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International Ocean Discovery Program Expedition 360 Scientific Prospectus

Southwest Indian Ridge Lower Crust and Moho

The nature of the lower crust and Moho at slower spreading ridges (SloMo-Leg 1)

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Abstract

International Ocean Discovery Program (IODP) Expedition 360 will form the first leg of a multiphase drilling project that aims to drill through the crust/mantle boundary at the ultraslow-spreading Southwest Indian Ridge and investigate the nature of the Mohorovičić seismic discontinuity (Moho). Expedition 360 is expected to drill ~1300 m into lower crustal gabbro and is unlikely to penetrate the crust–mantle transition or recover a significant amount of peridotite. Drilling will be sited at Atlantis Bank, on an elevated wave-cut platform on the east flank of the Atlantis II Transform. Previous drilling and mapping shows that Atlantis Bank is a large oceanic core complex, exposing a tectonic window of deep crustal and lithospheric mantle exhumed on the footwall of an oceanic detachment fault. The shallowest part of Atlantis Bank, at 700 m water depth, consists of a ~25 km² wave-cut platform rimmed by a thin bioclastic limestone cap. The platform is part of a continuous gabbro massif ~40 km long by 30 km wide, overlying granular mantle peridotite that forms the lower slopes of the eastern wall of the Atlantis II Transform. Mapping shows that basement on the wave-cut platform consists largely of shallow-dipping amphibolitized gabbro mylonite generated by detachment faulting. This fault rooted near-continuously into partially crystalline gabbro for >4 million years. The mylonite exposed on the platform, and by cross-faulting and landslips on the sides of Atlantis Bank, both cut and are cut by steeply north dipping greenschist-facies diabase dikes. Thus, the gabbro crystallized at depth was uplifted into the zone of diking at the ridge axis, creating, in effect, the equivalent to the base of a dike–gabbro transition seen in many ophiolites.

Previous Ocean Drilling Program (ODP) operations at Atlantis Bank drilled the 1508 m deep Hole 735B and 150 m deep Hole 1105A, both recovering long sections of gabbro. During Expedition 360, we propose to drill to a nominal depth of 1.3 km at a site on the northern edge of the Atlantis Bank platform, ~1 km north-northeast of Hole 1105A and ~2 km northeast of Hole 735B. A future drilling expedition, SloMo-Leg 2, aims to deepen the hole to ~3 km, with the overall goal of penetrating the crust–mantle transition, which is believed to be ~2.5 km above the seismically determined Moho. Specific objectives of Expedition 360 include establishing the lateral continuity of the igneous, metamorphic, and structural stratigraphies previously drilled to the southwest, testing the nature of a magnetic polarity transition, and investigating the biogeochemistry of the lower crust.

Schedule for Expedition 360

Expedition 360 is based on Integrated Ocean Discovery Program (IODP) drilling Proposal 800-Full (available at www.iodp.org/active-proposals). Following ranking by the IODP Scientific Advisory Structure, the expedition was scheduled for the R/V *JOIDES Resolution*, operating under contract with the *JOIDES Resolution* Science Operator (JRSO). At the time of publication of this Scientific Prospectus, the expedition is scheduled to start in Colombo, Sri Lanka, on 30 November 2015 and to end in Port Louis, Mauritius, on 30 January 2016 (total days = 61). Accounting for 5 days of port call and 14 days of transit, a total of 42 days will be available for the drilling, coring, and downhole measurements described in this prospectus (for the current detailed schedule, see iodp.tamu.edu/scienceops/). Further details about the facilities aboard the *JOIDES Resolution* can be found at www.iodp.tamu.edu/publicinfo/drillship.html.

Introduction

The IODP Science Plan 2013–2023 sets a number of basic challenges for the next decade of planetary exploration. It recognizes that in order to understand the inherent connections between the Earth's interior and its surface environment we must address fundamental questions about basic plate tectonic processes. Central among these questions are how seafloor spreading and mantle melting lead to the creation of oceanic lithosphere at mid-ocean ridges, and what controls the architecture of the ocean crust thus formed (IODP Science Plan Challenge 9). Constraining the composition, diversity, and architecture of the lower ocean crust and shallow mantle is critical to understanding the global geochemical cycle, particularly the exchange of heat, mass, and volatiles between the Earth's interior, oceans, and atmosphere.

Crust formed at mid-ocean ridges extends across three-fifths of the Earth's surface, comprising ~60% by area and ~30% by volume of the Earth's crust. The ocean crust, as determined by seismic refraction studies, is typically ~6–7 km thick and apparently relatively uniform. The lower portion, corresponding to seismic Layer 3, is widely assumed to consist of gabbroic rocks formed in a magma chamber beneath the ridge axis. Layer 3 is separated from the mantle beneath by the Mohorovičić seismic discontinuity (Moho) and is conventionally regarded as the boundary between the igneous crust above and tectonized mantle peridotite beneath. Alternative interpretations are, however, possible: seawater penetration into peridotite causes partial alteration

to serpentinite and reduces its velocity to that comparable to gabbro; hence, the seismic structure of Layer 3 in itself gives us little information as to its lithology. The Moho could equally represent an alteration front boundary between altered and unaltered peridotites and need not coincide with the crust/mantle boundary at all. Instead, the Moho could lie well within Layer 3. If this is the case, we know less about the architecture and composition of the ocean lithosphere than we thought we did and very much less about global magmatic, volatile, and heat budgets.

Until the advent of ocean drilling, the stratigraphy of Layer 3, the lower crustal layer, was largely unknown and widely misinterpreted. Even to date, only two penetrations of the lower crust >200 m have been attempted, and these ended no deeper than ~1508 m. Our direct knowledge, therefore, remains remarkably limited. What we have learned from deep drilling in the Indian Ocean and the Atlantic (e.g., Dick et al., 2000; Blackman et al., 2011), when compared to the shallow (~100–200 m deep) sections drilled at the East Pacific Rise (EPR; Gillis, Mével, Allan, et al., 1993; Gillis et al., 2014), is that the mechanisms of formation of the gabbroic lower crust at slow- and fast-spreading ridges differ profoundly (e.g., Sinton and Detrick, 1992; Coogan, 2014). At slow and ultraslow ridges, which represent ~60% of the global ridge system, tectonic stretching is recognized to be an integral part of the seafloor spreading process (e.g., Tucholke and Lin, 1994; Tucholke et al., 1998; Escartín and Canales, 2011). A consequence of this discovery is that tectonic windows exposing lower crust on the seafloor are widespread at slow and ultraslow ridges. In practice, they are the only places at which the crust/mantle boundary is likely to be accessible by drilling with current technology.

Rationale for the SloMo project

The aim of SloMo (shorthand for “The nature of the lower crust and Moho at slower spreading ridges”) is simple: to drill as deeply as possible through Layer 3 in order to set the stage for the first ever penetration of the crust/mantle boundary (SloMo-Leg 2). Thus SloMo will test the hypothesis that the Moho, at least at slow and ultraslow ridges, represents an alteration boundary rather than the igneous crust–mantle transition. In doing so it will also be able to address key questions, including determining how magnetic reversal boundaries are expressed in the lower crust, assessing the role of the lower crust and shallow mantle in the global carbon cycle, and constraining the extent and nature of life at deep levels within the ocean lithosphere.

Deep drilling on Atlantis Bank will also provide an important step toward the long-term objective of drilling a total crustal penetration in fast-spreading ocean crust in the Pacific Ocean by providing critically needed experience in engineering a deep hole in lower crustal rocks.

SloMo is not simply about drilling the crust/mantle boundary but is as much about the journey on the way there. By recovering a near-complete section of the igneous lower crust and crust–mantle transition at Atlantis Bank, we will be able to address many of the important questions posed in the IODP Science Plan’s Challenge 9, developed further in **Scientific objectives**. At slow- and ultraslow-spreading ridges, the lower crust uniquely preserves that critical link where magmatic and tectonic processes directly reflect plate dynamics, melt input, and the pattern of mantle flow. We now understand that at such ridges a substantial portion of plate spreading is accommodated in the lower crust by tectonic extension due to faulting and, in places, ductile deformation. Large-offset “detachment” normal faults exert strong control on melt distribution and transport in the lower crust and delivery to the seafloor. This is in marked contrast to fast-spreading ridges, where it is accepted that the crust principally undergoes magmatic accretion by the injection of melt into the lower crust, dikeing, and eruption of magmas on the seafloor; thus, rollover and corner flow by ductile flow accompanying mantle upwelling and plate spreading is believed largely limited to the mantle. However, at slower spreading ridges, which are cooler and support only ephemeral magma chambers, the lower crust can potentially support a shear stress. As a consequence, with lower rates of magma supply, and colder, stronger lithosphere formed directly beneath the ridge axis, slower spreading ridges have very different morphologies and crustal architectures. Thus, as stated in Challenge 9, a full picture of crustal architecture and accretion can only be drawn if both fast- and slow-spreading environments are addressed.

Geological setting

The Southwest Indian Ridge (SWIR) lies at the slow end of the mid-ocean-ridge spreading-rate spectrum, with a full spreading rate of 14 mm/y. The ridge trends approximately southwest–northeast for most of its length, spreading almost due north–south. Between ~52°E and 60°E, it is offset by a series of closely spaced, long-offset transform faults. One of these, the Atlantis II Transform at 57°E, offsets the SWIR sinistrally by 200 km (Engel and Fisher, 1975) (Figure **F1**). Between this and the Novara Transform, ~140 km to the east, the spreading axis is divided into two segments, sep-

arated by a nontransform discontinuity at 57°35'E (Hosford et al., 2003). The spreading rate here is asymmetric: at the short westerly Segment AN-1, adjacent to the northern ridge/transform intersection of the Atlantis II Transform, magnetic anomalies reveal rates of 8.5 mm/y to the south and 5.5 mm/y to the north (Hosford et al., 2003); in consequence, the transform has been lengthening by 3 mm/y for at least the past 20 million years (Dick et al., 1991b; Hosford et al., 2003). At ~20 Ma, a 10° counterclockwise change in regional spreading direction put the Atlantis II Transform into transtension for a period of ~12 million years (Dick et al., 1991b, Hosford et al., 2003; Baines et al., 2007, 2008).

Immediately to the east of the Atlantis II Transform, parallel to it and on a flow-line directly south of spreading Segment AN-1, is an elevated transverse ridge (Figure F1) consisting of a series of uplifted blocks connected by saddles that rise to as little as 700 m below sea level (Engel and Fisher, 1975; Dick et al., 1991b). Atlantis Bank, at 32°43'S, 57°17'E, forms the shallowest and northernmost portion of this ridge, 95 km south of the axis of the SWIR. The bank consists of a raised dome ~40 km long by ~30 km wide, rising from 5700 m depth at the base of the transform wall to 700 m on a ~25 km² flat-topped platform at its crest and then drops to 4300 m on its eastern flank across two prominent transform-parallel east-dipping normal faults (Baines et al., 2003; Hosford et al., 2003) (Figures F1, F2).

Hole 735B is located at the southwest corner of the flat surface of the Atlantis Bank platform, at 731 m water depth (32°43.395'S; 57°15.959'E) (Figures F2, F3). During ODP Legs 118 and 176, the hole was drilled to a total 1508 m below seafloor (mbsf), with 87% core recovery, all in gabbro (*sensu lato*) ~11 Ma in age (Robinson, Von Herzen, et al., 1989; Dick et al., 2000). Further operations during Leg 179 drilled the 160 m deep Hole 1105A in the center of the platform (32°43.13'S; 57°16.65'E) (Pettigrew, Casey, Miller, et al., 1999), also in gabbro and with similar overall core recovery rates.

Site surveys of the Atlantis Bank area have included multibeam, magnetic, and gravity surveys and rock sampling using seabed rock coring, remotely operated vehicle (ROV), submersible dives, and dredging (Dick et al., 1991b; MacLeod et al., 1998; Arai et al., 2000; Kinoshita et al., 1999; Matsumoto et al., 2002). A high-resolution bathymetric map of the ~25 km² summit region compiled from narrow-beam echo soundings (Dick et al., 1999) shows the platform to consist of a broadly flat pavement ranging from ~750 to 689 m water depth). Proposed deep drill Site AtBk6 is located at the center of the platform, ~1 km north-northeast of Hole 1105A and 2 km northeast

of Hole 735B (Figure F3). ROV survey results show the central pavement to be bare rock, locally knobby igneous outcrop surrounded on its periphery by a pavement of limestone (in some places ripple marked) and carbonate-cemented pebble conglomerate.

Using the British Geological Survey's 5 m diamond rock drill and 1 m BRIDGE oriented corer, MacLeod et al. (1998) drilled 42 successful cores on the surface of this platform region, recovering 33 igneous rocks (Figure F3). They reveal continuous gabbro outcrop on the platform surface, including at proposed drill Site AtBk6 (Figure F4) but pass into serpentinized peridotite and pillow-basalt breccia at its southern tip, where the flat platform narrows into a north-south spine (32°44.5'S). The dredging and submersible studies, conducted over a broader ~700 km² area, showed that gabbro is present for >35 km parallel to the spreading direction (Figure F2B), suggesting that accretion of a continuous gabbroic layer persisted for at least 4 million years (Dick et al., 1991a; Matsumoto et al., 2002).

Many of the gabbroic rocks in the shallow drill cores and seen in *ROPOS* ROV footage from the surface of the Atlantis Bank platform are mylonitic, displaying intense crystal-plastic deformation with subhorizontal fabrics. In Hole 735B, amphibolite facies crystal-plastic deformation of oxide gabbro and olivine gabbro was likewise found to be strong in the uppermost 500 m but diminished markedly downhole (Robinson, Von Herzen, et al., 1989; Cannat et al., 1991; Dick et al., 1991a; Miranda and John, 2010). Considered together, it is apparent that the upper surface of Atlantis Bank represents a detachment fault zone, effectively a high-temperature "plutonic growth fault" active (for >4 million years) during the accretion of the gabbroic lower crust and responsible for its exhumation. This "hot" detachment must have rooted in or near a melt lens at the top of a continuously replenished magma chamber/mush zone, close to the midpoint of the AN-1 spreading ridge (Dick et al., 1991a, 2000; Natland and Dick, 2001, 2002).

Oceanic detachment faults are now known to be widespread along slow- and ultraslow-spreading ridges (e.g., Escartín et al., 2008; Sauter et al., 2013), often responsible for exhuming elevated oceanic core complex massifs that expose mantle peridotite and/or gabbro on the seafloor. Oceanic core complexes at the Mid-Atlantic Ridge (MAR) typically display prominent spreading-direction-parallel corrugations on their flat-topped or domal upper surfaces (Cann et al., 1997; Tucholke et al., 1998). Sampling of fault rock from the detachment fault zones themselves shows that deformation typically localized on weak, low-temperature secondary minerals such as talc,

derived primarily from alteration of peridotite (Dick et al., 2001, 2008; MacLeod et al., 2002; Escartín et al., 2003; Schroeder and John, 2004). Where gabbro is present in the detachment footwall it may be unaffected or barely affected by crystal-plastic deformation (e.g. 15°45'N on the MAR: MacLeod et al., 2002, and Escartín et al., 2003; Atlantis Massif: Ildelfonse et al., 2007), whereas elsewhere it is heavily deformed, as at Kane Megamullion on the MAR (Dick et al., 2008) and at Atlantis Bank.

Submersible observations at Atlantis Bank (Kinoshita et al., 1999; Matsumoto et al., 2002) show that the detachment fault surface is preserved over large regions in the deeper waters on both sides of the platform. The damage zone and underlying gabbro are well exposed by high-angle normal faulting on the eastern side of the complex and in headwalls of large landslips on the western flank. Here, lower temperature fault rocks are present in addition to the amphibolite facies mylonite. These chloritized and weathered fault gouge and talc-serpentine schists, preserved locally on the fault surface (Dick et al., 2001; Miranda and John, 2010), are closely comparable to fault rocks found on the MAR core complexes (e.g., MacLeod et al., 2002; Escartín et al., 2003, Schroeder and John, 2004; Dick et al., 2008).

The absence of the low-temperature fault rocks on the flat surface of the Atlantis Bank platform compared to its flanks suggests they have been removed, a deduction entirely consistent with the long-held belief (Dick et al., 1991b; Palmiotto et al., 2013) that Atlantis Bank was once an ocean island, and its flat top results from erosion, before later subsiding to its present level. Shallow drilling and dredging on the summit and uppermost flanks of the Atlantis Bank platform amply verified this. Indurated carbonates were drilled at 24 sites from the periphery of the Atlantis Bank platform and were also recovered in dredges from its flanks (MacLeod et al., 1998, 2000; Palmiotto et al., 2013). Although some (probably recent) carbonate sand was recovered, most of the sediment is indurated bioclastic limestone (skeletal packstone to wackestone; MacLeod et al., 2000) of Miocene to Pleistocene age (Palmiotto et al., 2013). This sediment contains an abundant macrofauna, primarily bryozoans, mollusks, algal nodules, and echinoids but also some solitary corals. Benthic and, in some instances, large planktonic foraminifers are common. Whereas Palmiotto et al. (2013) suggest a water depth of ~100–200 m based upon assemblages in dredged carbonates from the flanks of the platform, green algal (dasyclad) assemblages in drill cores from the platform summit (G. Della Porta and V.P. Wright, pers. comm., 1999) indicate water depths at wave base or shallower, demonstrating that the platform was at sea level, and probably above. How much material has been removed by subaerial erosion is not known, potentially 100–200 m with reference to the inferred thickness of the de-

tachment fault damage zone. On the basis of pitted gabbro outcrops to ~1500 m below sea level that may reflect preferential subaerial weathering of plagioclase, Palmiotto et al. (2013) speculate that the Atlantis Bank island could have been elevated to as much as 1 km above sea level. ROV observations of steep sides up to 10 m, locally even 50 m, at the flanks of the gabbro pavement on the summit of the platform may represent coastal cliffs and small sea stacks resulting from the dispersal of wave energy on the flanks of the island during erosion.

The Atlantis II Transform transverse ridge, on which Atlantis Bank lies, is clearly analogous to oceanic core complex massifs found on the MAR (e.g., Cann et al., 1997; Tucholke et al., 1998; Dick et al., 2008), although here, as elsewhere along the SWIR (Cannat et al., 2006; Sauter et al., 2013), the prominent spreading-direction-parallel corrugations that are characteristic of the flat surfaces of the Atlantic oceanic core complexes are not so obvious and potentially present only on the down-dropped terrace on the eastern side of Atlantis Bank (Figure F2A). The Atlantis II Transform transverse ridge has, furthermore, clearly been uplifted far above the surrounding seafloor. Whereas flexural uplift of detachment fault footwalls to form oceanic core complexes is typically 1 ± 0.5 km (Tucholke et al., 1998; Lavier et al., 1999), the Atlantis II Transform transverse ridge has been uplifted by 3 km relative to surrounding seafloor of similar age (Baines et al., 2003). Dick et al. (1991b) and Baines et al. (2003) propose that the original detachment-related uplift at the ridge/transform intersection was accentuated by an additional phase of flexural uplift, imparted upon the transform in response to the change of spreading direction on the SWIR at 19.5 Ma, and accommodated by the reactivation as normal faults of originally transform-related north-south structures.

One consequence of the relative uplift of the Atlantis II transverse ridge is that the crust/mantle boundary, as mapped by dredging and submersible traverses, is exposed along its western wall for a distance of nearly 40 km (Figure F2B). This boundary was traversed at two locations by *Shinkai 6500* Dives 466 and 458 at 4500 and 4650 m water depth, respectively. Dives 467 and 459 immediately above each of them found the detachment surface at 3000 and 1755 m, respectively, potentially indicating gabbro layer thicknesses as little as 1500 and 2895 m. Elsewhere along the western flank of Atlantis Bank, serpentinized peridotite was recovered in dredges from depths as shallow as 2000 m water depth (Dredge JR31-DR8), though in other nearby places only at >3000 m (Figure F2B). At the southern end of the platform itself, serpentinized harzburgite was drilled at 839 mbsf (Site JR31-BGS12). Peridotite sampled at several locations above the contact mapped on the transform wall consists largely of talc-

serpentine schist that likely overlies the gabbro massif. This and serpentine pebbles found in beach conglomerates overlying gabbro near the crest of the platform indicate that a discontinuous talc-serpentine sheet was associated with the detachment fault at shallow levels and is now locally preserved on the detachment surface. The serpentinite drilled at the southern end of the platform, however, is relatively massive harzburgite with well-preserved pseudomorphs of pyroxene. Possible origins of these include a peridotite screen in gabbro, similar to those drilled at Atlantis Massif in Hole U1309D, an enclave of less deformed and altered serpentinitized peridotite in the original detachment fault shear zone, or juxtaposition through a northward-dipping ridge-parallel normal fault that demarcates the southernmost end of the flat platform at 32°44.4'S (Figure F3).

A wide-angle seismic refraction survey of the Atlantis II Transform region found the Moho at 5 ± 1 km beneath Atlantis Bank (Muller et al., 1997, 2000; Minshull et al., 1998) (Figure F5). The direct geological constraints outlined above offer strong support to the inference that the seismic Moho cannot therefore represent the crust/mantle boundary in this region. Whereas Muller, Minshull, and colleagues also concluded that it was likely a serpentinitization front, they based this conclusion on the geochemical argument that the original igneous crustal thickness there was originally ~4 km (based upon rare-earth element inversions), and with the basaltic carapace removed by detachment faulting, the remainder was likely to be ~2–2.5 km thick. However, they admit this interpretation is nonunique, primarily because of the overlap in *P*-wave seismic velocity between gabbro and ~20%–40% partially serpentinitized peridotite (e.g., Miller and Christensen, 1997).

At what level is the crust/mantle boundary likely to lie beneath Atlantis Bank? Projecting the detachment surface to the locations of the traversed crust/mantle boundary described above indicates that the crustal thickness at these points prior to mass wasting on the transform wall was significantly <2000 m, whereas the depth to Moho below the transform wall remains ~5 km (Figure F5). Given that the elevated core complex massif is produced by flexure during uplift into the rift-mountains due to a spreading direction change (Baines et al., 2003), it seems reasonable to conclude that the mapped boundary is most likely to project approximately subhorizontally beneath the center of Atlantis Bank, consistent with the igneous crustal thickness of 2–2.5 km suggested by Minshull et al. (1998).

Scientific objectives

Expedition 360 represents the first leg of the SloMo Project, which seeks to use the tectonic window into the lower crust at Atlantis Bank to recover the full lower section of the ocean crust, core through the igneous crust–mantle transition, determine if Moho represents a serpentinization front and, ultimately, core through the Moho (~5.5 km at an ultraslow-spreading ocean ridge). SloMo has two phases. Phase I uses the *JOIDES Resolution* to drill to 3 km to test the hypothesis that the Moho represents a serpentinization front and to recover the full lower crustal section and crust–mantle transition zone. Phase II will utilize the riser D/V *Chikyu* to drill down ~5.5 km through the seismic Moho itself. In order to achieve the Phase I objective, two expeditions will be needed. Expedition 360 will need to properly establish the borehole for Leg 2 and thereafter drill as deep as possible. Given optimal conditions, a depth of at least 1300 mbsf, with continuous coring, should be achievable.

Operations during Expedition 360 should allow us to address the following:

1. What is the igneous stratigraphy of the lower ocean crust?

The drilling will determine if the igneous, metamorphic, and structural stratigraphy found for Holes 735B and 1105A is laterally continuous across the wave-cut platform on Atlantis Bank. In combination with Holes 735B and 1105A and the existing surface mapping, this will provide a four-dimensional view of the lateral continuity and evolution of the lower crust and the process of emplacement in space and time.

2. How much mantle is incorporated into the lower crust?

An unanticipated finding in the cores from Hole 1309D at the Atlantis Massif in the north Atlantic was the incorporation of significant volumes of hybridized mantle peridotite (Blackman, Ildefonse, John, Ohara, Miller, MacLeod, and Expedition. 304/305 Scientists; Blackman et al., 2011; Drouin et al., 2009) (Figure F6). Comparable screens of mantle rock were not found in either Holes 735B or 1105A. This could reflect differences in accretion due to different magma budgets, or it could simply be happenstance, whereby further drilling will encounter equivalent ultramafic horizons at Atlantis Bank.

3. What are the modes of melt transport into and through the lower crust?

Several different modes of melt transport were identified in the Hole 735B cores. These included small intrusive bodies of cumulates, larger intrusive units on the scale

of hundreds of meters, anastomosing channels produced by focused flow and melt-rock reaction, and compaction of late iron titanium–rich melts into shear zones where they hybridized olivine gabbro to iron titanium oxide–rich gabbro and gabbro-norite. The continuity and scale of these features cannot be determined from a single deep hole. Thus, drilling during Expedition 360 seeks to further document these features in a younger section of the massif.

4. How does the lower crust shape the composition of mid-ocean-ridge basalt (MORB)?

The complex stratigraphies seen in Holes 735B and U1309D (Figure F6) differ in significant ways. What common factors, however, influence the composition of MORB? Recent work on gabbroic sections from the EPR has shown that the lower crust acted as a reactive porous filter homogenizing diverse melts that were intruded into it and modifying their trace element contents prior to their eruption to the seafloor (Lissenberg et al., 2013). To what extent do such processes operate at slower spreading rates?

5. What is the strain distribution in the lower crust during asymmetric seafloor spreading?

Asymmetric spreading produced by detachment faulting is now recognized as one of three major accretionary modes at slow-spreading ridges (symmetric, asymmetric, and amagmatic rifting). Although each of these is important, little is known of how magmatism and tectonism interact, and hence how lower crustal accretion differs in these environments. At present, two deep holes in oceanic core complexes, Holes 735B and U1309D, allow us to determine strain distribution with depth. The distribution of strain documented in these two locations differs significantly, with far more intense crystal-plastic deformation being found in the upper 500 m of Hole 735B than in Hole U1309D. We cannot assess the nature, extent, and role played by high-temperature deformation during lower crustal accretion with isolated, one-dimensional sections. Offsetting and drilling to the north of Hole 735B will allow us to determine the continuity of the strain distribution from Hole 735B across the Atlantis Bank core complex and thereby assess the role and broader significance of synmagmatic deformation in this tectonic environment.

6. What is the nature of magnetic anomalies?

Magnetic anomaly “stripes” are detectable across the Atlantis II Transform transverse ridge, including the Atlantis Bank platform itself (Dick et al., 1991b; Allerton and Tivey, 2001; Hosford et al., 2003; Baines et al., 2007, 2008). Whereas most of the platform is reversely magnetized, as are the gabbro intervals of Holes 735B and 1105A (Ki-

kawa and Pariso, 1991), a narrow normally polarized zone ~2 km wide is present near its northern end. This is equated to Anomaly C5r.1n (11.476–11.531 Ma) (Allerton and Tivey, 2001; Baines et al., 2008) (Figure F7). It is detectable on surface (Dick et al., 1991b; Hosford et al., 2003) and deep-towed magnetic profiles (Allerton and Tivey, 2001) and in the JR31 seabed drill cores; however, the precise location of the boundary in each case is slightly offset (Figure F7). Because the sea-surface magnetization signal is derived from a much greater volume of rock than the near-bottom signal in the cores, Allerton and Tivey (2001) deduced from the sense of offset that the magnetic anomaly boundaries are inclined. They modeled the southern limit of the anomaly as a planar boundary dipping ~25° toward the south, suggesting that the surface represented either an isotherm corresponding to the Curie point or the edge of an intrusion (Figure F7). Alternatively, the form of the southern edge of the anomaly may have been modified by faulting: extensive brittle deformation and cataclasis is observed in shallow drill cores from the location of the southern reversal boundary, probably corresponding to a northward-dipping normal fault at the kink/narrowing of the platform summit at 32°41.8'S. If so, the reversal boundary is likely to dip more steeply than the 25° proposed by Allerton and Tivey (2001).

An important objective of Expedition 360 is to drill through normal polarity Chron C5r.1n to determine the nature of its boundaries and what controls magnetic anomalies in plutonic rocks.

7. Is there life in the lower crust and hydrated mantle?

A primary objective of the SloMo Project is to determine the microbiology of the lower crust, the potential serpentinized mantle above Moho, and the underlying mantle, to address IODP Science Plan Challenge 6 “What are the limits of life in the subseafloor?” For this purpose, Expedition 360 will assess the microbiology of the upper portion of the lower crust.

8. What is the role of the lower crust and shallow mantle in the global carbon cycle?

Serpentinization and weathering of ultramafic rocks as well as alteration of basalts are known, under the right conditions, to cause the formation of carbonates. Such carbonates are present in the form of extensive veining in serpentinized peridotites at the southern edge of the Atlantis Bank platform (shallow drill Site JR31-BGS-12 and contingency drill Site AtBk4).

The extent of these reactions in the lower crust is, to date, largely unknown. Although we do not expect that carbon sequestration will be a significant process in the lower ocean crust based on Holes 735B and U1309D, the possibility exists that Expedition 360 may penetrate the base of the lower ocean crust and thus offer the first opportunity to determine if carbon sequestration is significant below it.

Operations plan

Drilling and coring strategy

The *JOIDES Resolution* will move directly to proposed Site AtBk6, lower the subsea camera, and do a short survey to find a flat and solid-looking plutonic rock surface suitable for deployment of a reentry system. Prior site survey data indicates a flat bare-rock gabbro pavement at this precise location (proposed Site JR31-BR-8) (Figure F4). If the weather is suitable (<1 m heave), we will deploy a reentry system and complete the primary hole as described below. If the weather is initially unsuitable for deployment of a reentry system but acceptable for drilling, we will instead proceed to contingency proposed Site AtBk4 at the southern end of the platform, where prior seabed rock drilling during the JR31 site survey cruise cored serpentinite. There we would initiate a bare-rock spud in and drill a single-bit hole until weather improves or until bit destruction. In the event that the weather remains unsuitable for the deployment of the reentry system, we will proceed to the second contingency proposed Site AtBk2 immediately east of the Atlantis Bank wave-cut platform and drill a single-bit hole where the original, uneroded detachment surface was down-dropped by a 1000 m offset east-facing normal fault. This would recover the uppermost section of the core complex that is missing at proposed Site AtBk6 due to erosion. If unsuitable weather continues, we will proceed to the third contingency proposed Site AtBk5 and drill another single-bit hole until the weather improves.

At the primary proposed Site AtBk6, deployment of a reentry system will be initiated as soon as weather permits. Reentry system Plan A begins with drilling-in a reentry cone with a 15 m long conductor casing (13.375 inches) using a mud motor. Two such systems will be carried on board. The conductor casing will be cemented in place and the cement plug will be drilled out before coring begins. If Plan A fails, we will proceed with Plan B: drilling an 18.5 inch hole, lowering a 16 inch casing into the open hole (15 m), and then deploying a free-fall hammer funnel (hard rock reentry system [HRRS]-type) over the 16 inch casing. Following deployment of the reentry

system, we will core with the rotary core barrel (RCB) to 220 m, log the hole, open the hole to a 12.5 inch diameter, and install 200 m of 10.75 inch casing. We will then drill as deep as time allows, reserving ~2 days for logging prior to departure.

From 220 m downhole, our intention is to core continuously. However, the primary objective of SloMo Project Phase I is to drill to 3 km, requiring that we drill as deep a hole as possible on Expedition 360 to enable a second expedition (SloMo-Leg 2) to achieve this objective. A conservative estimate of what can be drilled with continuous coring during Leg 1 is 1300 m, which is short of what is needed on Leg 1 to achieve the objectives of Leg 2. Accordingly, once penetration to a few hundred meters below the magnetic transition is achieved, and if time is an issue to achieve the primary objective, we will consider alternating four-cone coring bit runs with tricone drilling bit runs to achieve greater depth, alternating coring and drilling without coring between bit runs. A rough estimate is that drilling without coring would be nearly twice as fast due to the heavier weight that can be placed on a more robust tricone drill bit and no wireline time to retrieve core. If the stratigraphy of the lower kilometer is similar to Hole 735B, this would not greatly affect the overall science objectives, as the lower half of Hole 735B exhibited far less variability than the upper portion. If and when the hole reaches 1400 m, we would resume continuous coring as we entered depths deeper than Hole 735B.

Logging/downhole measurements strategy

Wireline logging will form an essential component of the operations at Atlantis Bank during Expedition 360. Downhole measurements of the in situ physical properties of the formation will complement and extend those measured on cores, assist in characterizing the nature of incompletely recovered intervals, and thereby help in refining the igneous, metamorphic, and structural stratigraphies of the borehole(s). Borehole wall imaging will be of great importance in establishing the true geometry of features such as lithological contacts, veins, and fractures; furthermore, by matching distinctive features in cores with their representations on borehole wall images, core pieces may subsequently be reoriented to geographical coordinates. This can in turn allow spatially anisotropic properties of cores, such as magnetic remanence directions, igneous petrofabrics, fault kinematics, and so on, to be considered in the geographic reference frame and allow upscaling and integration of data from the drill site with regional-scale geological and geophysical information.

At the primary proposed Site AtBk6, we intend to conduct wireline logging operations in two phases. The first phase will be after coring the hole to 220 mbsf and before deploying 200 m of 10.75 inch casing. This first set of logs from ~30 to ~220 mbsf is projected to take <1 day.

The second phase of downhole logging will take place at the end of Expedition 360 and will cover the interval from 200 mbsf to the bottom of the hole, projected to be at ~1300 mbsf. This should take ~2 days.

At the beginning of each logging phase, the hole will be filled with freshwater; based on experience from previous expeditions this enhances the quality of Formation MicroScanner (FMS) electrical borehole wall imagery (Blackman, Ildfonse, John, Ohara, Miller, MacLeod, and Expedition. 304/305 Scientists, 2006).

In both phases of downhole logging, we anticipate making three separate logging runs with the following tool configurations, in order: (1) triple combination (triple combo), (2) FMS-sonic, and (3) Ultrasonic Borehole Imager (UBI). In the second logging phase, the Versatile Seismic Imager (VSI) will be added as a fourth run.

The triple combo tool string consists of six separate probes:

- The Accelerator Porosity Sonde (APS) uses an electronic neutron source to measure the porosity of the formation.
- The Hostile Environment Litho-Density Sonde (HLDS) measures bulk density. The tool employs a single-arm caliper to push the sonde against the borehole wall and, by so doing, giving a measurement of borehole size.
- The Hostile Environment Natural Gamma Ray Sonde (HNGS) measures the natural radioactivity of the formation, including indications of the concentrations of Th, U, and K.
- The High Resolution Laterolog Array Tool (HRLA) measures the electrical resistivity of the formation at two different invasion depths.
- The Phasor Dual-Induction Spherically-Focused Resistivity Tool (DIT).
- The Magnetic Susceptibility Sonde (MSS-B) measures borehole magnetic susceptibility at two different vertical resolutions and depths of investigation.

The FMS-sonic tool string combines the FMS, Dipole Sonic Imager (DSI), and General Purpose Inclination Tool (GPIT) tools. It also carries an HNGS sonde to allow direct correlation with the data from other logging runs. The FMS consists of four orthogo-

nal pads with 16 electrodes on each pad mounted on arms that are pressed against the borehole wall. Resistivity measurements from the electrodes are combined to generate high-resolution electrical images of strips of the borehole wall (a single pass images ~22% of the circumference of the hole). In practice FMS images are particularly useful for the identification of (the orientation of) planar features such as faults, fractures, veins, borehole breakouts, and lithologic variations in the borehole wall. The images can resolve millimeter-scale features if they have sufficient resistivity contrast. They are oriented to the geographical reference frame by means of the GPIT. If distinctive planar features in the core can be matched directly to their representations on the FMS imagery, the cores may be reoriented to geographical coordinates. The DSI records a full set of acoustic waveforms to measure the compressional and shear-wave velocity of the formation (V_p and V_s). V_p can be combined with the density log to generate synthetic seismograms and provide high-resolution seismic-borehole integration.

The UBI tool measures the amplitude and transit time of an acoustic wave propagated into the formation. It provides medium–high resolution acoustic images of the borehole wall, which are geographically oriented by means of a GPIT sonde. Although of lower resolution than the FMS images, UBI data have the advantage of providing 100% coverage of the borehole wall. UBI and FMS images are utilized in a similar manner.

The VSI is a well seismic geophone used in conjunction with an air gun source at the surface to help constrain the velocity structure of the vicinity of the borehole. Measurements are made with the tool held at different depths within the borehole, typically 50 m apart.

In addition to the above, it is possible that borehole fluid temperatures may be measured on one or more occasions by deploying the Sediment Temperature Tool (SET), holding the drill bit just above the bottom of the hole, and allowing temperatures to equilibrate. This may be considered near the end of the expedition to ascertain formation temperatures at the base of the hole. We may also consider deploying the core orientation tool ; although useless in hard rock/RCB coring operations for orienting the core itself, the information would give a direct measure of borehole deviation.

More information about the capabilities of the downhole logging tools is available at iodp.tamu.edu/tools/logging/index.html.

Risks and contingency

The biggest imponderable and probably greatest risk to the successful implementation of the drilling plan is the weather. Although at a latitude of 32°S, Atlantis Bank lies to the north of the edge of the Antarctic Circumpolar Current and Southern Ocean and can be affected by storms and poor sea states at any time of year. This has occasionally affected scientific operations during previous research cruises. As detailed in [Operations plan](#), we have identified several contingency sites where we could drill single-bit bare-rock spud-in rotary-cored holes until the weather improves. These operations should be possible in sea states greater than the ≤ 1 m heave conditions required to set the hard-rock drill-in reentry system at the primary proposed Site AtBk6. It should be noted that these contingency sites are not envisaged as alternate deep-penetration sites. In marginal conditions there is a risk that the HRRS will not be drilled in perfectly vertically, which may cause problems for the setting of the casing strings and, ultimately, successful deep penetration during Expedition 360 and future drilling expeditions. A complete backup drill-in reentry system will be carried, as well as a less sophisticated drilling/casing system (Plan B), as outlined in [Operations plan](#). It should be noted that once the reentry system and casing strings have been installed, coring operations should be much less vulnerable to adverse weather conditions.

Hole conditions and core recovery in Holes 735B and 1105A on Atlantis Bank have been exceptional (average 87% recovery over >1500 m in Hole 735B); accordingly, we do not anticipate the difficult hole conditions encountered at almost all other ODP/IODP ocean basement drill sites.

Overall, we have allowed 3.8 days for weather contingency. If this is not required during Expedition 360, we will simply drill deeper at the primary proposed Site AtBk6.

Site survey data

The supporting site survey data for Expedition 360 are archived at the [IODP Site Survey Data Bank](#).

Sampling and data sharing strategy

Shipboard and shore-based scientists participating in the Expedition 360 project should refer to the IODP Sample, Data, and Obligations Policy and Implementation Guidelines posted on the Web at www.iodp.org/program-documents/. This document outlines the policy for distributing IODP samples and data to research scientists, curators, and educators. The document also defines the obligations that sample and data recipients incur. The Sample Allocation Committee (SAC), composed of Co-Chief Scientists, EPM/Staff Scientist, and IODP Curator (on shore) and curatorial representative (on board ship) will work with the entire scientific party to formulate a formal expedition-specific sampling plan for shipboard and postcruise sampling.

Shipboard scientists are expected to submit research proposals and associated sample requests (web.iodp.tamu.edu/sdrm/) ~3–6 months before the beginning of the expedition (exact timeline to be announced by the EPM/Staff Scientist). Based on the shore-based and shipboard sample requests submitted by this deadline, the SAC will prepare a tentative expedition sampling plan, which will be subject to modification depending upon the actual material recovered and collaborations that may evolve between scientists during the expedition. Modification of the sampling strategy during the expedition must be approved by the SAC.

The archive section half will not be sampled, except for a limited number of whole rounds if these are required to meet primary project objectives. Shipboard samples will be taken from the working section half, sparing the equivalent of one half of the section half (a quarter round) in all intervals if possible. All sample frequencies and sizes must be justified on a scientific basis and approval will depend to some degree on core recovery, the full spectrum of other requests, and the cruise objectives. Some redundancy of measurement is unavoidable or even desirable, but minimizing the duplication of measurements among the shipboard party and identified shore-based collaborators will be a factor in evaluating sample requests.

If critical intervals with particularly high sampling demand are recovered, special decisions may be required, including reduced sample size, collaborations and sharing of samples and/or measurements results. A sampling plan coordinated by the SAC is typically required before critical intervals are sampled. The actual sampling of critical intervals may be postponed and carried out in the shore repository after the cruise.

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Table T1. Operations plan for proposed sites, Expedition 360.

**Exp-360 Indian Ridge Lower Crust and Moho (Pro800)
Operations Plan Summary**

S. Midgley, 16 October 2014

Site No.	Location (Latitude Longitude)	Seafloor Depth (mbrf)	Operations Description	Transit (days)	Drilling Coring (days)	WL Log (days) ²
Colombo, Sri Lanka			Begin Expedition	5.0	Port Call Days	
Transit 2710 nmi from Colombo to Site AtBk-1a @ 10.5 knots				10.8		
AtBk-6	32° 42.3402' S	706	Hole A: Drill in reentry cone with ~15 m of 13 3/8" 54.5 lb/ft conductor casing and cement reentry system in place.		2.6	
EPSP	57° 16.6910' E		Drill out cement and RCB core to ~220 mbsf		5.6	
approved to			Wireline log pilot hole with Triple Combo w/ UBI, FMS-Sonic and MSS Tool Strings from 30 mbsf to ~220 mbsf.			0.8
TBD			Open hole to 14" diameter and run 10 3/4" casing string to ~200 mbsf and cement casing.		3.6	
			RCB core from ~220 mbsf to ~1300 mbsf		23.6	
			Wireline log pilot hole with Triple Combo w/ UBI, FMS-Sonic, MSS & VSI Tool Strings from 200 mbsf to ~1300 mbsf.			2.0
			Weather Contingency		4.0	
Sub-Total Days On-Site: 42.2						
Transit 762 nmi from AtBk-1a to Port Louis @ 10.5 knots				3.0		
Port Louis, Mauritius			End Expedition	13.8	39.4	2.8
Port Call:		5.0	Total Operating Days:		56.0	
Sub-Total On-Site:		42.2	Total Expedition:		61.0	

RCB = rotary core barrel, UBI = Ultrasonic Borehole Imager, FMS = Formation MicroScanner, MSS = magnetic susceptibility sonde, VSI = Versatile Sonic Imager.

Figure F1. 3-D perspective view of the Atlantis II Transform, looking north-northeast. Data compiled from multibeam data collected during *Conrad* Cruise C2709, *James Clark Ross* Cruise JR31, and *Yokosuka* and *Kairei* site survey cruises, combined with satellite gravity seafloor data and the Global Multi Resolution Bathymetry database.

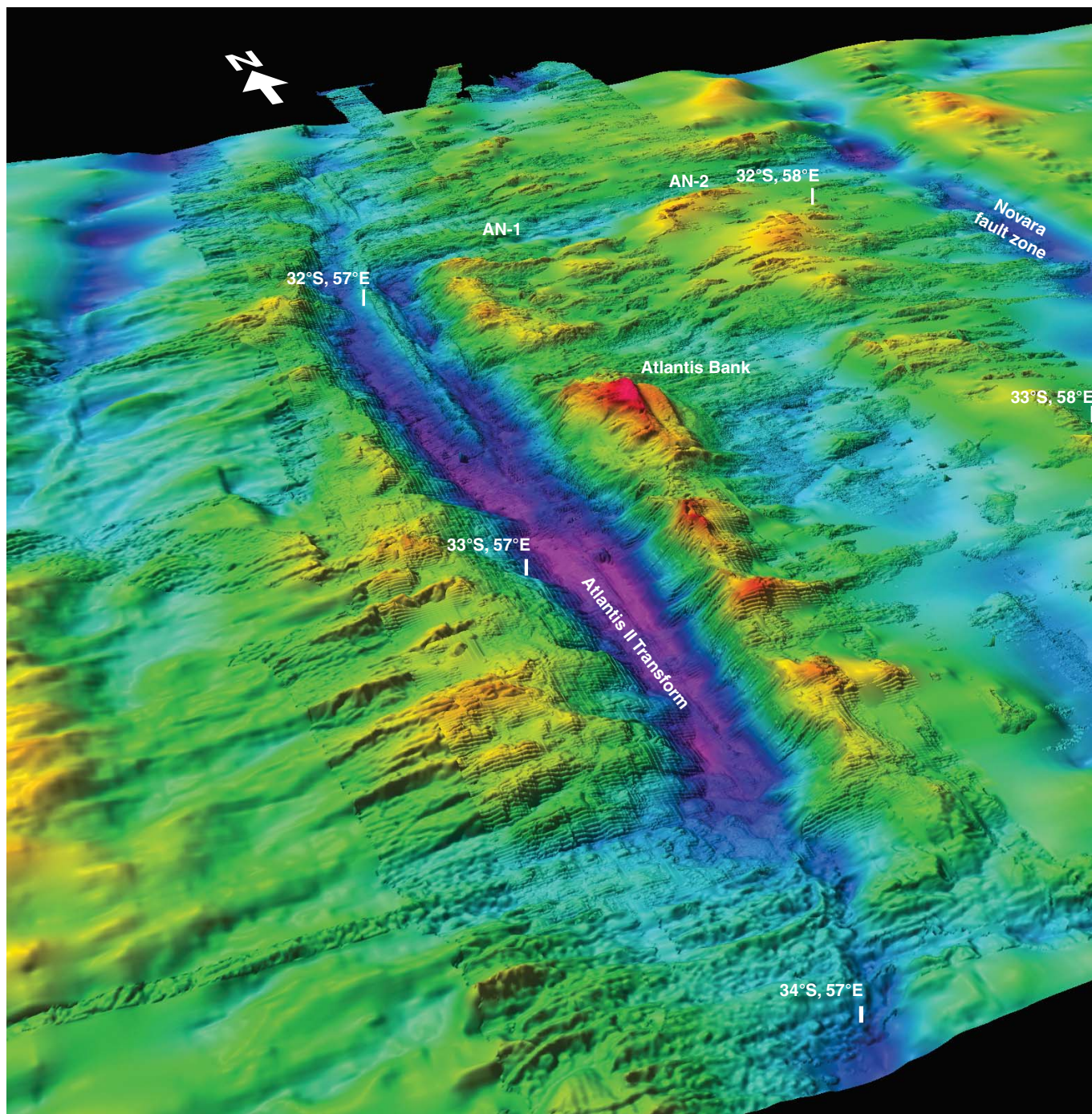


Figure F2. A. Bathymetry of the Atlantis Bank area, with past and proposed drill sites marked. B. Summary of geological mapping of the Atlantis Bank area, with geological interpretation.

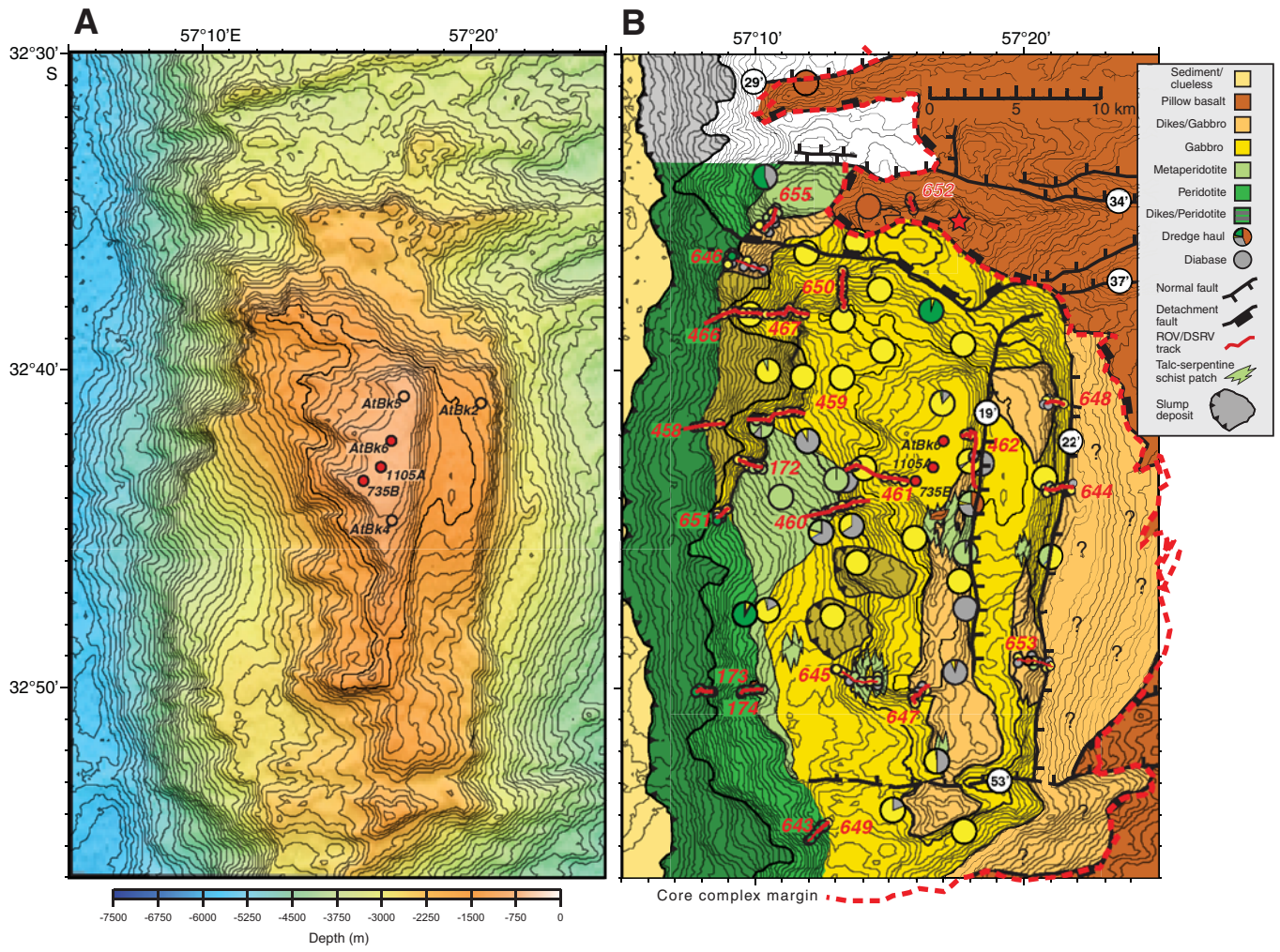


Figure F3. High-resolution contoured narrow-beam bathymetry map of Atlantis Bank wave-cut platform, showing remotely operated vehicle (ROV) and submersible dive tracks plus locations of shallow and deep drill cores. Primary proposed drill site is AtBk6; contingency Sites AtBk4 and AtBk5 are also marked.

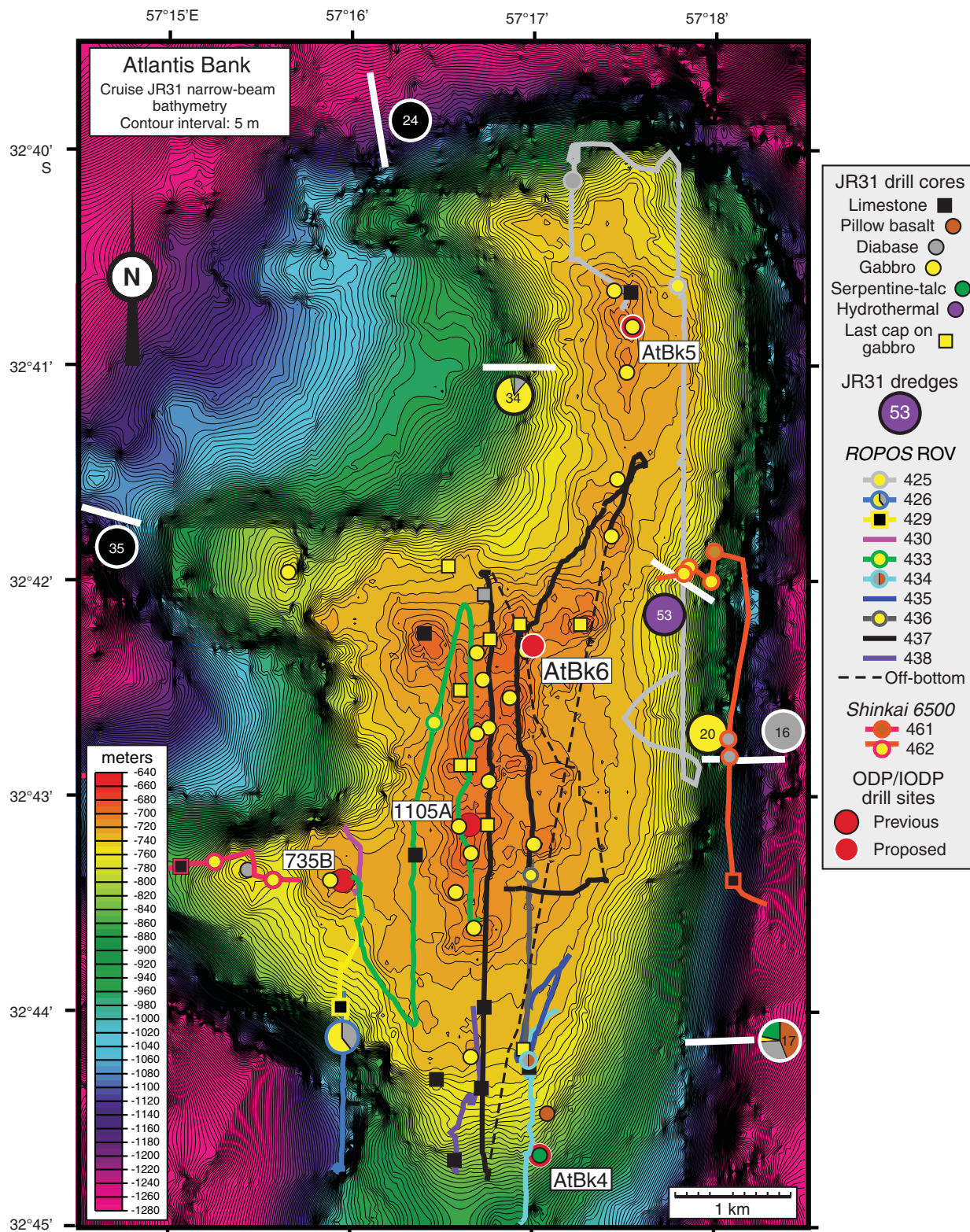


Figure F4. Bottom photo of primary deep drill proposed Site AtBk6, showing flat bare-rock pavement (with echinoid) and thin carbonate in distance. The leg of the BRIDGE seabed rock drill is in the foreground; drilling here (Site JR31-BR-8) yielded olivine gabbro with mylonitic shear bands. Field of view is ~4–5 m.

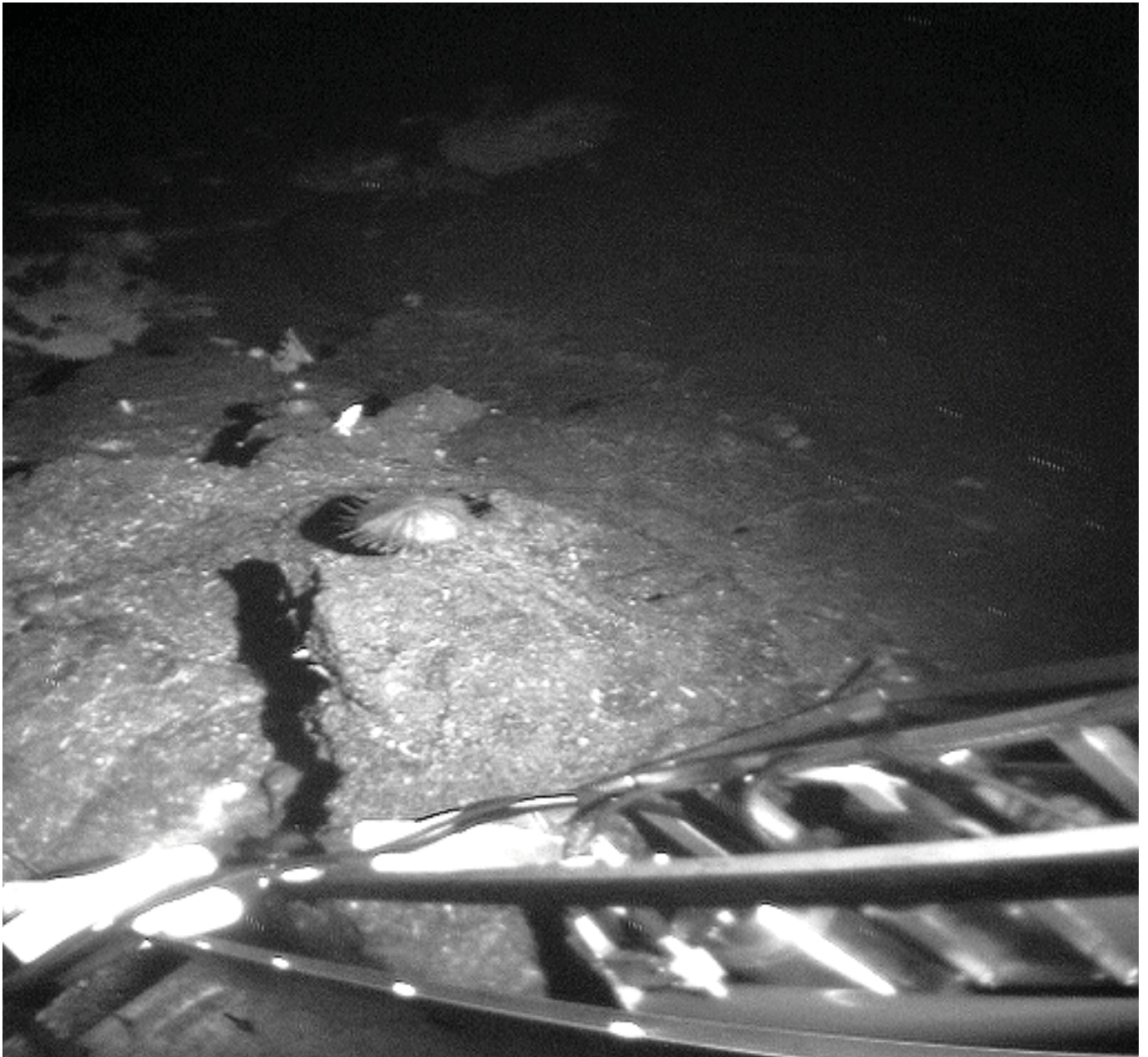


Figure F5. Velocity models for north–south seismic Line CAM101 over Atlantis Bank, together with principal proposed drill sites, modified after Muller et al. (2000). Green line = target depth of proposed Site AtBk6 drilled during Expedition 360, orange line = projected penetration during SloMo-Leg 2, red line = projected penetration during SloMo-Leg 2 (riser drilling). Velocity contours are 0.4 km/s. Upper panel shows an undifferentiated Layer 3; lower panel shows a lower serpentinized mantle Layer 3 and an upper gabbroic Layer 3. The models fit the data equally well. Triangles mark ocean-bottom hydrophones. Proposed Site AtBk6 lies on the line, and Hole 735B is projected from a kilometer to the west. Moho gaps are due to ocean bottom seismometer placement and are not real.

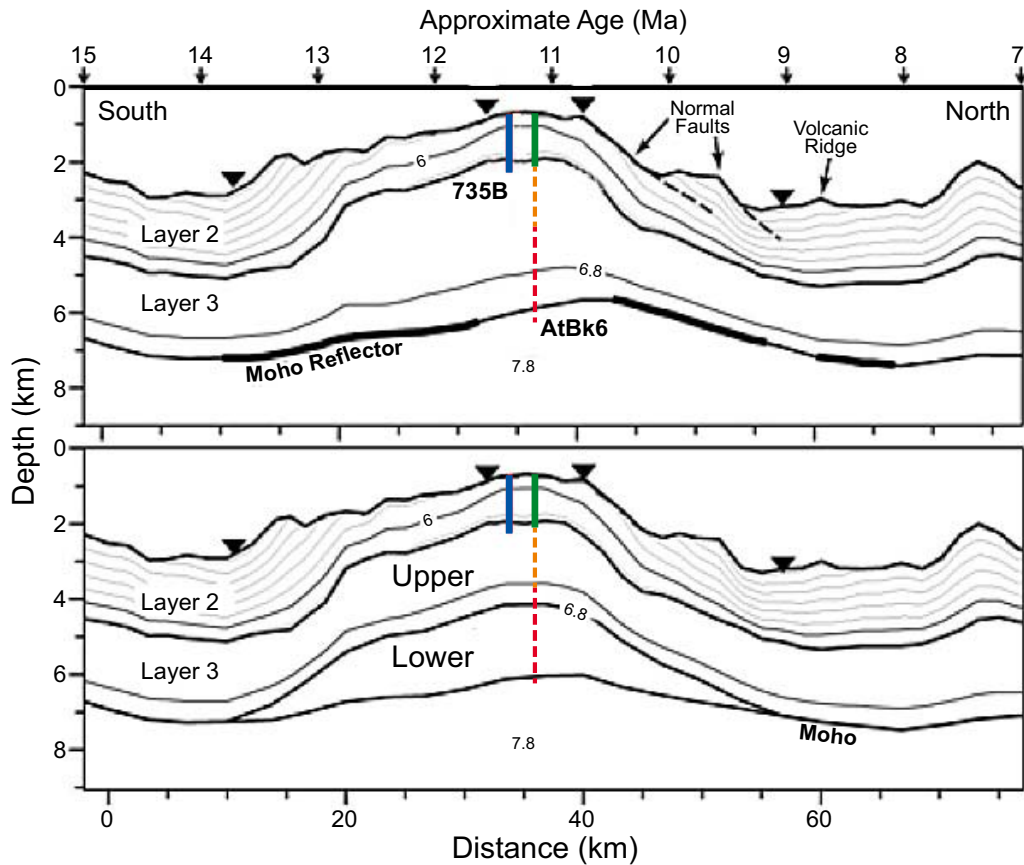


Figure F6. Lithostratigraphy of ODP Hole 735B and comparison with IODP Hole U1309D from the Mid-Atlantic Ridge at 30°N, modified from Dick et al. (2000) and Blackman et al. (2006, 2011). Lithologies are running 20 m downhole averages of the rock proportions, with those for Hole 735B normalized to 100% recovery, whereas those for Hole U1309D are shown as a proportion of the intervals drilled. Different symbols for the points in the whole rock Mg# diagram are for different lithologies based on modal mineralogy and can be found in the ODP Legs 118 and 176 *Initial Reports* volumes and IODP Expedition 304/305 reports (Robinson, Von Herzen, et al., 1989; Dick, Natland, Miller, et al., 1999; Blackman, Ildefonse, John, Ohara, Miller, MacLeod, and Expedition. 304/305 Scientists, 2006). These sections represent the descriptions of two different scientific parties, and whereas both followed AGI conventions on nomenclature, the exact definitions for each lithology described may vary. The red line at Mg# 80 is to emphasize the overall chemical differences in the sections. Primary melts emerging from the mantle would be in equilibrium with gabbroic cumulates and dunites with an Mg# ≥ 90 , which are largely missing in both sections.

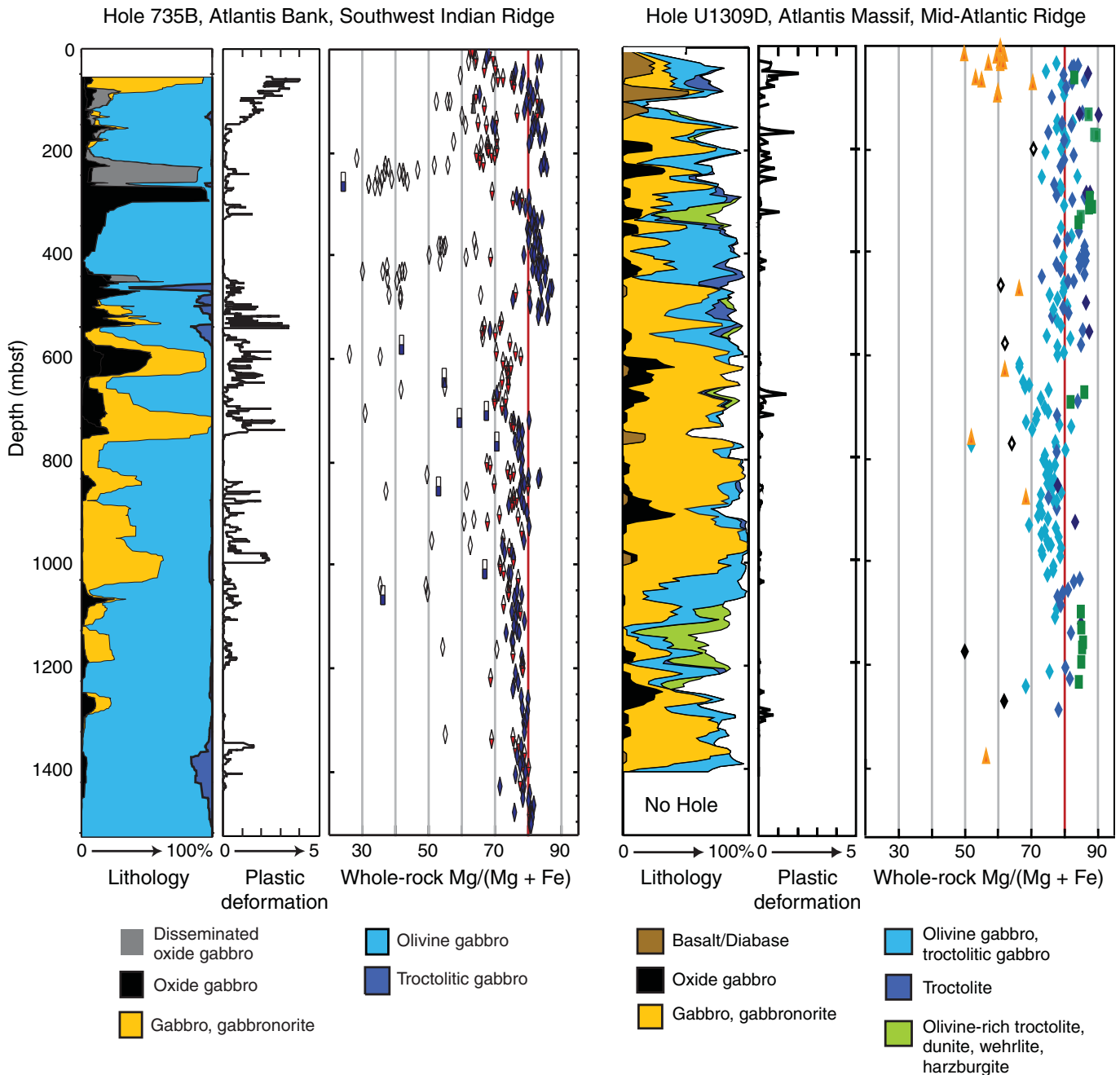
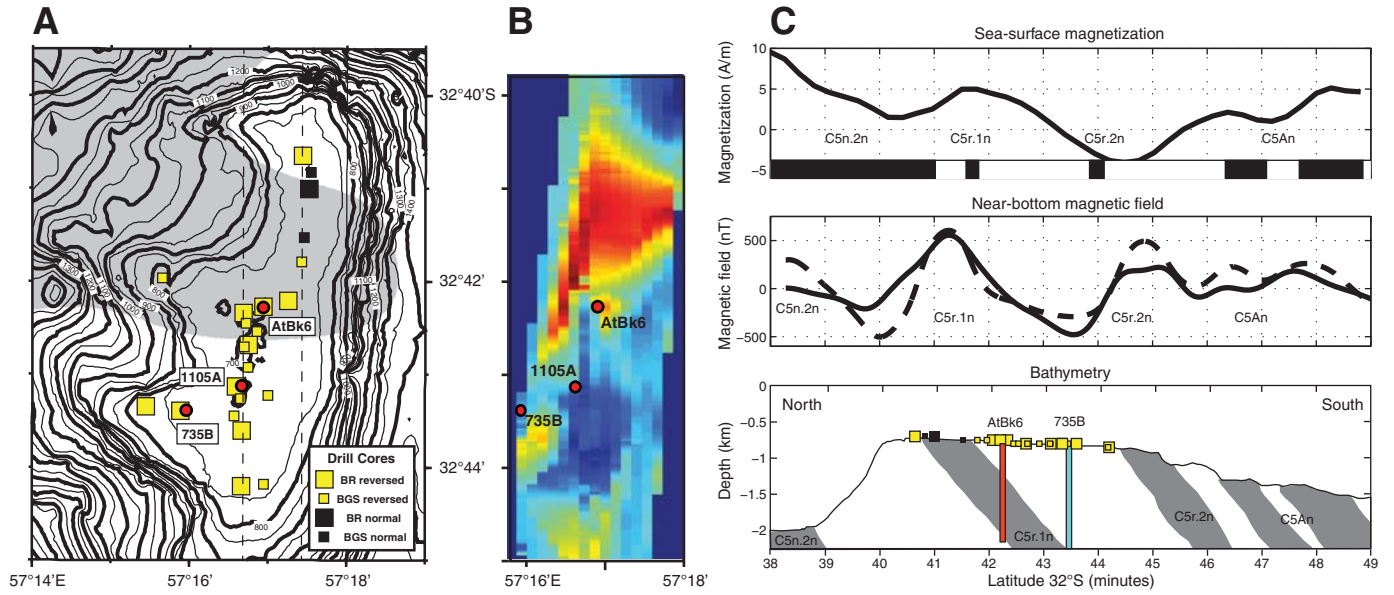


Figure F7. A. Location and magnetization of Atlantis Bank platform drill cores. B. Contoured deep-towed magnetization. C. Magnetic anomaly models with positions of Hole 735B and proposed Site AtBk6.



Site summaries

Site AtBk6

Priority:	1
Position:	32°42.3402'S; 57°16.6910'E North-central part of Atlantis Bank wave-cut platform
Water depth (m):	695
Target drilling depth (mbsf):	As deep as possible (>3 km)
Approved maximum penetration (mbsf):	To be agreed; but >3 km
Survey coverage (track map, seismic profile):	Seabed drill core Site JR31-BR-8
Objective(s):	Drill deep section through gabbro to crust–mantle transition
Drilling program:	Re-entry system: Plan A: 15-m long 13.375-inch drill-in casing Plan B conventional 15-m long 16-inch casing. RCB core to 220 mbsf; set 200-m long 10.75 inch casing (after logging). RCB core as deep as time permits. Log.
Logging/downhole measurements program:	Three runs with triple combo, FMS-sonic, and UBI before setting 200 m long 10.75 inch casing; same three runs plus VSI from 200 mbsf to maximum depth achieved.
Nature of rock anticipated:	Gabbro, possible rare diabase; ultimately serpentized and thence fresh peridotite

Site AtBk4

Priority:	2 (weather contingency)
Position:	32°44.6643'S; 57°17.0384'E Southern end of Atlantis Bank wave-cut platform
Water depth (m):	839
Target drilling depth (mbsf):	~150 (single bit)
Approved maximum penetration (mbsf):	To be agreed
Survey coverage (track map; seismic profile):	Seabed drill core Site JR31-BGS-12
Objective(s):	Drill short section of serpentized peridotite
Drilling program:	Single-bit bare-rock spud-in
Logging/downhole measurements program:	None
Nature of rock anticipated:	Serpentized peridotite

Site summaries (continued)

Site AtBk5

Priority:	2 (weather contingency)
Position:	32°40.8244'S; 57°17.5431'E Northernmost part of Atlantis Bank wave-cut platform
Water depth (m):	709
Target drilling depth (mbsf):	~150 (single bit)
Approved maximum penetration (mbsf):	To be agreed
Survey coverage (track map; seismic profile):	Seabed drill core Site JR31-BGS-20
Objective(s):	Drill short section of gabbro
Drilling program:	Single-bit bare-rock spud-in
Logging/downhole measurements program:	None
Nature of rock anticipated:	Gabbro

Site AtBk2

Priority:	2 (weather contingency)
Position:	32°41.00'S; 57°20.35'E
Water depth (m):	1700
Target drilling depth (mbsf):	~150 (single bit)
Approved maximum penetration (mbsf):	To be agreed
Survey coverage (track map; seismic profile):	
Objective(s):	Core the dike–gabbro transition
Drilling program:	Single-bit bare-rock spud-in
Logging/downhole measurements program:	None
Nature of rock anticipated:	Gabbro, diabase

Expedition scientists and scientific participants

The current list of participants for Expedition 360 can be found at iodp.tamu.edu/science-ops/precruise/indianridge/participants.html.