting linked to ocean crustal architecture?*
- *Challenge 10: What are the mechanisms, magnitude and history of chemical exchanges between the ocean crust and seawater?*
- *Challenge 13: What properties and processes govern the flow and storage of carbon in the seafloor?*
- *Challenge 14: How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?*

1.2: Response to SEP

SEP reviewed 937-Full in January 2019, supporting the scientific objectives of the proposal while making a number of valuable comments and suggestions. Below we address their comments:

1. **Fluid sampling:** SEP strongly recommended delaying resubmission until the new Multi-Temperature Fluid Sampler (MTFS) tool had been tested on Exp. 385T. Although the MTFS tool was fully ready for deployment, operational problems prevented testing.Our revised plan uses both the proven Kuster tool and the MTFS. Fluid sampling is a key part of our U1309D legacy strategy, and therefore success of samplers on this expedition, while desirable, is not essential to meet our long-term objectives.
2. **Clarifying objectives and hypotheses:** We have restructured the text to make objectives, deliverables and hypotheses clear throughout. Microbiology objectives show the results that can be obtained by new deeper sampling compared to Expedition 357. We emphasize a strategy to collect higher porosity intervals which are likely to yield higher cell counts.
3. **Distinguishing formation water from intruded seawater:** We will disturb Hole U1309D fluid as little as possible during sampling prior to drilling. However the fluid will in any case be seawater partially reacted with rock and/or with some admixture of formation water. Deviations from seawater will be modelled using geochemical software to predict endmember fluid compositions in equilibrium with rocks.
4. **Effects of cooling on proposed geochemical targets:** Cooling effects are well known in experiments (for example significant pH changes) and can be corrected for to reconstruct in situ composition in borehole fluids.
5. **Operations plan**: This has been expanded and modified to show which objectives can be met in various circumstances.
6. **Site survey**: Site 4A has been removed: we accept it was an inadequate alternate for our primary objectives. Zoomed-in velocity images were added on site forms.

2. Objectives

2.1: Objective 1: Life cycle of an oceanic core complex - Links between igneous, metamorphic, structural and fluid flow processes

2.1.1: Scientific justification

2.1.1.1: Internal structure, cooling history and hydrogeology of the Massif

Hole U1309D revealed that the Atlantis Massif (AM) central dome is cored by gabbroic rocks to a minimum depth of 1415 mbsf (Fig. 1). Recent Full Waveform Inversion (FWI) of previous geophysical data (Harding et al., 2016) reveals (Fig. 3) much more detail than previous tomography (Canales et al., 2008) and suggests that the gabbro body with P-wave velocities of 6-7 km/s extends southwards towards the LCHF with an irregular contact against lower velocity rocks interpreted as serpentinized peridotites. However since velocities of 4-5 km/s characterise the altered gabbros in the upper part of Hole U1309D, and partially altered peridotite could have velocities of 6-7 km/s, interpretations still need groundtruthing. The heterogeneous structure beneath the LCHF may be the best indication of variably serpentinised peridotites containing sill-like altered gabbro bodies.

The FWI velocity model only extends to the current base of Hole U1309D, but OBS refraction tomography (Fig. 3D) suggests that the high velocities will continue to the 2060 mbsf depth of our proposed extension in AMDH-1A. However this velocity could include significant intervals of partially altered ultramafic rocks similar to olivine-rich troctolites between 1100 and 1200 mbsf in U1309D (Fig. 1). *At some point the gabbroic body must transition into mantle rocks, as discussed below.*

Expedition 340T (Blackman et al., 2014) found that the temperature profile in U1309D was conductive below 750 mbsf, with a gentle curvature suggesting slow downflow of fluid above that depth (Fig. 1). Minor excursions in downhole temperature at 750 and 1100 mbsf suggests fluid influx into permeable fault zones. To vent at up to 90°C the LCHF must mine fluid to several km depth, based on inferences of circulation temperatures from fluid chemistry (Allen and Seyfried, 2004, 2005; Foustoukos et al., 2008a), and hydrothermal modelling (Lowell, 2017; Titarenko and McCaig, 2015). At high levels the LCHF is localized by faulting (Denny et al., 2016); whether more diffuse or multichannel flow occurs at depth, or if there is shallow recharge and mixing, is very important for the chemical and hence microbiological evolution of the system and therefore underpins all of our main objectives. A lateral permeability change could stabilise and sustain the LCHF over long periods of time

(Titarenko and McCaig, 2015). *New measurements of the thermal structure and fluid flow at depth close to Lost City will provide important constraints on the hydrogeology of AM.*

Initial cooling of the Massif was rapid, based on palaeomagnetic (Morris et al., 2009) and geochronological (Grimes et al., 2008; Schoolmeesters et al., 2012) data. This may have been linked to circulation of black smoker fluids within the detachment fault zone (McCaig et al., 2010; McCaig and Harris, 2012), in an early phase of circulation compared to the current Lost City phase.

2.1.1.2: Igneous processes. Rocks recovered in Hole U1309D include a sequence of primitive gabbro and olivine gabbro (Fig.s 1, 4), with intervals of troctolite and olivine-rich troctolite. Back-correcting for rotation, the diabase intrusions within the detachment zone could represent a lateral dyke-gabbro transition (McCaig and Harris, 2012). Olivine-rich troctolites are interpreted as mantle rocks modified by melt-rock reaction (Drouin et al., 2009; Ferrando et al., 2018; Lissenberg and MacLeod, 2016); less modified mantle rocks are confined to very short intervals (< 1 m) at shallow depths. The gabbro contains many internal contacts (Suhr et al., 2008) and local igneous layering. Plutonic rocks recovered from U1309D are amongst the most primitive ever recovered (Fig. 4). Unlike other plutonic sections drilled (Pacific Ocean: ODP Holes 147 and 1256D; Indian Ocean: ODP Holes 735B and 1105A, IODP Hole U1473A), many of the AM plutonic rocks are in equilibrium with mid-ocean ridge basalt (MORB), with some primitive enough to have formed directly from primary mantle melts. Hence, AM offers a unique opportunity to study the compositions of melts delivered to the crust from their mantle source, and how they evolve to MORB. This is paramount; crustal evolution of melt is now recognised to be significantly more complicated than previously realised, involving not only fractional crystallisation, but in-situ crystallisation and reactive porous flow (Lissenberg and MacLeod, 2016). Hence, interpreting MORB compositions, and implications for the upper mantle, is highly non-unique, unless melt evolution processes in the lower crust are quantified.

Intervals of gabbro within south wall serpentinites (Fig. 5) have an uncertain relationship to the main gabbro further north. They may be intrusions of different age or level of exhumation, or may be satellites of the larger body. Establishing the genetic relationship between these bodies is important.

2.1.1.3 Integrated studies of deformation, fluid-rock interaction, magmatism and deformation in a detachment fault zone.

The U1309D core was remarkable for the paucity of high temperature crystal-plastic fabrics, compared to the only other deep OCC holes at Atlantis Bank (Ildefonse et al., 2007). However, significant breccia intervals intruded by syntectonic diabase (Fig. 6) formed over a range of temperatures up to near magmatic in the top 100m of Site U1309 (Blackman et al., 2011; McCaig and Harris, 2012). Alteration is pervasive in the upper part of Hole U1309D, and isotopic data shows the detachment fault zone to be highly altered by seawater-derived fluids at temperatures similar to black smoker fluids (McCaig et al., 2010). Greater intensities of crystal-plastic deformation were found in gabbroic lenses in peridotite on the south wall of the Massif (Schroeder and John, 2004), and in the shallow cores of Exp. 357 (Früh-Green et al., 2018).

Intense alteration in the shallow Expedition 357 cores (Früh-Green et al., 2018; Rouméjon et al., 2018) is generally consistent with previous work on the south wall (Boschi et al., 2006). Early serpentine replacing olivine is locally overprinted by talc-tremolite-chlorite assemblages, often associated with mafic intrusions and/or shearing. Carbonate veining is surprisingly rare considering the proximity of several holes to Lost City (Fig. 1). Extensive water-rock interaction at variable temperatures is further reflected in heterogeneous sulphur isotope compositions. These document a complex evolution of the hydrothermal system with episodes of low temperature serpentinization and incorporation of seawater sulphate facilitating microbial activity and episodes of high temperature water-rock interaction controlled by the intrusion of microgabbroic veins, which is accompanied by considerable mass transfer (Liebmann et al., 2018).

Reaction permeability is common in the upper part of Holes U1309B and D, and has been found in chloritized gabbros in core from Exp. 357 (Fig. 7). Rapid dissolution of primary minerals can occur if far-from-equilibrium hot fluid is in excess, as is likely in the upflow zone of a black-smoker system (Cann et al., 2015). *We will target sampling of reaction permeability and other permeable zones for geochemical and microbiology investigations (see also objectives 2 and 3), and seek to quantify the extent of reaction permeability in both the gabbroic and serpentinite fault zones.*

2.1.1.4: Alteration, fluid-rock geochemistry and cooling history of AM

Alteration in U1309D records progressive fluid influx during cooling from magmatic to ambient temperatures. It is pervasive above 350 m, with olivine-plagioclase corona reactions reflecting temperatures above 500°C (Nozaka and Fryer, 2011). Deeper, the corona reaction is restricted to the vicinity of fault zones and lithologic contacts, but partial serpentinization of olivine is common in many intervals, often accompanied by prehnite and hydrogarnet replacing plagioclase (Frost et al., 2008). Serpentinization reactions are complex, including early brucite-antigorite veins followed by lizardite-magnetite (Beard et al., 2009). Lower temperature serpentinite is often accompanied by saponite (Nozaka et al., 2008), and this has recently been shown to contain (Fig. 8; see also objective 2) abiogenic amino acids (Ménez et al., 2018). Sr and O isotope alteration by seawater-derived fluids is common in the upper part of the hole, but decreases below 350 mbsf, and is mainly present in serpentine-rich intervals where the primary Sr content is low, and the seawater signal may be carried by carbonates (McCaig et al., 2010).

Field and experimental studies demonstrate that dissolved silica, boron, lithium, oxygen and strontium isotopes, together with redox constraints imposed by dissolved H_2 and coexisting sulfur species, provide important clues to the role of heat and mass transfer reactions on the chemical evolution of hydrothermal fluids (Allen and Seyfried, 2003; Foustoukos et al., 2008b). These data help constrain temperature, fluid/rock mass ratio, and potential sources of silica that may involve alteration of gabbro and/or peridotite (Bach et al., 2004; Bach and Humphris, 1999; Seyfried et al., 2015; Tutolo et al., 2018). Borehole fluid observations over a range of temperatures, will permit assessment of cooling-induced pH changes and B isotope fractionation processes, with insight on the effect of temperature on stable and metastable fluid-mineral equilibria. Modeling the effect of temperature and cooling on mineral solubility data and redox processes will be part of our study. Measurement of dissolved Ca, Mg and silica in borehole fluids will constrain phase equilibria and reaction kinetics involving serpentine minerals, possibly coexisting with tremolite and talc (Seyfried et al., 2004). Olivine metastability will be assessed from constraints imposed by dissolved silica and cation budget, together with mineral based observations. *Our deepened Hole will be the first in ocean drilling to access temperatures above 200°C in a stable environment.*

Serpentinization reactions take up boron and lithium from seawater, with many samples from the Atlantic enriched in boron with high values of $\delta^{11}B$ (Boschi et al., 2008; Harvey et al., 2014; Vils et al., 2009). These data have led to an assumption that all serpentine in subducting slabs will be enriched in boron, and can contribute to high [B] and $\delta^{11}B$, and systematic cross-arc changes in subduction zone volcanics (Konrad-Schmolke and Halama, 2014). However, data from Hess Deep suggest boron is easily removed from percolating seawater in crustal sections (McCaig et al., 2018), never reaching the underlying mantle. *We will test the hypothesis that the boron and lithium seawater signatures die out with depth in the Hole by both whole rock and in situ analysis.*

2.1.2: Expected outcomes:

We will study the evolution of the Atlantis Massif by deepening Hole U1309D to ~2060 mbsf, accessing ambient temperatures from 147 to ~220 °C, and by drilling a new 200m hole in serpentinite containing gabbro and mafic dykes close to the LCHF.

Objective 1 deliverables:

1A: Borehole fluids collected at temperatures up to 145 °C, particularly above and below zones of suspected fluid ingress into Hole U1309D, with aim for future sampling up to 220 °C.

1B: Rock samples, forming part of the longest continuous section through young gabbroic crust to date, allowing study of igneous processes, and also alteration processes in rocks that have never been below 150°C (other than briefly during drilling).

1C: A complete section from 15-200 mbsf through an oceanic detachment fault zone in serpentinised ultramafic rocks, and into less deformed rocks below, complemented by logging and palaeomagnetic data for full structural re-orientation. Temperature measurements will allow improved modelling of LCHF circulation.

1D: A new 80m Hole (U1309-J) at site AMDH-01 allowing calculation of the average strike and dip of diabase intrusions already correlated between Hole U1309B and D (Fig. 6A)

Objective 1 hypotheses:

1E: The proportion of ultramafic rock will increase as Hole U1309D is deepened reflecting a gradual transition into mantle rocks; much of both the main gabbro and smaller bodies to the south will show evidence of assembly by melt-rock reaction rather than discrete intrusion.

1F: Reaction porosity will be found on the margins of gabbroic intervals in contact with ultramafics (blackwall zones) within the detachment fault zone, and will yield formation waters distinct from Lost City vent fluids due to isolation from the main flow system.

1G: Deformation within the south wall fault zone will be multistrand, and strain will not be focussed into shearing of serpentine but rather into tremolite-rich assemblages as seen in the cores from Exp. 357.

1H: Isotopically heavy seawater-derived boron will not be present in the deep section of Hole U1309D, and may die out with depth in Hole AMDH-2A. Boron profiles will allow a better estimate of the boron content of slow-spread crust to be made than those based on near-surface collected samples.

This objective will address IODP Science Plan Challenges 9, 10 and 14 (see also section 1)

2.2 Objective 2: Accessing the chemical kitchen preceding the appearance of life on Earth: formation of organic molecules of prebiotic interest at high and low temperatures

2.2.1 Scientific justification

It is axiomatic that before life could begin on Earth or other worlds in the solar system, precursors of DNA, RNA, proteins and other biologically-relevant macromolecules must have been synthesised without biological intervention (Stüeken et al., 2013). One site where such synthesis has been proposed are deep-sea vents such as the LCHF (Kelley et al., 2002; Martin et al., 2008). Moreover, life relies on the use of chemical disequilibria that are widespread at all scales in hydrothermal environments. LCHF is characterised by highly alkaline fluids venting at 40-90°C, rich in H_2 and CH_4, and is hosted in serpentinite. Serpentinization and abiotic related organic synthesis reactions play a major role in generating H_2 and organic C-species including methane, ethane, propane, small carboxylic acids such as formate, and amino acids (Kelley and Fruh-Green, 1999; Kelley et al., 2002; Klein et al., 2013; Lang et al., 2010; Lang et al., 2018; McCollom and Bach, 2009; McCollom and Seewald, 2013; Ménez et al., 2018; Proskurowski et al., 2008). Additionally, new paradigms are emerging for abiotic organic synthesis in hydrothermal settings (Andreani and Menez, 2019). These are not CH_4 centred, but rather include the formation of compounds such as polycyclic aromatic hydrocarbons (PAHs) or carbonaceous matter, possibly mediated by minerals. Some reduced compounds, such as methane and short-chain alkanes, are believed to form through Fischer-Tropsch-type reactions at temperatures well above the known limit to life (Klein et al., 2019; Wang et al., 2018), perhaps catalyzed by Fe-, Ni-, and Cr-bearing minerals (Foustoukos and Seyfried, 2004). The abiotic production of carboxylic acids, amino acids, PAHs, and carbonaceous compounds likely proceeds at lower temperatures (< 400°C), including within thermal regimes conducive to life (McDermott et al., 2015; Klein et al., 2019). For example, the abiotic synthesis of amino acids and other organic heterocycles, presumably via a Friedel-Crafts-type reaction, has recently been documented (Fig. 8) in iron-rich saponitic clay from Hole U1309D samples (Ménez et al., 2018; Pisapia et al., 2018). *The thermal limits of organic synthesis and diversity of products are uncertain, and the new continuous section in Hole U1309D from low temperatures to 220°C will allow systematic investigation.*

Recent work on Lost City fluids suggests that CH_4 was generated at temperatures of around 300 °C, far above the current vent temperature (Wang et al., 2018). Fluid inclusions in gabbro have been suggested as a significant source for abiogenic CH_4 (Kelley and Fruh-Green, 1999, 2001). Secondary fluid inclusions in olivine have been shown to contain H_2, CH_4 and C_2H_6, including in IODP Hole U1309B (Klein et al., 2019). H_2 and hydrocarbons are suggested to form within fluid inclusions by reaction between fluid and olivine, or be inherited from earlier reactions and trapped (Andreani and Menez, 2019). Carbon isotope ratios in the inclusions are consistent with those in vent fluids (McDermott et al., 2015). New data from AM (Lilley, in prep) suggests that gabbros and troctolites contain higher concentrations of CH_4 and heavier $\delta^{13}C$ than serpentinized peridotites, suggesting that gabbros, and not peridotites, are the likely source of methane at LCHF. However, the pathways for methane formation and movement, and the quantities involved, remain a pending question as is the diversity of abiotic organic compounds that are formed in serpentinizing environments at both high and low temperatures.

While fluid inclusions could be an important source of H_2 and CH_4, it is unlikely they are the only source. H_2 is likely to be generated from reduction of H_2O in any circumstance where the average Fe^{3+}/Fe^{2+} of secondary minerals is higher than that of primary minerals (Andreani et al., 2013; McCollom and Bach, 2009), although experiments suggest generation rates are highest around 300°C (McCollom et al., 2016). We hypothesise that gradients in H_2 and CH_4 may exist in the Massif due to diffusion of volatiles from depth.

2.2.2 Expected outcomes

We will sample H_2 and organic molecules in fluid inclusions, in borehole fluids, and in formation waters in both the deepened Hole U1309D and at the new site AMDH 2A, using a full range of imaging and analysis methods (see Sampling Plan).

Objective 2 deliverables:

2A: Rocks of variable lithology sampled over the temperature range 147-220°C from 1414mbsf to ~ 2060mbsf in Hole U1309D. Any organic compounds in these samples will be of abiogenic origin since they have been above the limit for life throughout their geological history. Whole rock measurements will be complemented by formation fluid sampling if sufficient porosity exists, and organic carbon imaging and in situ analysis in porosity and fluid inclusions. We will ensure sampling of any potential zones of fluid flow, including fault zones and zones of more intense alteration, reaction porosity and veining.

2B: Systematic measurement of the Fe^{3+}/Fe^{2+} ratio of secondary and primary assemblages formed at all metamorphic temperatures and depths in the Hole, in order to assess sites of H_2 generation in the past and present, for which a single deep borehole is ideal.

2C: Samples at lower ambient temperatures (Holes AMDH-02A and U1309-J), thought to be suitable for the abiotic formation of organic compounds more diverse than hydrocarbons, including formate and acetate and amino acids. We will seek these compounds in formation waters contained in reaction porosity and other permeable zones such as dyke margins and fault rocks (Fig. 7). Together with U1309D core, we aim to establish a depth limit for phyllosilicate-hosted amino acids and other types of organic compound.

2D: Place additional constraints on the carbon budget of AM via more systematic sampling through the detachment zone. Hole AMDH-2A will complement the sparse carbonate vein findings of Expedition 357, targeting zones that might represent recharge zones for LCHF fluids.

Objective 2 hypotheses:

2E: That gradients in H_2 and CH_4 will exist in vent fluids and fluid inclusions in plagioclase and quartz (where these gases are unlikely to be generated in situ), indicating flux of gases from depth. This hypothesis will also be tested by fluid sampling in the existing Hole U1309D (this Expedition, and later in the entire Hole).

2F: That if H_2 and CH_4 are in part generated in olivine-hosted fluid inclusions, different ratios of gases (including mantle Helium) will be found in the fluid inclusions from the LCHF vent fluids, reflecting mixing of different sources.

2G: That saponite and other iron-bearing minerals whose formation is accompanied by H_2 production (e.g., hydrogarnets), will provide rich microsites for abiotic organic synthesis, and that lithogical contacts and alteration zones may generate higher concentrations of more complex compounds due to enhanced chemical disequilibria.

Objective 2 will contribute to IODP Science Plan Challenges 10, 13 and 14. In addition, this work will be of great interest to astrobiologists investigating the likelihood of Life evolving on Mars or icy worlds thought to host serpentinizing hydrothermal systems.

2.3: Objective 3: Deep biosphere and limits for life: controls of lithological substrate, porosity and permeability, temperature, fluid chemistry and reactive gradients on microbiology.

2.3.1 Scientific Justification

To date, there is very little information about the existence of a deep biosphere in subseafloor serpentinizing systems. The warmest, highest pH domains of carbonate chimneys are dominated by a single clade of Lost City Methanosarcinales (Schrenk et al., 2004). However other microbial species reliant on possibly abiotic organic matter, have been found in the Lost City vent fluids by DNA sequencing and lipid biomarker analyses (Bradley et al., 2009; Brazelton and Baross, 2010; Brazelton et al., 2010; Brazelton et al., 2006; Méhay et al., 2013).

Prior to Expedition 357 it was hypothesised that mixing of diffuse hydrothermal fluids and seawater, together with organic rich zones related to serpentinization, would lead to a more diverse ecosystem (Frueh-Green et al., 2015), including both chemolithoautotrophs and heterotrophs. It was also hypothesised that serpentinizing environments would sustain higher biomass than gabbro-dominated domains such as that sampled in Hole U1309D, where cell counts were below detection limit, but gene sequencing revealed evidence for bacteria largely related to hydrocarbon degraders (Mason et al., 2010).

Results from shallow (<16.4 mbsf) coring on the southern wall during Expedition 357 indicate a very low biomass ecosystem (Fig. 10) compared to other crustal subsurface systems (Früh-Green et al., 2018). However this coring did not reach target depths of 50-80m, and it is doubtful that any part of the active Lost City flow system was accessed. Sampling probably did not sufficiently target porous and permeable zones likely to contain more abundant biomass. For example the highest cell count of 4.1 x 10^3 cells cm^{-3} was found in metagabbro (M0071A 2R1 66-86). This sample was taken adjacent to highly chloritized gabbro with relict reaction porosity (Fig. 7), which was filled with chlorite down to conditions of <100°C, potentially suitable for microbe growth. There are a number of reasons why reaction porosity in mafic lithologies may increase microbial activity, including lower local pH, nutrient access through permeability, and chemical gradients related to lithological boundaries and ongoing mineral precipitation (Andreani and Menez, 2019; Lang and Brazelton, 2019). Operational restrictions during Expedition 357 inhibited the ability to properly characterise the microbiology of serpentinizing seafloor; deeper and more targeted samples are necessary to determine if there are robust depth-, temperature- or lithology-driven patterns in the abundance or diversity of microbial life, and if there are connectivities between this deeper ecosystem and that observed at LCHF. Similarly, sample collection in Expeditions 304/305 was not targeted on porous, permeable and reactive zones, (Mason et al., 2010) and may not be representative. We will therefore drill a new single bit hole in the gabbroic domain (U1309-J) with the primary aim of sampling known porous zones such as amphibole-filled vugs, the interior and margins of diabase intrusions (Fig. 7), leucocratic veins, and fault breccias.

The thermal structure of AM also allows study of the temperature limits of deep biosphere in a crustal system, as fluid temperatures in the existing Hole U1309D (Fig. 1) are expected to cross both the known upper thermal limit for life in laboratory cultures (122ºC) and the lower suspected temperature limit (~80-90ºC) for life in energy-limited subsurface crustal systems (Heuer et al., 2016).

2.3.2 Expected outcomes:

Objective 3 deliverables:

3A: Fluid sampling for microbiology in Hole U1309D down to 1400mbsf. If the MTFS tool is successful (see operations), we will collect up to nine samples at temperatures ranging from 78 to 148°C (Fig. 10). Otherwise we will collect samples at 75-80°C with the Kuster tool and additional samples at depths corresponding to 100, 120, and 130°C.

3B: We will leave Hole U1309D and AMDH-2A open as legacy holes for future fluid sampling, temperature measurements, and potentially installation of equipment. The thermal regime at AMDH-2A will yield vital information about shallow fluid flow directions and permeability structure close to the LCHF, and the interaction between hydrogeology, the sources of components such as H_2 and CH_4, and microbiology, thus linking to objectives 1 and 2.

3C: A microbiology sampling strategy focussed on porous and permeable zones in both gabbroic rocks cut by diabase in Hole U1309-J, and in serpentinite containing gabbro and diabase intrusions close to the LCHF in Hole AMDH-2A.

Objective 3 Hypotheses:

3D: That a more diverse microbial biosphere will be found than in the LCHF chimneys.

3E: That higher cell counts (> 4 x 10^3 cellscm^{-1}) will be found in porous and permeable zones such as reaction porosity in the edges of gabbroic intrusions, fault rocks and fractures potentially channelling Lost City fluids.

3F: That higher cell counts and specific types of microbial life will be associated with local fluid chemistry (including H_2, CH_4, organic acids, other organic compounds, cation and anion ratios and if possible pH, see Obj. 2C).

Objective 3 will address IODP Science Plan Challenges 5 and 6.

2.4: Drilling technology, new instrumentation and legacy

Achieving these scientific objectives will also have two important *value-added benefits*. First, we will test the technological capabilities of the *JOIDES Resolution's* coring, logging, and sampling program in ways that are highly complementary to the community aims of future "MoHole" drilling (M2M proposal 805-MDP and SloMo proposal 800-Full). There is great current interest in deep drilling technology (Deep Crustal Engineering Working Group Rpt, 2017) and it is important to determine coring rates in hot gabbros. Second, we will leave Holes U1309D and AMDH-2A open for legacy operations, including fluid sampling and temperature measurements, and potentially future installation of a CORK-Lite borehole observatory (Wheat and others, 2012) for continued sampling and monitoring.

3. Operational plan, challenges, opportunities and contingencies

3.1: Primary operational plan (Table 1, Fig. 11):

1. A new 200 m hole with ~15 m of casing and a re-entry funnel drilled-in using a mud motor and under-reamer at site AHMD-02A. A camera survey and pilot hole are scheduled to assess conditions for casing. We intend to run plastic core liners and synthetic tracers (perfluoromethyl decaline, PFMD) during drilling and coring to assess sample contamination. This gently sloping location is ~100 m from Expedition 357 Site M0069 (Fig. 3 and site form), which gave good recovery of diabase intrusives cutting talc-amphibole-chlorite schist, a brittle fault zone at ~13 mbsf, and undeformed serpentinites to 16.5 mbsf (Fig. 5). Proximity to the LCHF is necessary to address Objective 1C. The target penetration is at least 200 mbsf to recover the entire detachment fault zone (Objective 1).
2. Re-entering Hole U1309D (site AMDH-01A) for tool runs on the coring line to 1415 mbsf to collect fluid samples and temperature data. We target variations in fluid chemistry related to lithology (olivine-rich vs olivine-poor), temperature, and potential inflow of formation water along fault zones. A priority interval for sampling is the olivine-rich troctolites at 1100-1200 mbsf (Fig.1B), which are at roughly 100-125 ºC, to assess differences in water-rock reactions (objectives 1, 2) and the thermal limits of the biosphere (objective 3). Tool runs will include:

a. Several runs of the Kuster Flow Through Sampler (de Ronde et al., 2019) to collect pristine borehole fluid samples 50 m above, at, and 50 m below the inferred fluid flow zone at 746 mbsf (~80ºC) for microbiological and geochemical analyses (objectives 2 and 3).
b. One run of the new Multi-Temperature Fluid Sampler (MTFS; described in more detail below) and the Elevated Temperature Borehole Sensor (ETBS; maximum operating temperature of 232ºC de Ronde et al., 2019) to collect ~12 pristine borehole fluid samples at different temperatures and to determine the thermal profile of the borehole before drilling disturbance. The ETBS record will confirm depth intervals where the MTFS collected samples, based on the temperature ranges of the tool triggers.
c. If the new MTFS tool fails, the Kuster tools can again be run into the hole to collect samples from deeper intervals prior to drilling. The tool is mechanically triggered with a clock and performs across the expected temperature range in the hole.
d. If obstructions prevent the lowering of these tools, these sampling operations would be canceled, to clean out the hole before the next operation. We do not anticipate this issue, however, as Expedition 340T experienced good hole re-entry conditions.

3. Re-entering the hole with a reverse circulating junk basket to retrieve small pieces of a logging tool lost during Expedition 340T (Expedition-340T-Scientists, 2012).
4. RCB coring in Hole 1309D for 9-10 bit runs to approximately 2060 mbsf (150-220ºC based on the linear temperature gradient in the bottom 750 m of the existing Hole (Blackman et al., 2014)). Only gradual changes in lithology are expected from geophysics (Fig. 3). During Expedition 305, the Hole was deepened by 1014 m in 40 days on site. We have assumed slower drilling rates in hotter conditions, down to 1m/hr below 2000 mbsf, and half-length RCB cores to account for challenging penetration conditions (Table 1). Core barrels will run without core liners (plastic liners begin to melt at 80ºC and aluminium split cores are only marginally useful), with the contents shaken out into split core liners upon recovery, as done on the Brothers Arc Expedition 376 (de Ronde et al., 2019).
5. Logging (with flasked tools to protect electronics from high temperatures) from 1300 mbsf to as deep as temperatures allow. Depression of borehole temperatures during drilling and hole conditioning should allow a high proportion of the deepened hole to

be logged. A first standard Triple Combo logging tool string run would chart hole conditions (caliper) while logs of density (HLDS tool) and resistivity (HRLA tool) will be most valuable for wall rock characterization. The Formation MicroScanner (FMS)-Sonic tool string would be run next to image structural features, document fracture orientations, and measure wallrock seismic velocity. If time and circumstances allow (i.e., no marine mammals in the area), we would also run the Vertical Seismic Imager (VSI). This will generate extended crustal architecture logs for synching with new lithological analysis of deep, hot gabbros (objective 1).

6. A new 80m RCB Hole ("U1309-J") at Site AMDH-1A aimed primarily at sampling porous zones in gabbro and diabase for microbiology and porewater chemistry.
7. Returning to Site AMDH-02A to assess if fluid flow is occurring, measure temperature and log the Hole with the same tools as (5) above.

Based on communication with the *JOIDES Resolution* Science Operator (JRSO, Table 1), conservative estimates for this expedition are 61 days including transit. We have not included a general contingency allowance. Operational delays could be absorbed by leaving logging at Site AMDH-02A as a legacy operation, and by cutting the last two bit runs (6 days) from IODP Hole 1309D (table1), losing only 80 m of penetration, such that objectives would not be seriously compromised.

3.2: Contingency plans (Fig. 11):

Contingency 1: The most extreme contingency is required if the re-entry cone for Hole U1309D is dislodged so that the Hole cannot be deepened or sampled for fluid. In this case, our backup plan would be drill Hole U1309-J, and then to resume operations at Site AMDH-02A but extend the total penetration depth as far as possible. Assuming 35 days (Table 1) and a relatively slow average penetration rate of 2m/hr, this would allow deepening to ~ 1000m. Based on the FWI image on site Figure AMDH-02A, the Hole would pass through an inversion in the P-wave velocity which dips north and leads towards the LCHF. We speculate that this may be a fault-controlled hydrothermal feeder zone, perhaps controlled by a larger gabbroic intrusion above. This contingency plan would:

- Allow deliverables and hypothesis tests 1D, 1F, 1G and 1H (in part) still to be achieved, and enhance objective 1C

- Allow deliverables and hypothesis tests 2B, 2C, 2D, 2E (part) 2F and 2G to be achieved or expanded
- Allow all the microbiology deliverables and hypothesis tests except 3A and part of 3B to be enhanced by additional sampling in the zone of potential subsurface biosphere.

A new objective to significantly enhance groundtruthing of the Full Waveform inversion (Fig. 3B, C) would be achieved. This area is characteristic of the 'Intermediate Velocity' material identified by Canales et al. (2008) and Henig et al. (2012). Ground-truthing this interpretation is useful as current models of OCC structure and evolution depend on it

Contingency 2: If neither Hole U1309D deepening or AMDH-2A coring are possible, we would establish a new re-entry hole at alternate site AMDH-03A, 2 km west of and ~400 m downslope of AMDH-02A (Figure 3) This site is between Exp. 357 sites M0070 (carbonate rich breccias) and M0071 (serpentinite with chloritized metagabbro containing reaction porosity). It shows similar velocity variations in the FWI image to site AMDH-2A (Harding et al., 2016) (site Form AMDH-3A and Fig. 3). At this site we can achieve all the objectives listed in contingency 1 except that temperature measurements (Obj. 1C) would not constrain the thermal structure around the LCHF as well.

Contingency 3: If we are unable to place casing and a re-entry cone at either site AMDH-2A or AMDH-3A, we propose to drill single bit Holes close to as many of the Exp. 357 shallow holes as time allows. We consider the geophysics to be sufficiently indicative of the general conditions in this area that for a single bit Hole the bathymetry available from the 50 m multibeam bathymetry collected on Exp. 357 (Früh-Green et al., 2018), together with seabed conditions via a camera survey will be sufficient to site Holes. We would avoid drilling closer than 100m to sites with unsampled borehole plugs (M0068 and 75), and also sites with some drilling hardware left in them (M0069A, 71C and 76B). This would allow most of the objectives of the expedition to be achieved with the probable exception of a full section through the detachment fault zone, temperature measurements and fluid sampling. Only modest surficial groundtruthing of geophysics would be possible.

3.3: Other considerations:

Achieving objective 1 requires collection of deep gabbros, which we anticipate to vary in *in situ* temperature from 150ºC to 220ºC . During IODP Expedition 376 at Brothers Arc, drilling and coring operations were possible up to 260ºC (de Ronde et al., 2019) thus, operationally, achieving this objective is feasible.

Collection of hot, pristine fluids (up to 150ºC) of ~600 mL volume with the Kuster tool was proven on Expedition 376 (de Ronde et al., 2019).

Improved fluid sampling is reliant on the use of the new Multi-Temperature Fluid Sampler (MTFS, Fig. 10), designed and built by proponent Geoff Wheat and colleagues (NSF award OCE-1830087). The MTFS uses a trigger mechanism based on change of a shape-memory alloy that is activated at a specific temperature range (details not provided as the method is under review for a provisional patent). Twelve ~ 1L units were built for IODP Expedition 385T, but a stuck packer could not be removed from Hole 504B, preventing deployment and trial of the MTFS. However, laboratory tests have confirmed the temperature ranges of the available triggers up to 183ºC, and shipboard operations during 385T allowed detailed planning with the rig floor on how to deploy the tool in combination with the ETBS. Figure 10B presents an overview of the depth ranges for fluid samples that could be captured by the existing MTFS samplers, as well as the target depths for preliminary Kuster tool runs.

4. Sampling and analysis plan

4.1: To achieve objective 1, rock samples will be studied by the full range of hard rock methods; optical and SEM observation, EMPA, XRD, major and trace whole rock analysis (including in situ methods), palaeomagnetic analysis, radiometric dating of zircons and fluid inclusion analysis, and analysis of radiogenic and stable isotopes (see also objective 2). Petrophysical properties of the deep section will be documented.

We will ensure that unwanted pieces (e.g. the outside) of whole round cores removed for microbiology and other analyses are returned as soon as possible to be available for description, analysis and archiving. If samples are broken up on board ship we will involve members of the rock description teams in assisting in this process in order to preserve way up and other data. If they are broken up at a later date we will take steps to archive them properly in the core repository.

4.2: High temperature core samples: To achieve objectives 1 and 2, we will core hot (>150ºC) rocks at Hole U1309D that have never been cold (other than briefly during drilling), but which have been affected by gradual geological cooling with limited fluid access. We are keen to avoid any contamination, degradation or changes in the mineralogy of selected samples prior to analysis. Serpentinites can oxidise rapidly in a moist, ambient atmosphere at room temperature, with likely effects on organic molecules and the oxidation state of the sample. It will be impossible to limit sample contamination during coring above 147ºC using normal microbiology protocols (i.e., core barrels are run without plastic core liners that begin to melt at 80ºC, synthetic tracers commonly used for contamination tracing volatilize at those temperatures). We have not yet finalised protocols in this area. Options include:

1. **Cleaning whole round samples and storing under inert, dry conditions:** Immediately after shaking out the contents of the core barrel into fresh split core liners, photographing and measuring the core pieces, we will remove a small fraction (<5% core section) of the whole round core (WRC) and immediately transfer it to the Chemistry/Microbiology lab for storage preparation. This will involve rinsing the sample with nitrogen-sparged filtered seawater (to remove potential microbial contamination) and gently drying under a stream of filtered nitrogen, transferring it to gas-tight plastic-lined aluminium bag (as commonly used with anoxic sediment core WRC), flushing the bag and sample with nitrogen headspace before impulse sealing. Samples may be broken up using a titanium chisel for shipboard work.
2. **Cleaning samples as above and then storing in ovens at a temperature close to the sample depth in Hole:** This may prevent low temperature reactions and samples may be useful for further work such as fluid-rock interaction or microbial culturing. Container materials such as aluminium and Teflon may catalyse reactions or themselves degrade, particularly at high temperature (Andreani and Menez, 2019).
3. **Critical point drying to preserve organic compounds.** This would need to be established in the Microbiology Laboratory

Further tests are needed to establish what measures will best protect the samples. If the Expedition is scheduled we will develop detailed protocols in collaboration with JRSO. Different subsamples may be treated in different ways to allow comparison.

To characterise organic compounds in rock core, a subset of samples will be analysed using Synchrotron Fourier Transform Infrared (FTIR) imaging to characterize organic molecules in microscale porosity (Ménez et al., 2018; Pisapia et al., 2018). This will be complemented with Fourier-transform ion cyclotron resonance mass spectrometry (FT-ICR-MS) and Time of

Flight secondary ion mass spectrometry (TOF-SIMS) imaging and SEM analysis. *In situ* observations in core will give control information on what compounds, both organic and inorganic, are actually produced at temperatures >140°C in young (<1.2 Ma) gabbroic rocks which have never been at lower temperature. If sufficient hot material is available, some of the samples could be used for incubation experiments to examine microbial colonization of crustal material that has never been exposed to life, following approaches used with sterilized rock substrates in other warm deep biosphere environments (Ramírez et al., 2019).

4.3 Low temperature rock sampling: Achieving objectives 2 and 3 requires removing WRC from the southern wall hole (AMDH-02A) core sections immediately after collecting and initial cataloguing to prevent organic geochemical and microbiological contamination, as has been done on recent expeditions (de Ronde et al., 2019; Hickok et al., 2018; MacLeod et al., 2017). We will process the samples either within HEPA-filtered "KOACH" workstations (to minimize particle/cell contamination) and/or inside anaerobic chambers (to minimize oxygen exposure of anoxic samples) in the Chemistry/Microbiology laboratory after initial removal of WRC from the core splitting room. We will use similar types of contamination control, geochemical, and microbiological samples as was done on previous expeditions (de Ronde et al., 2019; Fruh-Green et al., 2017), with an emphasis on high resolution sampling for rock crushing experiments to examine fluid inclusion gas contents. We will also recover fluids and microbial samples from larger scale reaction porosity and fault zones, using modified methods for fluid inclusion crush-leach analysis to analyse cations (Banks and Yardley, 1992), halogens and isotopes (McCaig et al., 2000), together with organic acids and other organic compounds (Albert and Martens, 1997).

We will sample for the full range of microbiological techniques as conducted on recent hard rock expeditions (de Ronde et al., 2019; MacLeod et al., 2017), including ATP analysis, cell counts, viral analysis, cultivation experiments and molecular biology.

4.4: Borehole fluids: Experience gained from recent expeditions (i.e., 360, 376, 385T) will guide protocols for processing of borehole fluid samples for microbiological and geochemical characterization (objectives 1, 2 and 3). Prior to deployment, fluid tool sampling surfaces will be cleaned with detergents (to remove grease), dilute bleach (to kill any surface-attached microbes), dilute acid (to remove any leachable metals), distilled water (to remove all of the above), and alcohol solutions (to remove remaining organics and for final sterilization before deployment). Upon recovery, fluid samples will be split for standard ship-based dissolved solute measurements and a variety of shore-based analyses including cell density measurements, flow cytometric-based cell sorting and subsequent DNA sequencing, possible culturing experiments, dissolved inorganic and organic carbon concentration and isotopic composition measurements, and isotopic analysis of dissolved solutes (Li, B, Ca, Mg, Sr). These analyses will be conducted to better understand phase equilibria and rock-fluid interaction processes as well as deep biosphere microbial activity and structure. Fluid composition data and fluid-rock interaction will be modelled as described in section 2.1.1.4.

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Table 1.

Atlantis Massif (P937)

Operations Plan Summary Slimmed

midgley, 27 September 2019

Site No.	Location (Latitude Longitude)	Seafloor Depth (mbrf)	Operations Description	Transit (days)	Drilling Coring (days)	LWD/MWD Log (days)
Barbados			Begin Expedition 5.0	Port Call Days		
			Transit 1409 nmi to Site AMDH-02A @ 10.5 knots	5.6		
AMDH-02A	30.131700° N	836	Hole A: Seafloor Survey for Hole A and pilot hole		1.5	
	42.1202° W		Hole B: Reentry system for Hole B		1.6	
			Hole B: Coring Bit Run #1 - to 100 mbsf		2.1	
			Hole B: Coring Bit Run #2 - to 200 mbsf		2.1	
			Sub-Total Days On-Site: 7.3			
			Transit 2 nmi from Site AMDH-02A to Site U1309D @ 8.9 knots	0.0		
U1309D	30.168658° N	1656	Hole D: Fluid Sampling and temperature logging			1.0
	42.1186° W		Hole D: Fish Caliper with RCJB at U1309D to 1415.5 mbsf		0.8	
			Hole D: Bit Run #1 - to 1495.5 mbsf - 2 m/h penetration rate		3.3	
			Hole D: Bit Run #2 - to 1575.5 mbsf - 2 m/h penetration rate		3.3	
			Hole D: Bit Run #3 - to 1655.5 mbsf - 2 m/h penetration rate		3.4	
			Hole D: Bit Run #4 - to 1735.5 mbsf - 2 m/h penetration rate		3.4	
			Hole D: Bit Run #5 - to 1800.0 mbsf - 1.5 m/h penetration rate		3.3	
			Hole D: Bit Run #6 - to 1860.0 mbsf - 1.5 m/h penetration rate		3.2	
			Hole D: Bit Run #7 - to 1920.0 mbsf - 1.5 m/h penetration rate		3.3	
			Hole D: Bit Run #8 - to 1980.0 mbsf - 1.5 m/h penetration rate		3.3	
			Hole D: Bit Run #9 - to 2020.0 mbsf - 1.0 m/h penetration rate		3.0	
			Hole D: Bit Run #10 - to 2060.0 mbsf, log with triple combo, FMS sonic and VS		3.4	1.5
			Hole U1`309-J: RCB coring to 80 mbsf		1.8	
			Sub-Total Days On-Site: 38.1			
			Transit 2 nmi from Site U1309D to Site AMDH-02A @ 8.9 knots	0.0		
AMDH-02A	30.131700° N	836	Hole B: Logging and sampling at AMDH-02A		0.5	0.8
	42.1202° W					
			Sub-Total Days On-Site: 1.2			
			Transit 936 nmi from Site AMDH-02A @ 10.5 knots	3.7		
Ponta Delgada			End Expedition	9.3	43.3	3.3
		Port Call: 5.0	Total Operating Days:	56.0		
		Sub-Total On-Site: 46.6	Total Expedition:	61.0		

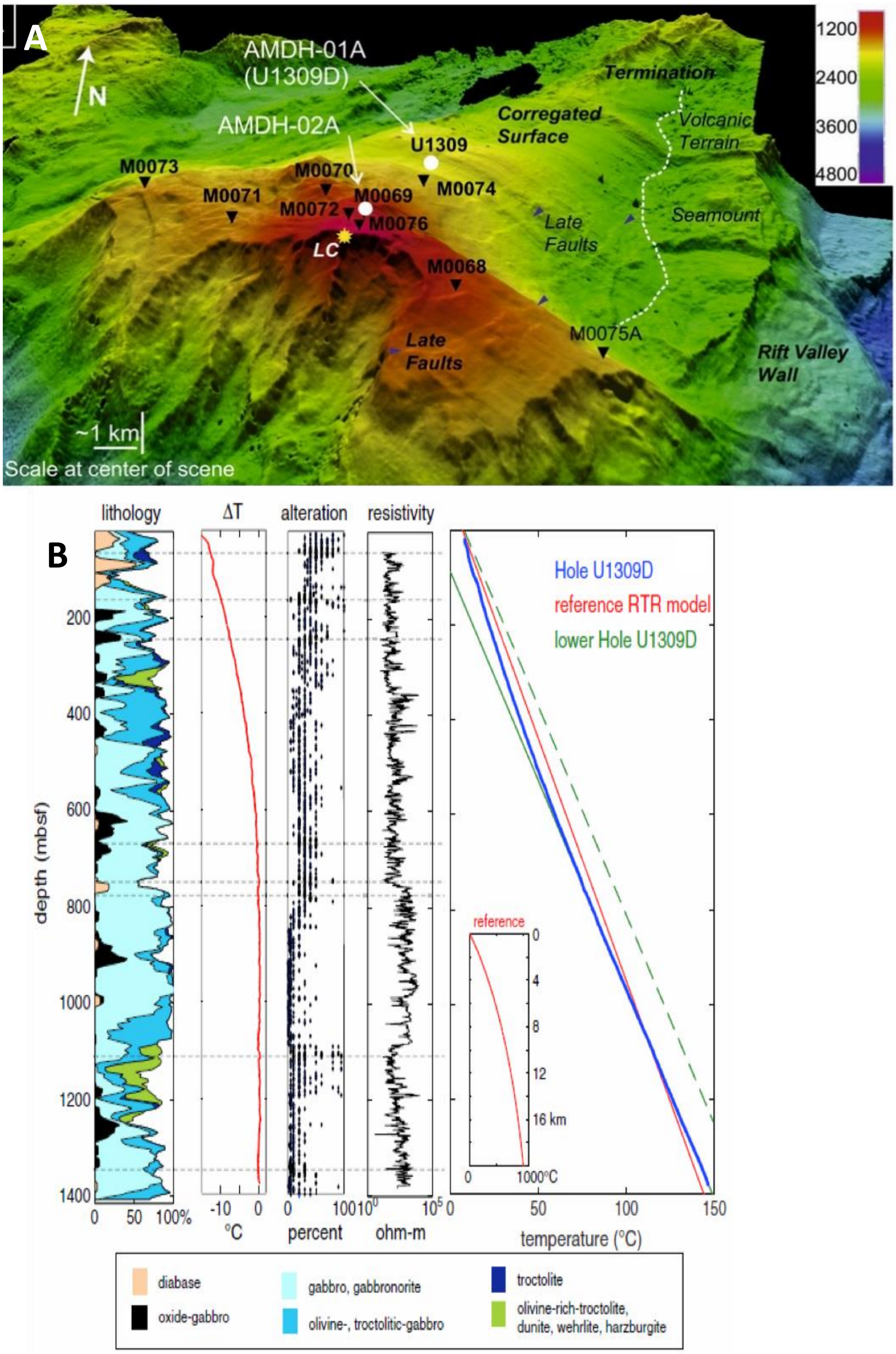

Figure 1*. A: 3-D perspective view of the Atlantis Massif showing the main structural features, the location of the Lost City Hydrothermal Field (LC), and the main sites drilled in Expedition 357. The main two drilling locations proposed here are shown by white dots. From Früh-Green et al. (2018). B: Lithology, temperature and resistivity logging results from Expeditions 304/305 and 340T (from Blackman et al., 2012). ΔT is the difference between the observed temperature and an extrapolation of the conductive gradient at depth to the surface. Minor excursions in temperature are interpreted as zones of fluid flow at 746 mbsf, where the temperature gradient changes from convective to conductive, and at 1107 mbsf, near the zone of olivine-rich troctolite.*

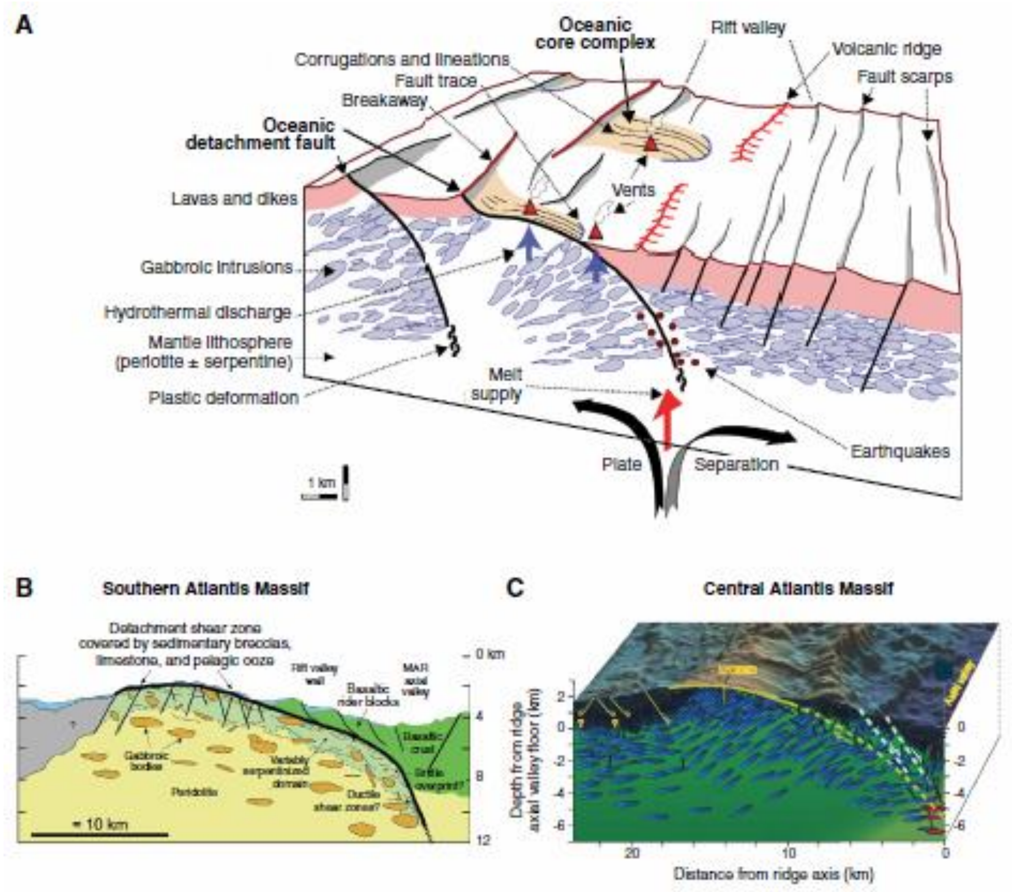

__Figure 2.__ Conceptual sketches of the tectono-magmatic evolution of a heterogeneous lithosphere and denudation of mantle rocks as detachment faulting progresses. A: Generic "detachment mode" seafloor (Escartin and Canales, 2011). B: The southern wall is dominated by variably altered peridotites with gabbroic lenses (Boschi et al., 2006) At the summit is a 100m thick detachment fault zone containing talc-tremolite-chlorite metasomatic schists (Karson et al., 2006) C: in contrast, major gabbroic intrusions dominate the central dome (Grimes et al., 2008)

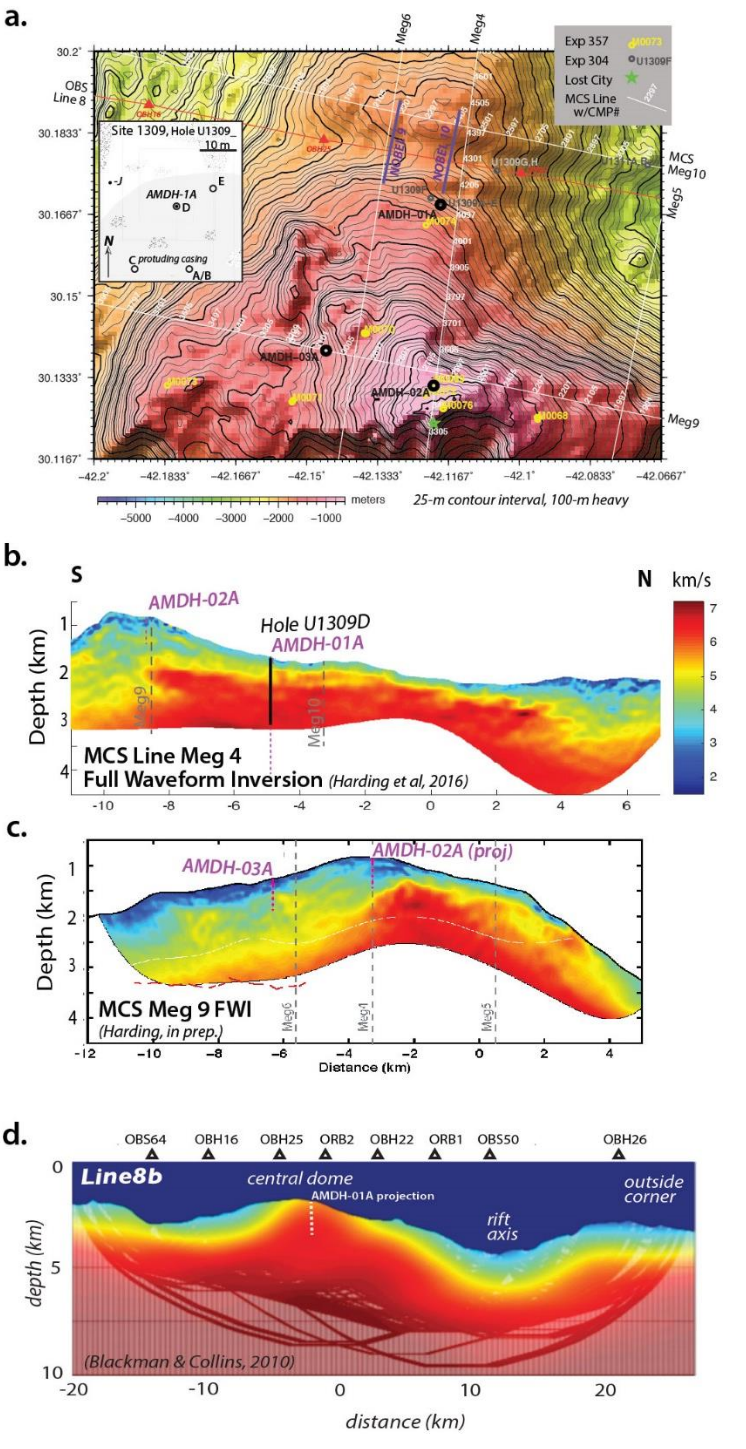

Figure 3: *Seismic crossing lines and seismic velocities across the Atlantis Massif.* ***A:*** *orientation of crossing lines in relation to previously drilled locations and primary and alternate sites of this proposal. (inset map shows relative locations of existing Holes at Site U1309, and proposed Hole U1309-J)* ***B:*** *full waveform inversion (FWI) of multichannel seismic (MCS) P-wave velocities along seismic line Meg4 (from Harding et al., 2016), with the two primary sites indicated.* ***C:*** *FWI of MCS line Meg9 showing alternate site AMDH-3A* ***D:*** *Tomographic inversion of Ocean Bottom Seismometer (OBS) velocities along refraction line 8 that crosses near Hole U1309D, showing expected continuation of P wave velocities between 6 and 7 km/s in the deepened Hole.*

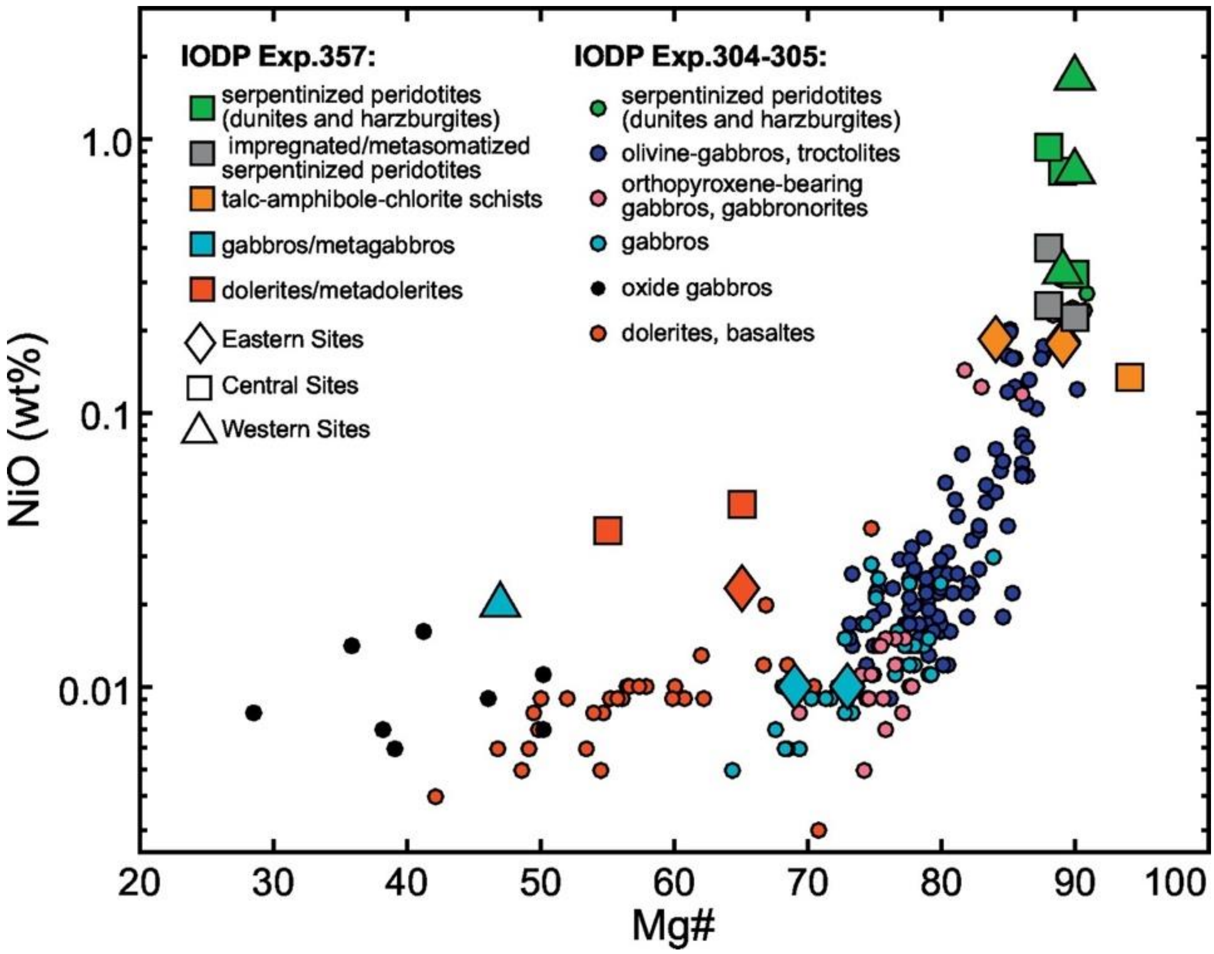

Figure 4. *Summary of igneous compositions in Hole U1309D (Godard et al., 2009) and in IODP Expedition 357 core samples (from Früh-Green et al., 2018). Note the very primitive compositions of many of the gabbroic rocks compared to the diabase dykes, which are similar to MORB at 30° N in the Atlantic*

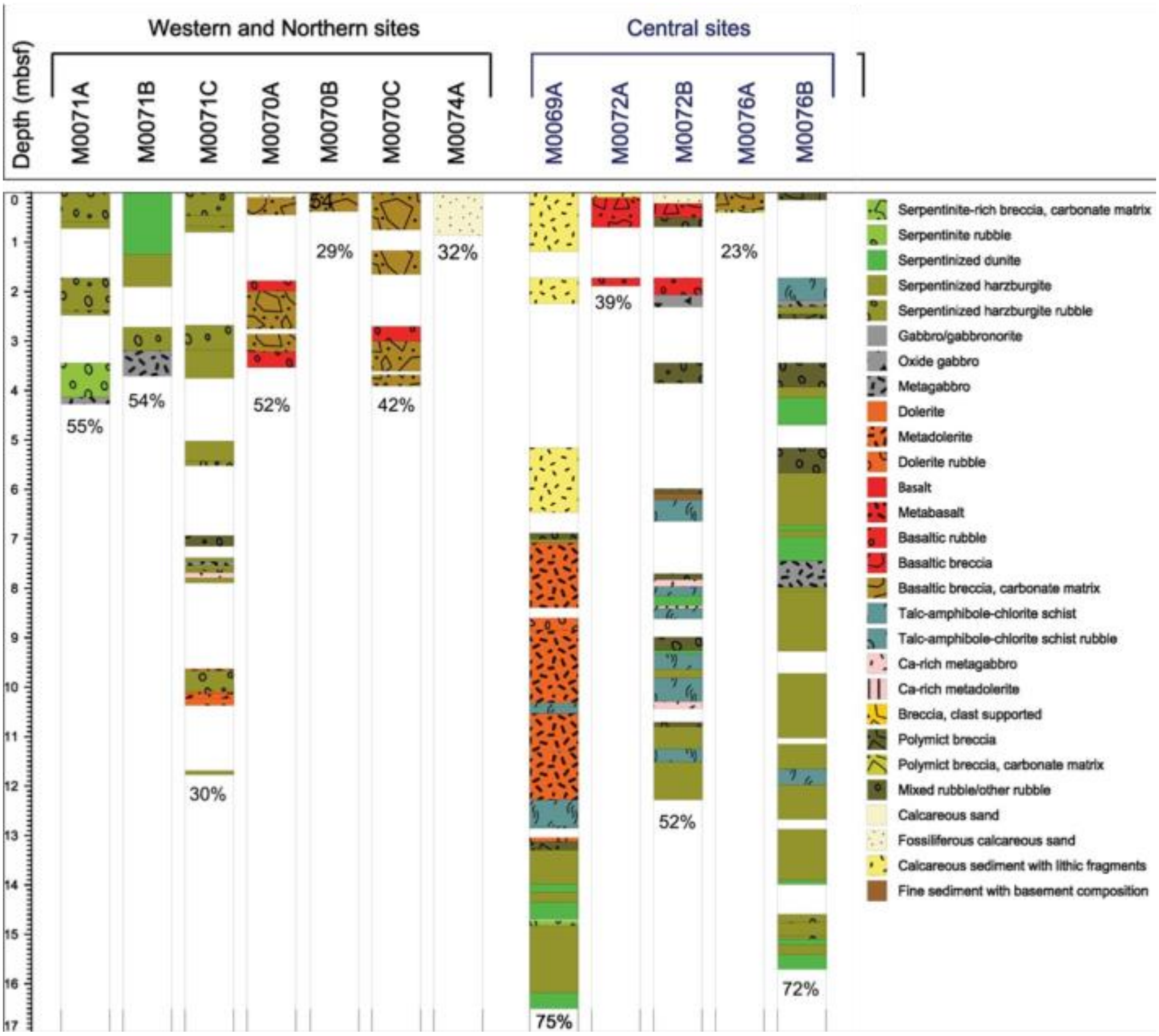

***Figure 5**. Lithological summaries from IODP Expedition 357 Holes along the southern wall of AM, focusing on the central and eastern sites (from Früh-Green et al., 2018). Our proposed primary southern wall site AMDH-02A is close to Hole M0069A, where metadolerite intrudes into talc-tremolite-chlorite schists, which are brecciated and underlain by a sub-horizontal brittle fault zone at ~13 mbsf. Below this fault are little-deformed serpentinized harzburgite and dunite. Beneath the soft sediment layer, recovery in the Hole was excellent.*

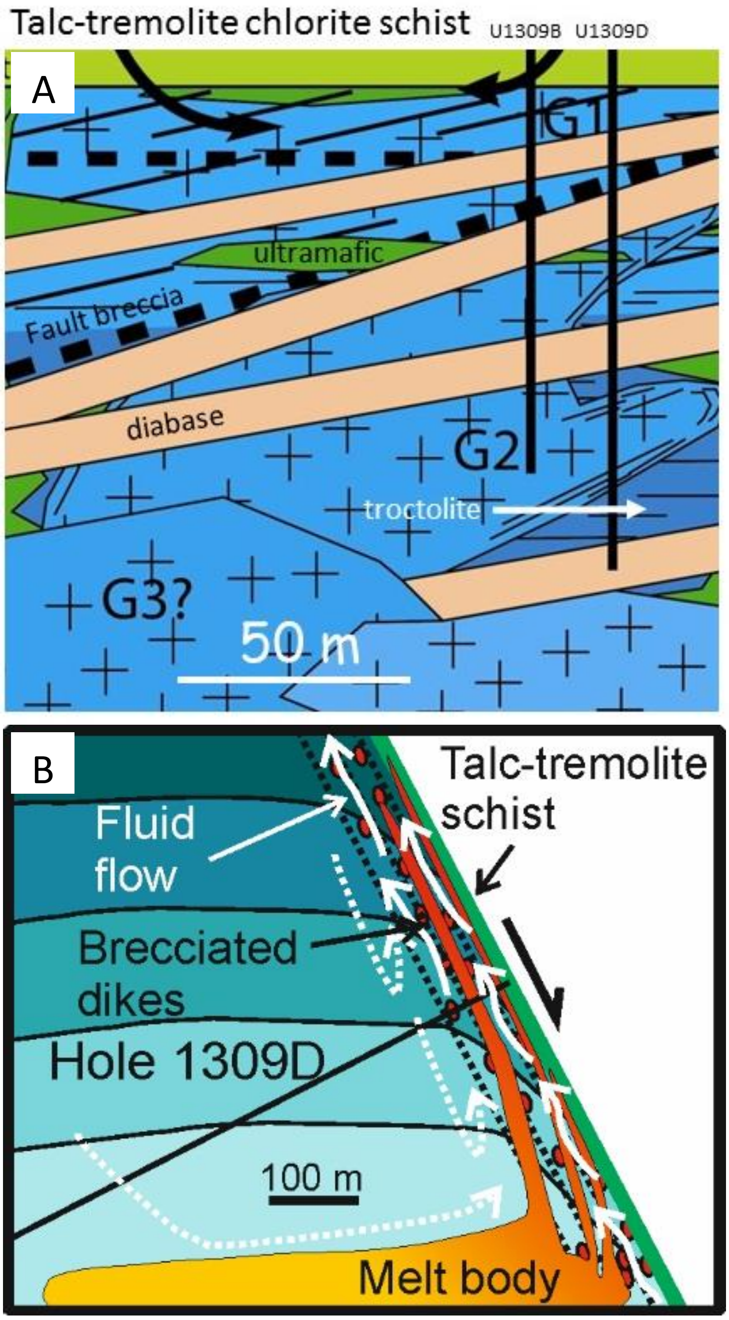

***Figure 6. A:** Interpretation of the geology at Site U1309 after 1 bit run in Hole U1309D (drawn by Michael Abratis). Diabase intrusions interpreted as sills within a heterogeneous fault zone cutting multiple gabbroic intrusions. Arrows indicate fluid pathways **B:** Proposed structure of the detachment zone at Site U1309 before rotation of the fault into the current sub-horizontal orientation(McCaig and Harris (2012). The fault zone is interpreted as a thermal boundary layer between gabbroic melt and hydrothermal circulation in the fault zone and hangingwall. Similar diabases occur in some of the Exp 357 cores chilling against serpentinites, talc-tremolite-chlorite schist and fault breccia, and occurring as clasts in breccia (Fig. 5). In our new Hole AMDH-02A we expect to sample a similar sequence of fault rocks and syntectonic intrusives, but in predominantly serpentinised peridotite, not gabbro.*

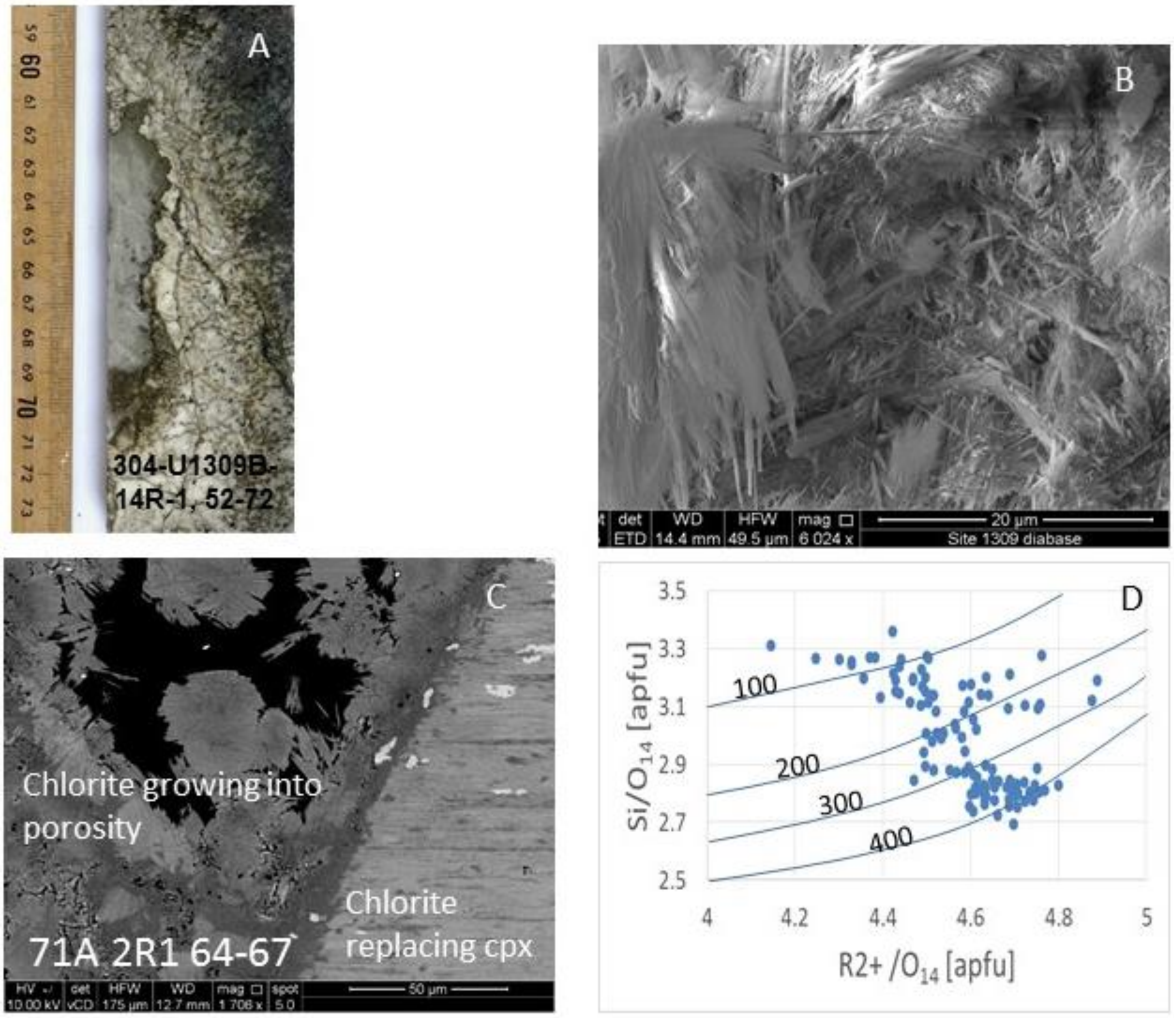

Fig. 7: Reaction porosity in the Atlantis Massif. A: amphibole filled vug in gabbro with bleached reaction rim of sodic feldspar and minor amphibole, 72mbsf in IODP Hole 1309B. Relict porosity is common both in the vug and the reaction rim. The vug is interpreted as a section through a stockwork pipe for black smoker fluid flowing up the detachment fault. B: Fibrous amphibole filling porosity formed by dissolution of clinopyroxene in diabase, IODP Hole 1309B. C: chloritized gabbro with plagioclase completely dissolved and the space filled by chlorite, Exp. 357, Hole M0071A. D: chlorite geothermometry (Bourdelle and Cathelineau, 2015) showing that the vugs filled over a temperature range from 400 to <100 °C

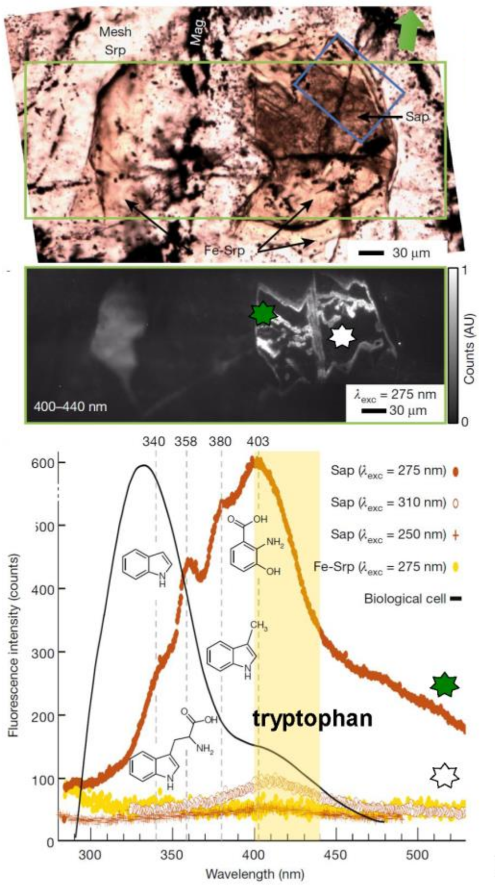

Figure 8. Endogenous UV-autofluorescence locally revealed by synchrotron deep ultraviolet (S-DUV) imaging of a highly altered mantle-rock recovered at 173.15 m below sea floor from IODP Expedition 304 Hole U1309D (Ménez et al., 2018). UV-fluorescence emerged from heteroatomic aromatic compounds shown to be spatially restricted to an Fe-rich clay in which they are heterogeneously distributed. From top to bottom: Optical image showing yellow to brownish phases identified as Fe-rich serpentine (Fe-Srp) and Fe-rich saponite (Sap), hosted in a serpentinized harzburgite with olivine being replaced by magnetite (Mag) and serpentine exhibiting a characteristic mesh texture (mesh Srp); the green arrow indicates sample orientation. Below is full field S-DUV image of the area depicted above by the light-green rectangle, collected between 400 and 440 nm using excitation (λexc) at 275 nm. AU, arbitrary units. At the bottom is the fluorescence emission spectra collected with excitation wavelengths of 250, 275 and 310 nm at the location shown by an asterisk in the D-SUV fluorescence map. The spectra collected at 250 and 310 nm do not show a notable UV-autofluorescence signal, whereas the spectrum at 275 nm displays fluorescence characteristic of indole at 340 ± 6 nm, tryptophan at 358 ± 3 nm, skatole at 380 ± 3 nm, and hydroxyanthranilic acid at 403 ± 3 nm18 (mean ± s.d. of three independent fits performed on three areas). Also shown are a fluorescence emission spectrum collected at 275 nm in the Fe-rich serpentine and the typical emission spectrum of a biological cell showing maximum fluorescence emission, mainly arising from protein-forming tryptophan, shifted to 335 nm21. The orange area represents the fluorescence detection range.

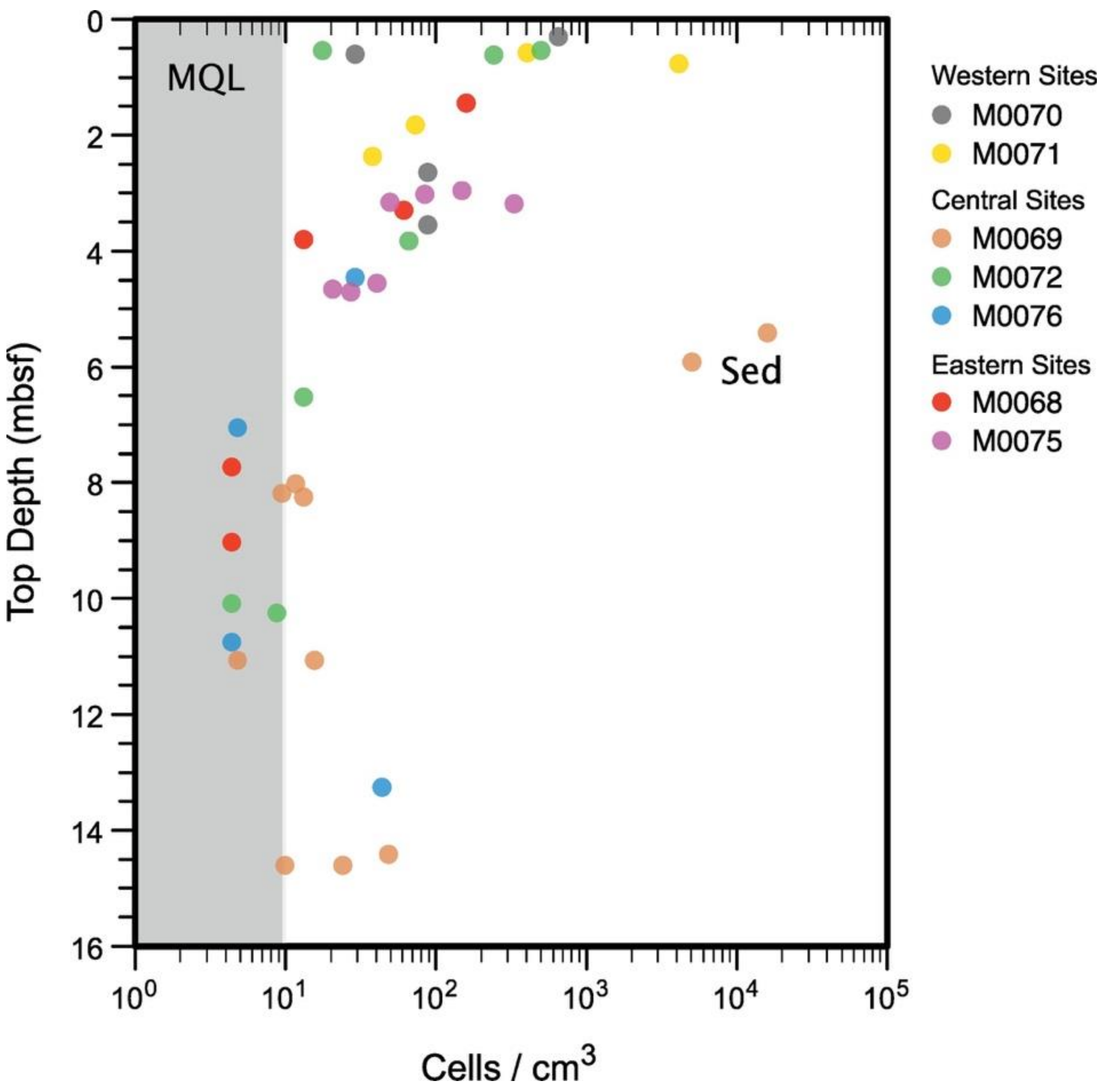

Figure 9. *Cell densities in samples collected from the southern wall of AM during Expedition 357 show the very low biomass levels in shallow, highly altered serpentinites (from Früh-Green et al., 2018). The shaded region shows the range of counts below the minimum quantification limit (MQL) of 9.8 cells cm^{-3}. Two deeper sediment samples (Sed) from Hole M0069A had higher cell densities than most of the rock core samples. The highest bedrock cell density of 4.1 x 10^3 cells cm^{-3} was found in metagabbro from M0071A 2R1 66-86. This sample was taken adjacent to highly chloritized gabbro with relict reaction porosity (Fig. 7)*

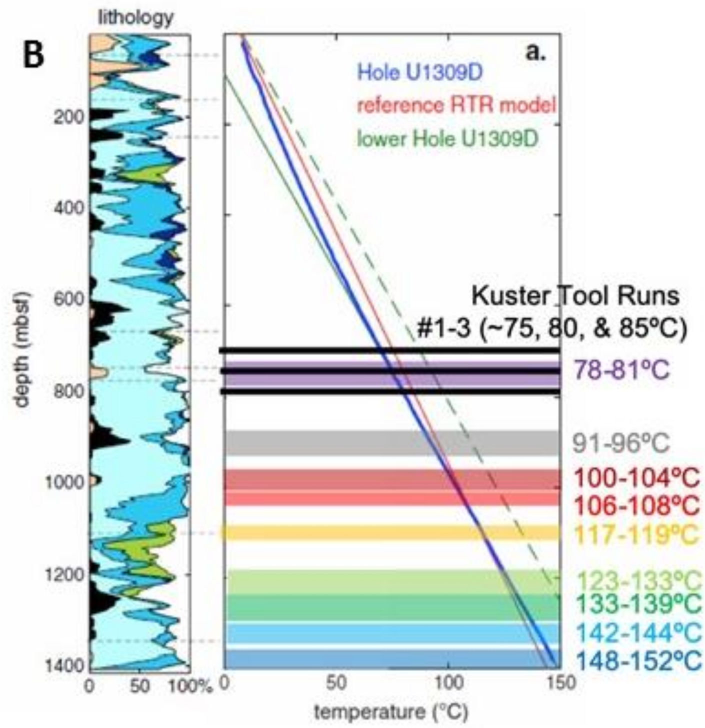

Fig.10 A: *The Multi-Temperature Fluid Sampler (MTFS) assembled and ready for deployment on the catwalk during IODP Exp. 385T. Photo by Geoff Wheat.* ***B:*** *Estimated temperature and depth ranges for fluid sample collection in Hole U1309D with the new Multi-Temperature Fluid Sampler (MTFS; Geoff Wheat, unpublished data), as well as estimated locations of Kuster Tool fluid sample collections, in comparison to lithology and temperature logs from Hole U1309D from Expeditions 304/305/340T (Blackman et al., 2011, 2012). Small temperature excursions occurred at ~100, ~ 750 and ~ 1100 mbsf suggesting fluid influx (see Fig. 1B).Temperature ranges of the MTFS triggers are based on several (n=3+) laboratory tests of each trigger (Geoff Wheat, unpublished data). Note that in Exp. 340T, the maximum temperature was 146.2 C at 1405 mbsf. We will leave the final SMA sampler on the string in case the temperature is higher after another 9-10 years of equilibration since Exp. 340T.*

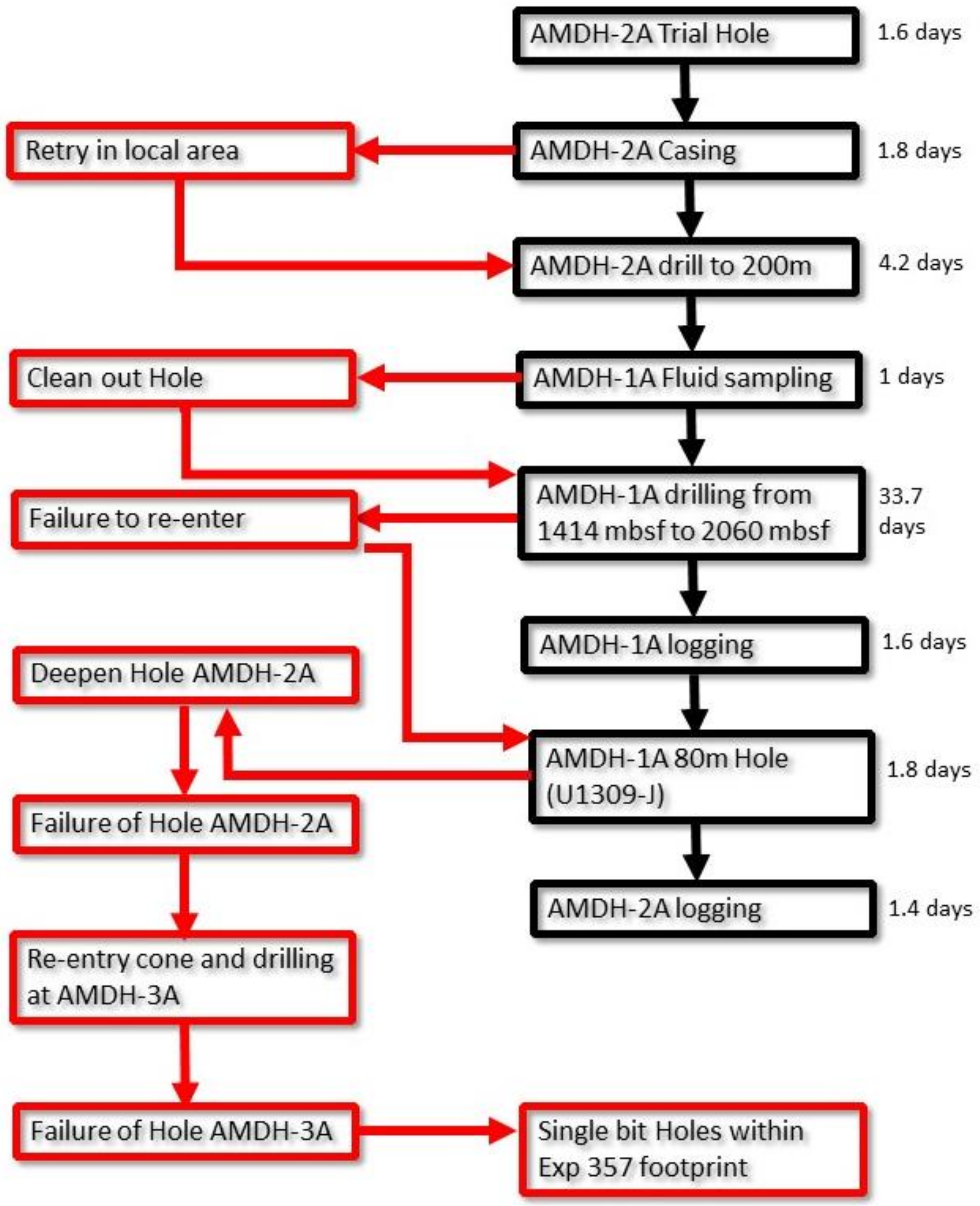

Figure 11: *Decision tree for drilling operations. Primary plan (Table1) is in black. Various alternate plans at different stages in the proposal are shown. Only failure to re-enter Hole U1309D would necessitate a major change in plan. On JRSO advice we have not included a specific contingency, but some loss in penetration in Hole U1309D at Site AMDH-01 could be accommodated without major harm to the objectives.*

Note that in our final contingency we request permission to drill single bit Holes anywhere within the Exp.357 footprint. The main criteria for siting would be closeness to Exp.357 Holes, and seabed conditions from camera survey including low slope angle. Geophysical conditions in the top 100m are similar everywhere, and there is no probability of hazards such as clathrate

IODP Site Forms

Form 1 – General Site Information

937 - Full 2

Section A: Proposal Information

Proposal Title	Accessing the Building Blocks of Life: Deepening Hole U1309D, Atlantis Massif, Mid-Atlantic Ridge
Date Form Submitted	2019-10-10 17:10:16
Site-Specific Objectives with Priority (Must include general objectives in proposal)	(i) Sample fluids and measure temperature in existing Hole 1309D down to 1414 mbsf (expected temperature 225 centigrade). (ii) Deepen existing Hole U1309D by ~650 m and collect samples for petrology and geochemistry of abiotic organic compounds and H2; (iii) log Hole with flasked tools. (iv) Drill new 80m Hole 20-30 m north of Hole U1309D, for microbiology sampling of porous rocks, fault zones, and correlation with Holes U1309B and D. This Hole is designated "U1309-J" in the text and site form. Note that Hole 1309C with protruding casing needs to be avoided.
List Previous Drilling in Area	Expeditions IODP 304, 305 and 357

Section B: General Site Information

Site Name:	AMDH-01A	Area or Location:	Atlantis Massif, Mid-Atlantic Ridge
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#	U1309D		
Latitude:	Deg: 30.1687	Jurisdiction:	none
Longitude:	Deg: -42.1186	Distance to Land: (km)	
Coordinate System:	WGS 84		
Priority of Site:	Primary: ✓ Alternate: ☐	Water Depth (m):	1656

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	0	660
	Total Sediment Thickness (m): 2	
		Total Penetration (m): 660
General Lithologies:	unconsolidated	gabbro, serpentinite

Coring Plan: (Specify or check)

Continuation of Expedition 305 coring. Multiple re-entry
Additional single bit Hole West of U1309D, termed "U1309-J"

APC ☐ XCB ☐ RCB ☑ Re-entry ☑ PCS ☐

Wireline Logging Plan:

Standard Measurements		Special Tools		
WL	☑	Magnetic Susceptibility	☐	Other tools: Fluid sampling hopefully using new MTFS tool. Also the 3rd party Kuster tool. For temperature the ETBS tool is requested.
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: Fluid sampling

Estimated Days: Drilling/Coring: 38 | Logging: 2 | Total On-site: 40

Observatory Plan:

Longterm Borehole Observation Plan/Re-entry Plan

Casing with re-entry cone already in place.Hole has been re-entered many times. Hole should be left clear for future logging and fluid sampling.

Potential Hazards/ Weather:

						Preferred weather window
Shallow Gas	☐	Complicated Seabed Condition	☐	Hydrothermal Activity	☐	December to May, avoiding Atlantic hurricane season
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): none

Other: maximum predicted temperature is 225 C at 2100 mbsf, based on gradient in the lower 750 m of Hole U1309D

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Proposal #: 937 - Full 2	Site #: AMDH-01A	Date Form Submitted: 2019-10-10 17:10:16

Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	no	
1b High resolution seismic seismic reflection (crossing)	no	
2a Deep penetration seismic reflection (primary)	yes	Line: Meg4 Position: Meg4 , CMP 4145 closest, ~400 m to east; RP#3378 closest in meg4_stack_2400_5280.segy
2b Deep penetration seismic reflection (crossing)	yes	Line: Meg10 Position: Meg10, ~1.8 km north, CMP 2405 close perpendicular projection
3 Seismic Velocity	yes	Harding et al. 2016- Meg4 waveform inversion & updated checkshot data from borehole; Blackman et al. 2014- complete sonic log to ~1400 mbsf. (older versions Canales et al. (2008) and Henig et al. (2012) Meg4 downward continued streamer tomography, former to datum above seafloor and latter to seafloor)
4 Seismic Grid	yes	Meg4, Meg5, Meg6, Meg9, Meg10- Canales et al., 2004 (Meg8 outside corner)
5a Refraction (surface)	yes	OBS refraction- Blackman and Collins 2010; Line 9a crosses Site; Line 8 is 1.8 km to N
5b Refraction (bottom)	yes	NOBEL- Harding et al. 2016 waveform inversion for Line 10, just north of hole Collins et al. 2009 shows older tomography for Lines 9 & 10.
6 3.5 kHz	no	
7 Swath bathymetry	yes	CD100 EM12, MARVEL2000 SeaBeam2000, 100-m regional grid Blackman et al., 2008. EM120 20-50m grid Früh-Green et al., 2017.
8a Side looking sonar (surface)	no	
8b Side looking sonar (bottom)	yes	CD100 Tobi MARVEL2000 DSL120
9 Photography or video	yes	MARVEL 2000 Alvin and Argo images
10 Heat Flow	yes	Temperature throughout borehole; from deep section heat flow prediction is 257 mW/m2, Blackman et al., 2014
11a Magnetics	yes	Pariso et al., 1996; MARVEL2000 deep-tow
11b Gravity	yes	Blackman et al . 2008
12 Sediment cores	yes	Holes U1309A, U1309E, U1309F, U1309G
13 Rock sampling	yes	CD100 Dredge, MARVEL2000 Alvin; Hole U1309D core to 1415mbsf
14a Water current data	no	
14b Ice Conditions	no	
15 OBS microseismicity	no	1 yr study, Collins et al. 2012
16 Navigation	yes	MCS, OBS & NOBEL refraction, DSL120, Alvin rock sample & dredge locations
17 Other	no	

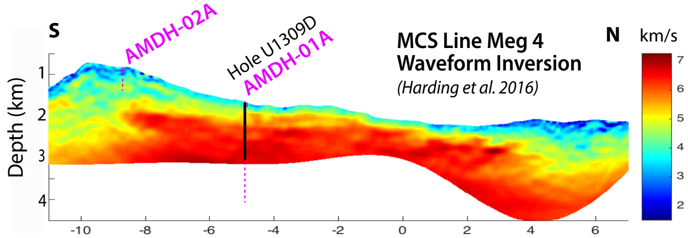
Proposal #: 937 - Full 2	Site #: AMDH-01A	Date Form Submitted: 2019-10-10 17:10:16

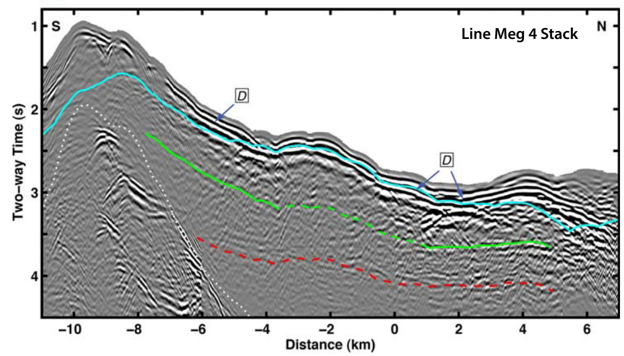
Pollution & Safety Hazard	Comment
1. Summary of operations at site	visual check for flow; re-enter; slow down-run for minimally-perturbed T measure; up run for caliper & (initial) borehole fluid sampling; additional fluid sampling to cover desired intervals (if dont have multi-sample capability); RCB coring; logging of at least newly-penetrated section, full section if time.
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?	minimal disturbance in hole until initial T measurement & fluid sampling are complete. During final logging temperature needs to be monitored to avoid damge to temperature-limited logging tools
7. What abandonment procedures need to be followed?	standard for tool stuck in hole, if that were to occur
8. Natural or manmade hazards which may affect ship's operations	~20m casing was left protruding from seafloor at Hole U1309C in 2004
9. Summary: What do you consider the major risks in drilling at this site?	moderately high temperature as hole deepens (~150-250 °C expected)

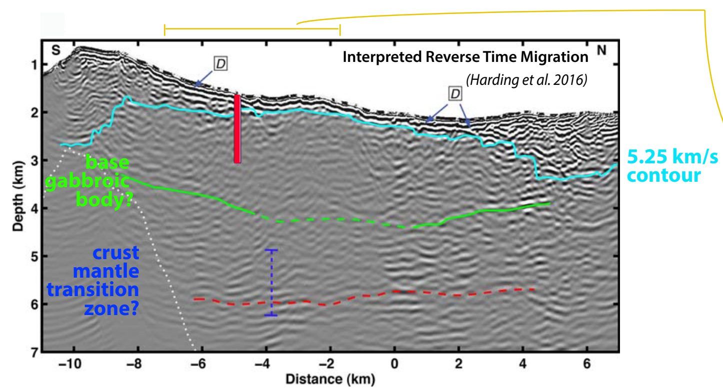
Proposal #: 937 - Full 2	Site #: AMDH-01A	Date Form Submitted: 2019-10-10 17:10:16

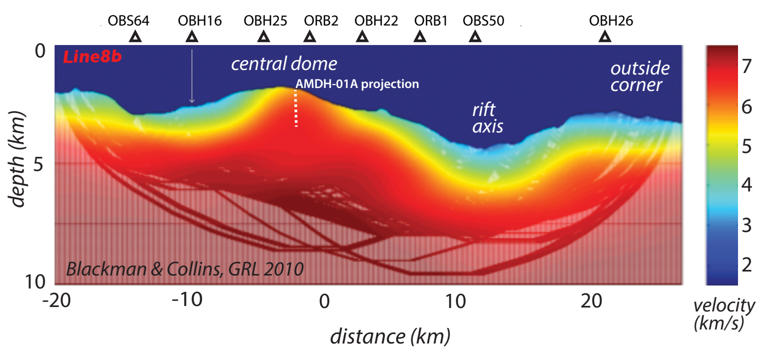
Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 150	detachment zone	~1.2 Ma rocks	3.5	few m of fault zone, metadiabase, metagabbro		n/a	upper 20 m cased. Age from Grimes et al (2008) applies to whole section
350 - 380	highly altered rock, likley reflector source		5.3	olivine-rich troctolite, trotolite, gabbro			reflectivity modeling by Collins et al., 2009 velocity control by waveform inversion, 304/305/340T checkshots, sonic log (Harding et al. 2016)
750 - 750	(paleo) fault		5	fault gouge, diabase			
1080 - 1200	portions highly altered, possible reflectors		5.8	oliveine-rich troctolite (serpentinized) interfingered gabbro			
4000 - 4000	green reflector Meg4		6.9	base gabbro?			Harding et al 2016

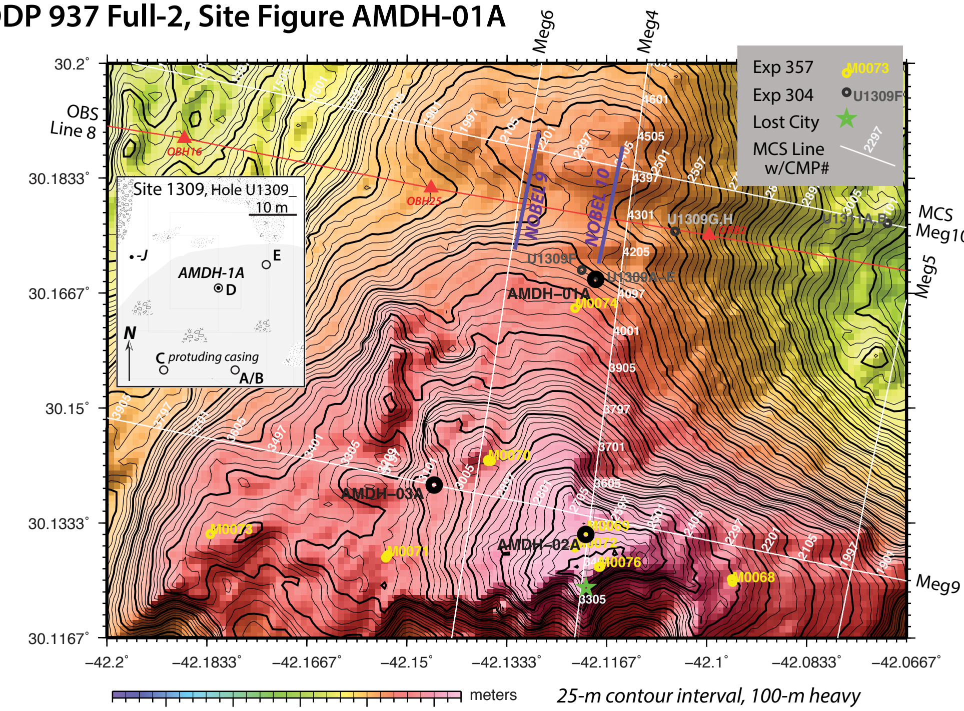
IODP 937 Full-2, Site Figure AMDH-01A

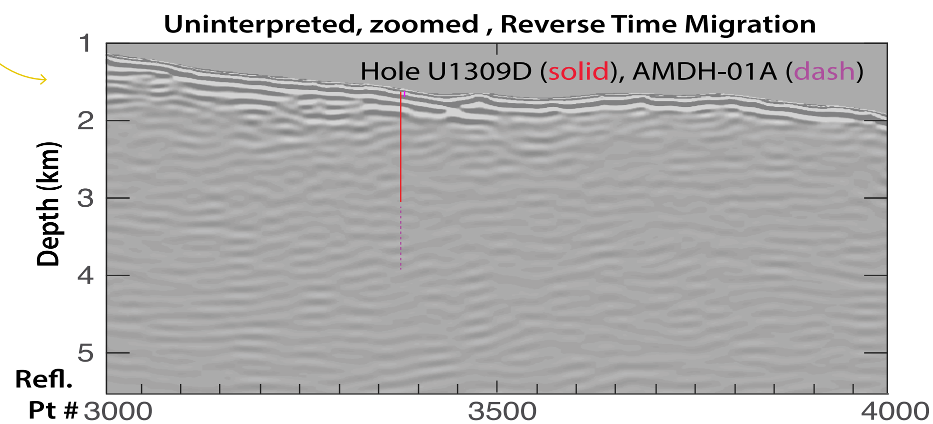












MCS: meg4_stack_2400_5280.segy (correct nav), meg4migrated.segy (needs nav), meg4.cdp_nav_bt_twtt
Refraction: obs64ch*n08.segy, obh16n8r.segy, obh25n8r.segy, orb2n08.segy, obh22n8r.segy, orb1n08.segy, obs50ch*n08cor.segy, obh26n8r.segy

IODP Site Forms

Form 1 – General Site Information

937 - Full 2

Section A: Proposal Information

Proposal Title	Accessing the Building Blocks of Life: Deepening Hole U1309D, Atlantis Massif, Mid-Atlantic Ridge
Date Form Submitted	2019-10-10 17:10:16
Site-Specific Objectives with Priority (Must include general objectives in proposal)	200mHole with re-entry. Complete section through detachment fault zone in serpentinized peridotite. Sample for deformation, alteration, igneous petrology, microbiology and organic/inorganic geochemistry. Log for temperature and other properties. Legacy Hole for sampling fluids and gases, establishing temperature profile, potential instrumentation
List Previous Drilling in Area	IODP Expedition 357, IODP Expedition 304/305

Section B: General Site Information

Site Name:	AMDH-02A	Area or Location:	Mid Atlantic Ridge, Atlantis Massif
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#	50m from MOO69A		
Latitude:	Deg: 30.1317	Jurisdiction:	common
Longitude:	Deg: -42.1202	Distance to Land: (km)	
Coordinate System:	WGS 84		
Priority of Site:	Primary: ✓ Alternate: ☐	Water Depth (m):	825

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	3	200
	Total Sediment Thickness (m) 3	
		Total Penetration (m): 203
General Lithologies:	loose foram sand	serpentite, talc-tremolite chlorite schist, metadiabase, metagabbro, breccia, fault rock

Coring Plan: (Specify or check)

Pilot Hole 50m; hard rock re-entry system with ~15m casing; 2-bit Hole to 200m

APC ☐ XCB ☐ RCB ☑ Re-entry ☑ PCS ☐

Wireline Logging Plan:

Standard Measurements		Special Tools		
WL	☑	Magnetic Susceptibility	☐	Other tools: MTT tool, ETBS tool, WSTP tool, potentially Kuster tool (exact choice of tools may be an operational choice)
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:
5.1	0.5	5.6

Observatory Plan:

Longterm Borehole Observation Plan/Re-entry Plan

Hard rock re-entry system. Potential for observatory

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	☐				

Preferred weather window: December to May (avoiding Atlantic hurricane season)

Sensitive marine habitat (e.g., reefs, vents): Lost City Hydrothermal Field is ~0.5 km away

Other: Pieces of RD2 drill string left in MOO69A may not be visible. Hardrock seabed with rubble and small sediment ponds

Proposal #: 937 - Full 2	Site #: AMDH-02A	Date Form Submitted: 2019-10-10 17:10:16

Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	no	
1b High resolution seismic seismic reflection (crossing)	no	
2a Deep penetration seismic reflection (primary)	yes	Line: Meg4 , Position: CMP# 3480 closest, 190 m to east; ~RP# 2726 in meg4_stack_2400_5280.segy
2b Deep penetration seismic reflection (crossing)	yes	Line: Meg9 Position: CMP 2750, 375 m north
3 Seismic Velocity	yes	Harding et al. 2016 & in prep- Meg4 & Meg9 waveform inversion (older version Henig et al. 2012 Meg4 & 9 downward continued to seafloor streamer tomography)
4 Seismic Grid	yes	Meg4, Meg5, Meg6, Meg9, Meg10- Canales et al., 2004 (Meg8 outside corner)
5a Refraction (surface)	yes	OBS refraction- Blackman and Collins 2010; Line 9a near site
5b Refraction (bottom)	no	
6 3.5 kHz	no	
7 Swath bathymetry	yes	CD100 EM12, MARVEL2000 SeaBeam2000, 100-m regional grid Blackman et al., 2008. EM120 20-50m grid Früh-Green et al., 2017.
8a Side looking sonar (surface)	no	
8b Side looking sonar (bottom)	yes	CD100 Tobi MARVEL2000 DSL120
9 Photography or video	yes	MARVEL 2000 Alvin and Argo images
10 Heat Flow	no	
11a Magnetics	yes	Pariso et al., 1996; MARVEL2000 deep-tow
11b Gravity	yes	Blackman et al., 2008
12 Sediment cores	no	
13 Rock sampling	yes	CD100 Dredge, MARVEL2000 Alvin; Exp357 Holes M0069A; M0072A,B; M0076A,B
14a Water current data	no	
14b Ice Conditions	no	
15 OBS microseismicity	no	1 yr study, Collins et al. 2012
16 Navigation	yes	MCS, OBS refraction, DSL120, Alvin rock sample & dredge locations
17 Other	no	

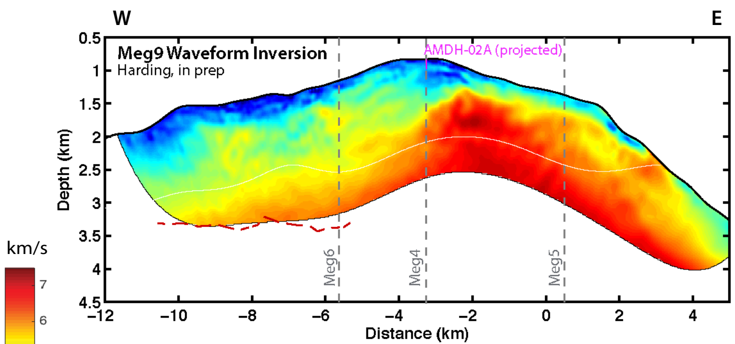
Proposal #: 937 - Full 2	Site #: AMDH-02A	Date Form Submitted: 2019-10-10 17:10:16

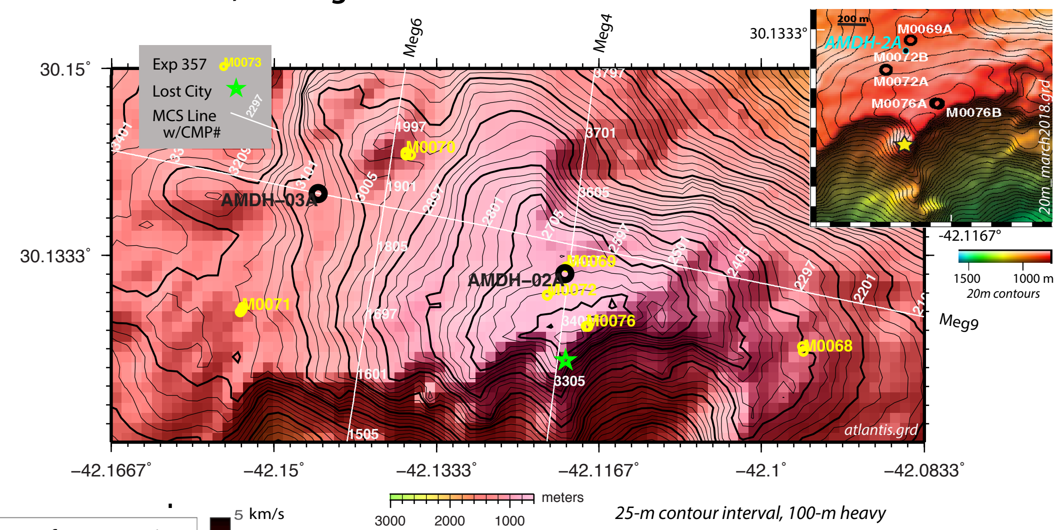
Pollution & Safety Hazard	Comment
1. Summary of operations at site	RCB pilot Hole 50m; Hard rock re-entry system with ~17 m casing; RCB to 100mbsf; temperature log at end of drilling and logging, temperature, and fluid sampling at end of expedition
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP 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?	standard
8. Natural or manmade hazards which may affect ship's operations	junk in Hole M0069A
9. Summary: What do you consider the major risks in drilling at this site?	serpentinite fault zone so drilling conditions may be difficult

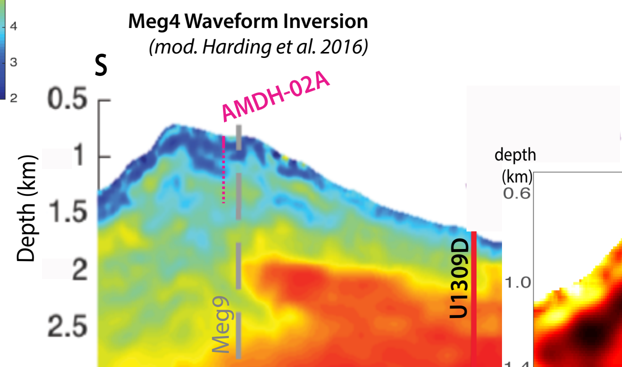
Proposal #: 937 - Full 2	Site #: AMDH-02A	Date Form Submitted: 2019-10-10 17:10:16

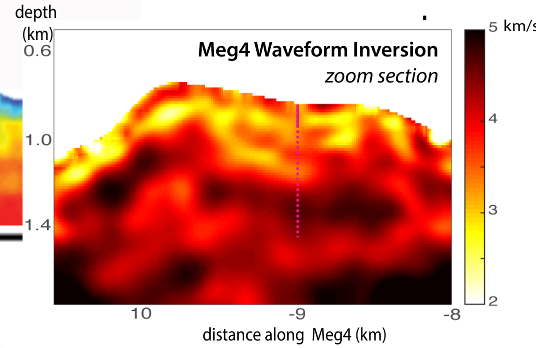
Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
0 - 6.5		0		loose carbonate sand in pockets. rubble possible			Based on M0069A, 50 m away, but sediment pockets very variable
6.5 - 12		1		metadiabase			based on M0069A. Good recovery in this section, but may not occur based on moderately dipping contact
12.5 - 13.2		1		sub-horizontal fault zone and breccia			based on M0069A. Similar fault zones likely throughout section
13.2 - 100				heterogeneous fault/shear zone dominated by serpentinite			13-16.5 mbsf section in M0069A was massive serpentinite with good recovery

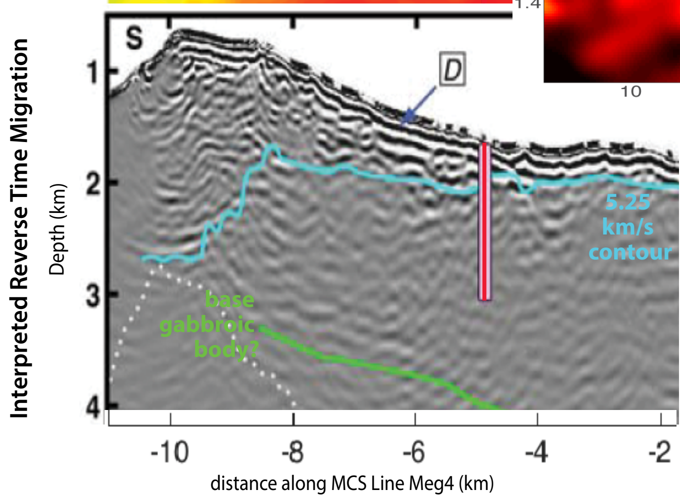
IODP 937 Full-2, Site Figure AMDH-02A

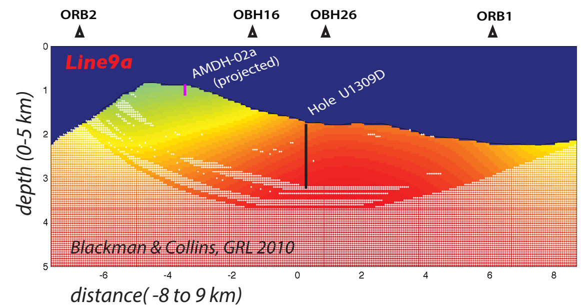


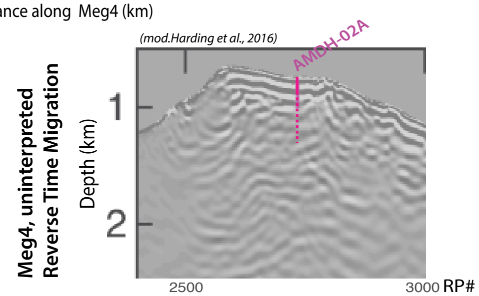


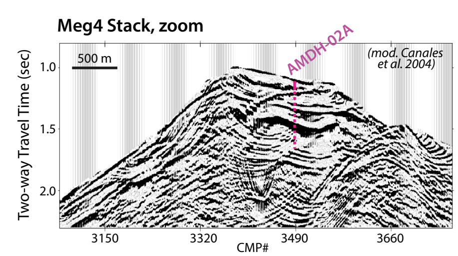


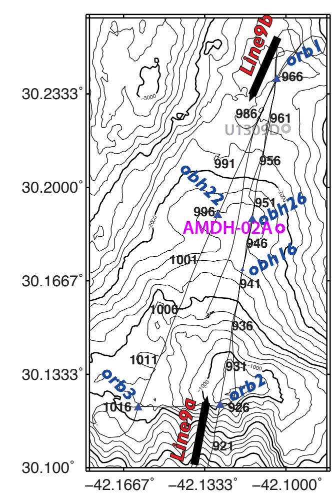












MCS: meg9migrated.segy, meg9stack.segy, meg9.cdp_nav_bat_twtt,meg4_stack_2400_5280.segy (correct nav), meg4migrated.segy (needs nav), meg4.cdp_nav_bt_twtt
Refraction: orb1n09.segy, obh16n9.segy, obh26n9.segy, orb2n09.segy

IODP Site Forms

Form 1 – General Site Information

937 - Full 2

Section A: Proposal Information

Proposal Title	Accessing the Building Blocks of Life: Deepening Hole U1309D, Atlantis Massif, Mid-Atlantic Ridge
Date Form Submitted	2019-10-10 17:10:16
Site-Specific Objectives with Priority (Must include general objectives in proposal)	Drill through detachment fault shear zone; igneous petrology, alteration, deformation fabrics, microbiology, organic geochemistry. potential for post-detachment volcanic rocks. Temperature profile, fluid sampling, potential to provide re-entry system for legacy
List Previous Drilling in Area	IODP Exp 357; IODP Exp 304/305

Section B: General Site Information

Site Name:	AMDH-03A	Area or Location:	Mid Atlantic Ridge, Atlantis Massif
If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#			
Latitude:	Deg: 30.1389	Jurisdiction:	common
Longitude:	Deg: -42.1455	Distance to Land: (km)	
Coordinate System:	WGS 84		
Priority of Site:	Primary: ☐ Alternate: ☑	Water Depth (m):	1275

Section C: Operational Information

	Sediments	Basement
Proposed Penetration (m):	5	200
	Total Sediment Thickness (m) 5	
		Total Penetration (m): 205
General Lithologies:	loose foram sand; carbonate cemented breccia	serpentite, talc-tremolite chlorite schist, metadiabase, metagabbro, breccia, fault rock

Coring Plan: (Specify or check)

single bit to destruction, but if AMDH-01A fails completely, deeper Hole with re-entry. Sediment thickness is likely maximum based on previous Holes (M0070; M0071, Site U1309)

APC ☐ XCB ☐ RCB ☑ Re-entry ☐ PCS ☐

Wireline Logging Plan:

Standard Measurements		Special Tools		
WL	☑	Magnetic Susceptibility	☐	Other tools: MTT, ETBS for temperature. Kuster and/or WSTP tool for fluid sampling (temperature probably too low to use new SMA tool)
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: 4 | Logging: 1 | Total On-site: 5

Observatory Plan:

Longterm Borehole Observation Plan/Re-entry Plan

depending on time, a re-entry system may be installed with potential for future instrumentation

Potential Hazards/ Weather:

						Preferred weather window
Shallow Gas	☐	Complicated Seabed Condition	☐	Hydrothermal Activity	☐	December to May (avoiding Atlantic hurricane season)
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 #: 937 - Full 2	Site #: AMDH-03A	Date Form Submitted: 2019-10-10 17:10:16

Data Type	In SSDB	Details of available data and data that are still to be collected
1a High resolution seismic reflection (primary)	no	
1b High resolution seismic seismic reflection (crossing)	no	
2a Deep penetration seismic reflection (primary)	yes	Line: Meg9 Position: ~CMP 3125
2b Deep penetration seismic reflection (crossing)	yes	Line: Meg6 Position: ~600m to east
3 Seismic Velocity	yes	Harding et al. 2016 & in prep- Meg9 waveform inversion (older version Henig et al. 2012 Meg9 downward continued to seafloor streamer tomography)
4 Seismic Grid	yes	Meg4, Meg5, Meg6, Meg9, Meg10- Canales et al., 2004 (Meg8 outside corner)
5a Refraction (surface)	yes	OBS refraction- Blackman and Collins 2010; Line 9b closest to site
5b Refraction (bottom)	no	
6 3.5 kHz	no	
7 Swath bathymetry	yes	CD100 EM12, MARVEL2000 SeaBeam2000, 100-m regional grid Blackman et al., 2008. EM120 20-50m grid Früh-Green et al., 2017.
8a Side looking sonar (surface)	no	
8b Side looking sonar (bottom)	yes	CD100 Tobi MARVEL2000 DSL120
9 Photography or video	yes	MARVEL 2000 Alvin and Argo images
10 Heat Flow	no	
11a Magnetics	yes	Pariso et al., 1996; MARVEL2000 deep-tow
11b Gravity	yes	Blackman et al 2008
12 Sediment cores	no	
13 Rock sampling	yes	CD100 Dredge, MARVEL2000 Alvin; Exp 357 cores, M0070A-c and M0071A to C most relevant
14a Water current data	no	
14b Ice Conditions	no	
15 OBS microseismicity	no	1 yr study, Collins et al. 2012
16 Navigation	yes	MCS, OBS refraction, DSL120, Alvin rock sample & dredge locations
17 Other	no	

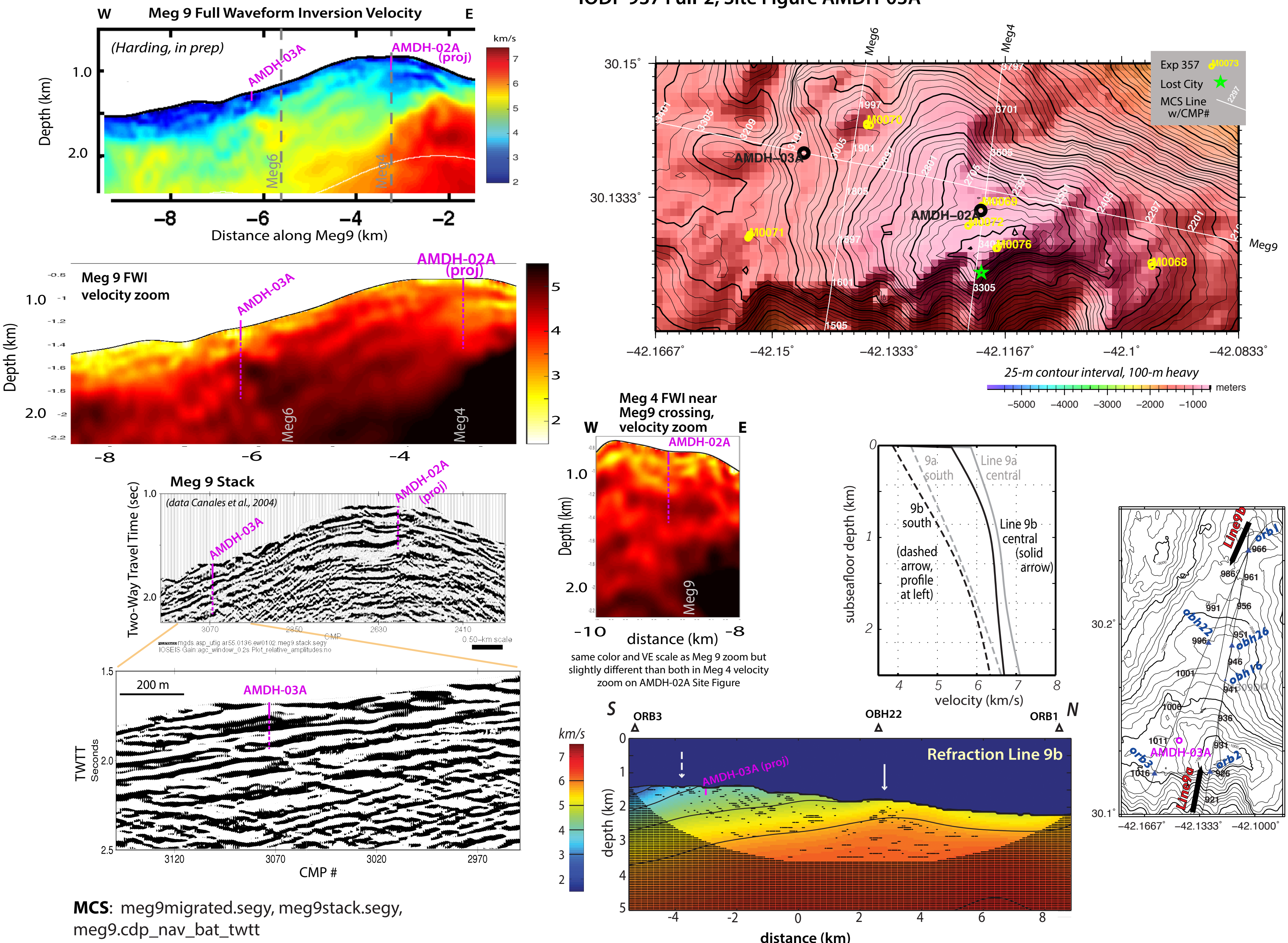
Proposal #: 937 - Full 2	Site #: AMDH-03A	Date Form Submitted: 2019-10-10 17:10:16

Pollution & Safety Hazard	Comment
1. Summary of operations at site	
2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling	
3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows	
4. Indications of gas hydrates at this location	
5. Are there reasons to expect hydrocarbon accumulations at this site?	
6. What "special" precautions will be taken during drilling?	
7. What abandonment procedures need to be followed?	
8. Natural or manmade hazards which may affect ship's operations	
9. Summary: What do you consider the major risks in drilling at this site?	

Proposal #: 937 - Full 2	Site #: AMDH-03A	Date Form Submitted: 2019-10-10 17:10:16

Subbottom depth (m)	Key reflectors, unconformities, faults, etc	Age (My)	Assumed velocity (km/s)	Lithology	Paleo-environment	Avg. accum. rate (m/My)	Comments
N/A							

IODP 937 Full-2, Site Figure AMDH-03A



MCS: meg9migrated.segy, meg9stack.segy, meg9.cdp_nav_bat_twtt
Refraction: orb3n09.segy, obh22n9.segy, orb1n09.segy
Velocity models (waveform inversion): Meg9velModel.txt