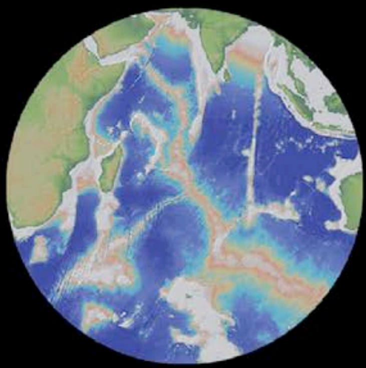

Indian Ocean Crust & Mantle Drilling

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

WORKSHOP FOR SCIENTIFIC DRILLING IN THE INDIAN OCEAN CRUST & MANTLE

May 13th to 16th, 2015 Woods Hole MA, USA

US - China International Discovery Program Workshop

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Plate 1. Forty-two of the 60 participants at the Workshop clambake.

The conveners and the organizing committee would like to acknowledge the following individuals who contributed to writing this report: Pablo Canales, Henry Dick, Robert Dunn, Virginia Edgcomb, Alastair Harding, Raleigh Hood, Benoit Ildefonse, Chris MacLeod, Mladin Nedimovic Maurice Tivey, James Natland, Huaiyang Zhou.

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Executive Summary

The Workshop for Scientific Drilling in the Indian Ocean Crust and Mantle was held May 13-16, 2015 at the Woods Hole Oceanographic Institution, bringing together 60 scientists from Australia, Canada, China, France, Germany, Great Britain, Italy, Japan, the Netherlands, Poland, Portugal and the United States. The meeting was co-sponsored by IODP China and the United States Scientific Support Program. Forty-four half hour talks were given, with an extensive overview of the tectonics, geophysics, geochemistry, and biogeochemistry of the principal regional interest, the SW Indian Ridge (SWIR). Two new and one scheduled drilling proposal were presented and reviewed. Twelve 30-minute discussion sessions provided time for audience input, resulting in specific workshop recommendations as outlined below.

The SW Indian Ridge (~14) mm/yr is the best-studied ultra slow end-member for seafloor spreading. In addition to the unique tectonics of ultra slow spreading, the crust ranges from near zero to some of the thickest ocean crust measured far from a mantle hotspot. Thus, it is a unique laboratory for the study of lithospheric accretion. Unlike faster spreading ridges, the mantle is directly exposed over approximately a quarter of the seafloor formed along it. Mantle peridotite is a highly reactive substrate for water - rock interaction compared to the basaltic crust at faster spreading ridges. This may have significant implications for the global carbon budget. The workshop was particularly timely as it coincided with planning for the 2016 to 2020 2nd International Indian Ocean Expedition.

The meeting reviewed plans for the first leg of the SloMo Project (Slow Spreading Ridge Moho). This allowed an exchange between the expedition science party and the community on operation plans and objectives for drilling there, and for forming collaborations between ship and shore-based scientists. A review of existing Atlantis Bank surveys identified needed site survey data, including new surveys based on recent state-of-the-art seismic experiments to characterize the internal structure of the crust, as well as constrain the nature and variability of Moho. Near-bottom high-resolution bathymetric surveys are also needed to constrain the tectonic evolution of the Atlantis Bank Core Complex are needed.

Presentations of seismic, bathymetric, submersible, biologic, and geochemical data were made for the Dragon Flag hydrothermal area (49°40'E) and the Dragon Bone Amagmatic Segment (53°E). The former represents the early stages of seafloor massive sulphide (SMS) formation, where shallow drill holes can establish the basic pattern of hydrothermal circulation during SMS formation, which is obscured by long episodic cycles of hydrothermal circulation at older deposits such as TAG. Local exposure of mantle peridotite at Dragon Flag adjacent to the thick crust of the volcanic segment to the east and the non-transform discontinuity to the west is an opportunity to explore the nature of the transition from basaltic to ultramafic outcrops along axis. Drilling mantle peridotite at the Dragon Bone Segment would compare mantle from two adjacent extreme melting environments. It was agreed, though, that additional survey data; particularly near-seafloor bathymetric mapping, is needed for both sites prior to a preliminary drilling proposal.

A proposal was presented for drilling 'smooth seafloor' at 64°30'E on the SW Indian Ridge, which represents the magma-starved end-member of ultra-slow spreading ridges. This region lacks the characteristic roughness of most slow spread ocean crust, and crustal rock is virtually absent over large regions with the mantle directly exposed to the seafloor. Moreover, this represents another extreme mantle environment whose geochemistry should contrast sharply to the Dragon Flag and Dragon Bone areas. Based on the existing magnetic, seismic, geologic and bathymetric surveys, the consensus was that this was an important objective for lithosphere drilling, and that it is ready for a pre-proposal to IODP.

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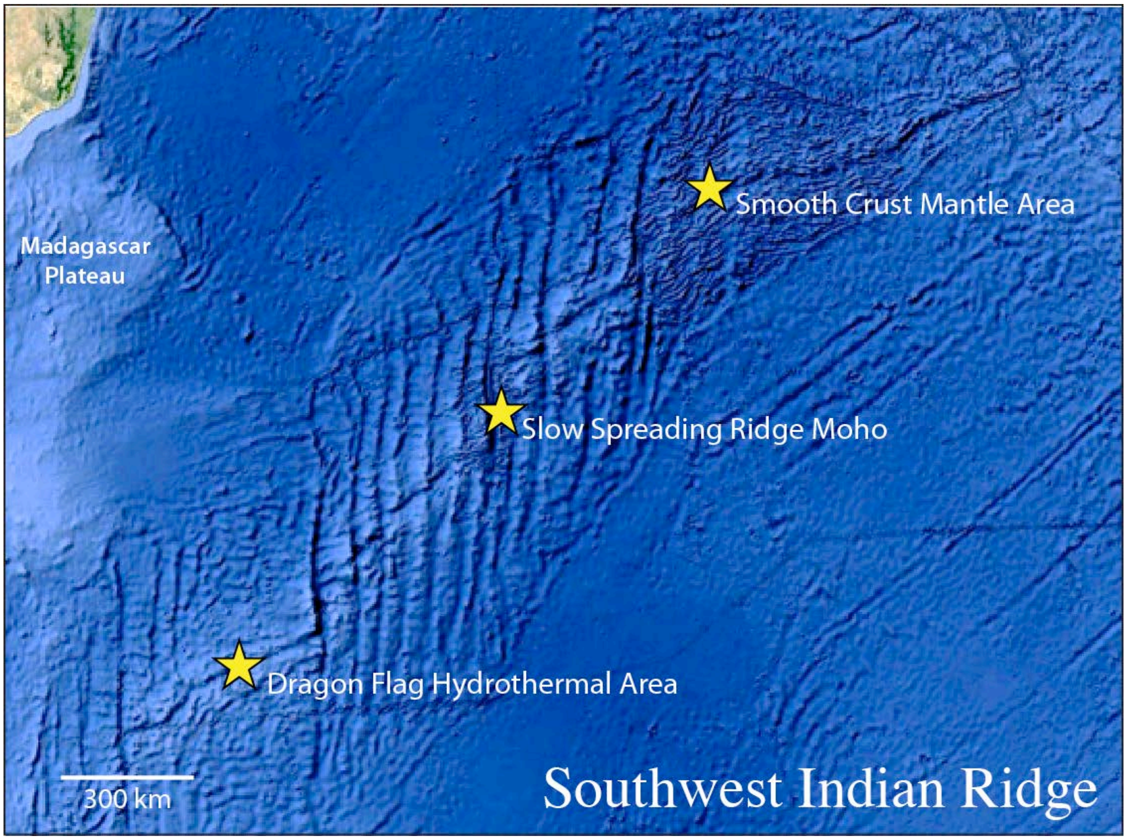

Figure 1. Map of the eastern Southwest Indian Ridge showing the drilling location for IODP Expedition 360 and the two new proposed drill sites discussed in this report.

1. Introduction

1.1 Overview:

The Workshop for Scientific Drilling in the Indian Ocean Crust and Mantle was held May 13-16, 2015 at the Woods Hole Oceanographic Institution. Sixty scientists from Australia, Canada, China, France, Germany, Great Britain, Italy, Japan, the Netherlands, Poland, Portugal and the United States, met in Woods Hole Massachusetts to discuss plans for future deep drilling in Indian Ocean crust and mantle. The meeting was co-sponsored by IODP China and the United States Scientific Support Program. The ECORD Magellan Program provided additional support for European travel. The workshop included an extensive overview of the tectonics, geophysics, geochemistry and geology of the principle area of interest, the SW Indian Ridge. Thirty-three half hour talks were presented, including 21 papers on current slow-spreading ridge research on mantle geochemistry, petrology, geophysics, geology, biogeochemistry, and crust – ocean interaction (Appendix I). Specific presentations were made for the pending and proposed drilling, with 12 half hour discussion sessions allowing extensive input from the participants on their plans and objectives, which resulted in specific workshop recommendations.

A significant portion of the workshop was devoted to a review of Phase I of Project SloMo. This consists of Expedition 360 scheduled for December 2015 and January 2016, and an approved but yet to be scheduled leg, to drill through the lower crust into mantle at Atlantis Bank at 57°E in the southern rift mountains of the SW Indian Ridge. The extensive review of the available data for Atlantis Bank allowed the workshop to identify key site survey data that was needed for the scientific objectives of Leg 2. The majority of the Expedition 360 scientific party was present, and the workshop provided an opportunity for exchange between them and the larger scientific community on the operation plan and expedition objectives, as well as reviewing the available site survey data. Detailed consideration was given to the objectives and methods of the biogeochemical sampling in hard rock core. These discussions proved invaluable for gaining pre-cruise insights into the detailed geology of the Atlantis Bank area, for refining experimental objectives and sampling approaches, and for establishing shipboard and shore-based scientific collaborations. The latter, given the large amount of core and complex stratigraphy of previous deep crustal drill holes, represents an extraordinary analytical challenge to the scientific community, is critical to the success of the project.

A major workshop objective was to solicit new Indian Ocean lithosphere drilling proposals, and two were presented. The first, presented in a series of talks on the Dragon Flag Hydrothermal Area (49.6° to 49.7°E), was to drill a series of shallow drill holes to explore the nature and extent of hydrothermal circulation and deposition at the early stages of the development of a seafloor massive sulphide deposit. The second was to drill the mantle in 'smooth' seafloor (Cannat et al., 2006) along the eastern SW Indian Ridge ~ 62° to 63°E, where there are large areas with little or no crust, and peridotite is exposed directly to the seafloor over 1,000's km^2 (Sauter et al., 2013).

The SW Indian Ridge spreads at ~14 mm/yr, and represents the best studied ultraslow end-member for seafloor spreading and formation of the great tectonic plates at mid-ocean ridges. Only the relatively inaccessible Gakkel Ridge spreads more slowly. It differs from faster spreading ridges, such as the Mid-Atlantic Ridge and the East Pacific Rise, in that magmatic crustal thickness varies from ~10 km west of the Gallieni Transform to nearly zero over large regions that likely include the crest of the Marion Rise (Zhou & Dick, 2013; Dick & Zhou, 2015). Sitting adjacent to the Bouvet and Marion hot spots, it has two corresponding rises where ridge depth increases from 4,500 to 500 m and 5,500 to 1000 m respectively. In addition to the unique tectonics of amagmatic spreading where the mantle spreads directly to the seafloor, it spans the range of melt production from effectively zero to some of the thickest ocean crust ever measured away from a mantle hotspot. Thus, it is a unique laboratory for the study of magmatic processes and related tectonics of crustal and lithospheric accretion. Unlike faster spreading ridges, long stretches of the ridge erupt minor amounts of extremely low degree melts that uniquely sample the enriched end-member components of the mantle, which allows geochemists to more directly isolate and characterize them. The SW Indian Ridge seafloor is believed to be ~23% mantle peridotite, which represents a highly reactive substrate for water – rock interaction compared to the largely basaltic crust at faster spreading ridges. This has the potential to at least partly explain differences in the fauna and chemistry of the oceans, with significant implications for the global carbon budget.

1.2 International Collaboration

Fifty years ago the Indian Ocean was the focus of the International Indian Ocean Expedition; a time when huge advances were made in understanding the evolution of this key, and relatively unknown portion of our planet. Since then, however, scientific research has largely focused on the Atlantic an Pacific Oceans with a great emphasis on the eastern Pacific and the north central Atlantic, while research on the Indian Ridge system has in good part languished. IODP only returned to the Indian Ocean in late 2014 after a hiatus of 15 years following drilling on Broken Ridge and the Kerguelen Plateau, and will return again to the western Pacific in October 2016, drilling a single hole into Indian Ocean Lithosphere, starting the SloMo deep hole at Atlantis Bank. Recognizing the urgent and critical need for a more focused effort from the scientific community for the study of the Indian Ocean, the *Scientific Committee for Ocean Research* (SCOR) established a working group to plan the *Second International Indian Ocean Expedition* (IIOE-2). This group has completed a science plan and is working with numerous national working groups on the development of an international implementation plan. The Expedition is scheduled be begin in the late fall of 2015 and it will run through 2020.

This report therefore sets the stage for the *International Ocean Discovery Program* to return to the Indian Ocean as part of IIOE-2, both to complete Phase II of the SloMo Project, and to take up the hydrothermal and microbiological objectives of Theme 6 of the IIOE-2 Science Plan:

- "*The Southwest Indian Ridge is one the largest ultraslow spreading ridge systems in the world, with vents associated with both magmatic and amagmatic rifting. These spreading centers are almost certainly important sources of trace elements in the deep Indian Ocean and Southern Ocean and possibly also in the surface and the global ocean, but the element fluxes from these ridges have yet to be fully qu*antified."
- "*How similar are Indian Ocean hydrothermal vent communities to those that are found in the other ocean basins? Have alternative new chemautotrophic symbioses evolved in association with any of these spreading centers? How do these communities persist in the face of the ephemeral hydrothermal vents and how far can the larvae of these organisms travel along and between the ridges? Is there significant gene flow between the hydrothermal vent communities found in different parts of the basin? In general, the hydrothermal vent communities need to be explored and studied in the Indian Ocean.*" (Hood et al., 2015).

2. IODP Expedition 360: Southwest Indian Ridge Lower Crust and Moho

IODP Expedition 360, with a nominal target depth of 1.3 km (Dick et al., 2015), is Leg 1 of Phase I of the SloMo Project. It is scheduled to depart Colombo Sri Lanka on November 30, 2015 and end in Port Louis, Mauritius on January 31, 2016. SloMo (or Slow Spreading Ridge Moho) is a plan to drill through the lower crust in a tectonic window at Atlantis Bank located at 57°E in the southern rift mountains of the SW Indian Ridge (Fig. 2). It is a multi-phase drilling project (MDP) to penetrate the crust to 500-m below Moho. The Phase I goal is to drill to 3-km, and possibly the crust-mantle transition, which may lie as much as ~3 km above Moho. Phase I consists of two approved legs, the second of which will be scheduled after the successful completion of Leg 1. SloMo Phase II will bring the riser drilling ship Chikyu to Atlantis Bank to deepen the Phase I hole to 500-m below Moho which lies at ~5.5 km mbsf (Minshull et al., 1998).

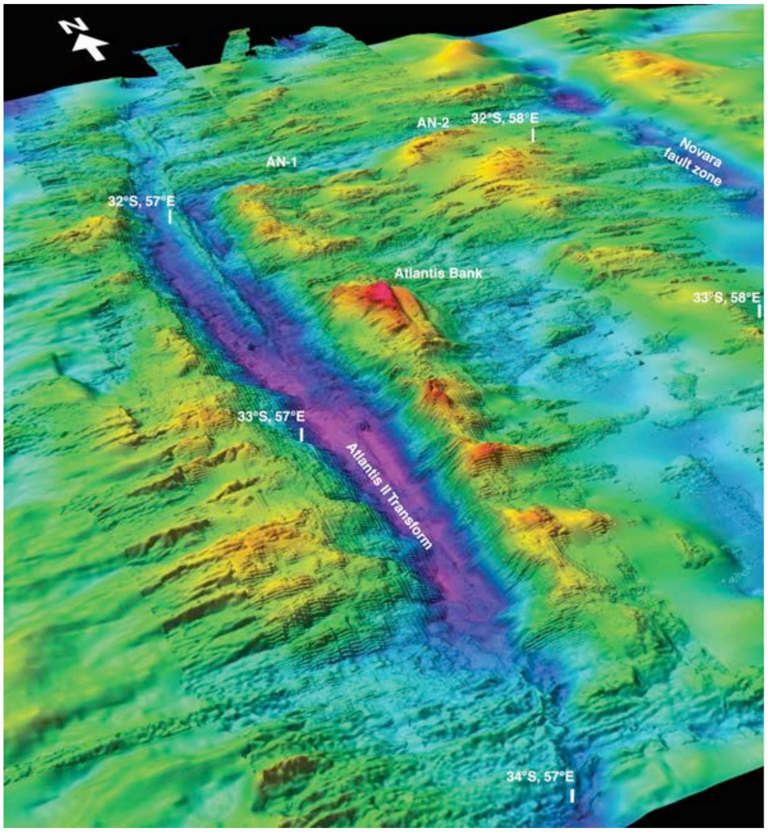

Figure 2. Atlantis Bank, SW Indian Ridge, modified from the Expedition 360 Scientific Prospectus (Dick et al., 2015).

Past drilling and mapping at Atlantis Bank has demonstrated that it represents ~3.4 million years of continuous exposure of lower crustal gabbro with numerous inliers of the dike-gabbro transition. The principal rock type, gabbro, represent a 2-km plus thick layer overlying the mantle. Expedition 360 is projected to end above the crust-mantle transition, while Leg 2 will deepen the Hole to ~3 km in the first attempt ever to penetrate the crust–mantle transition. Based on geologic mapping and seismic refraction studies it is believed that Moho here may be a hydration front due to circulation of seawater through the overlying crust during tectonic uplift into the rift-mountains (e.g.: Minshull et al., 1998). This would alter the mantle rock (density of 3.3 g/cm^2) to serpentinite (density of 2.2 g/cm^2), and Moho would then represent the serpentine stability limit (Hess, 1962), or the maximum penetration of hydrothermal fluid, as proposed by Canales et al. (2000) in a similar tectonic setting beneath a non-transform offset on the MAR at 35°N.

Ten speakers reviewed all available geologic and geophysical data for Atlantis Bank, as well as the results of ODP Leg 118, and IODP Legs 176 and 179 at Holes 735B and 1105A. On the basis of the available information it was the consensus that Site AtBk6 was appropriately chosen, and should be the highest priority for drilling. Some concern was expressed with the possibility that Expedition 360 might not core the full section, however, it was accepted that this might be necessary in order to drill a sufficiently deep hole as to allow Leg 2 to achieve the 3-km objective below seafloor. This would most likely consist of drilling and coring on alternate bit runs, if the lower section of the hole proved to be homogeneous. The importance of biological sampling was also emphasized, as well as the necessity of recovering as uncontaminated samples as possible. Various sampling strategies were discussed in detail by several speakers, to arrive at a biological sampling protocol in accord with necessity and expedition priorities (see section: *5. Microbiology/Biogeochemistry* in this report). Conflicts with obtaining a fully representative sampling of the cores due to the priority for biological sampling were extensively discussed, and it was agreed that this would be mitigated by returning the unused portions of the sections to the core liners for description. Alternate drill sites were also discussed, focusing on AtBk2 and AtBk4 as the highest priorities.

AtBk4 is located at the southern end of the Atlantis Bank wave-cut platform in 839 m of water on a gentle slope where RV James Clark Ross Cruise 31 Leg 2 recovered over a meter of serpentinite psuedomorphing granular peridotite. This could represent a portion of the discontinuous serpentinite sheath that locally is preserved on the detachment surface, consistent with the gently dipping slope preserving this surface below the wave-cut platform. It is unlike the sheared talc-tremolite-serpentinite found elsewhere over the bank overlying gabbro, and it could represent a screen of mantle peridotite originally enclosed in the gabbro such as was seen in Hole 1309D at Atlantis Massif on the Mid-Atlantic Ridge. Such screens, though fairly abundant in Hole 1309D, often extensively hybridized by basaltic melt to form olivine rich troctolite Drouin 2007, 2009, 2010; Suhr, 2008), were not found in Hole 735B or 1105A, and it is important to determine whether or not they are a common feature in gabbro sections elsewhere.

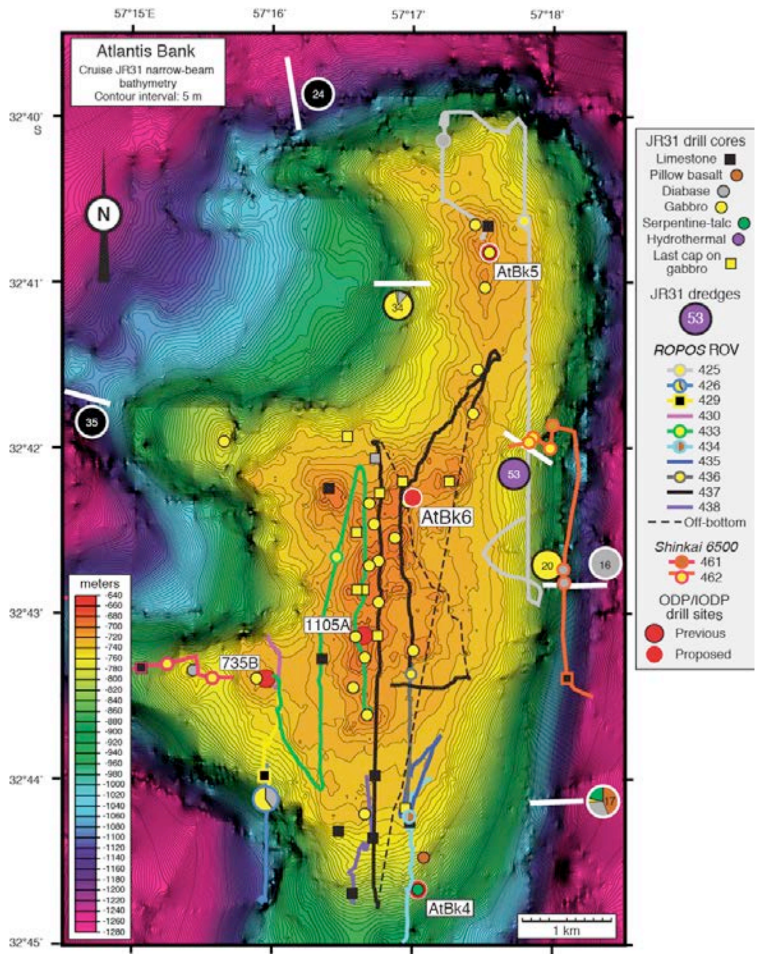

Figure 3. High-resolution contoured narrow-beam bathymetric map of the Atlantis Bank wave-cut platform showing ROV and submersible dive tracks, plus the location of over-the-side rock cores, ODP Holes 735B and 1105A and proposed drill sites AtBk 4 to 6.

AtBk2 is located in 1700-m of water at the top of a ~500 meter dike-gabbro transition section mapped a steep high-angle fault faces by DSV Shinkai 6500 Dive 648 on the north end of the eastern bench below the wave cut platform. Based on sampling up the ~1-km fault face the section begins in massive gabbro, and ends in massive sheeted dikes with a few gabbro screens, where the dikes cut the gabbros. Unlike Hole 1256D in the eastern Pacific, the dikes are not recrystallized as granoblastic two-pyroxene granulites, and similar material was easily drilled on Leg 118 in Hole 735B.

Alternate Site AtBk4 is given first priority and AtBk2 second priority in the Scientific Prospectus for Expedition 360 in the event of catastrophic hole failure at AtBk6, and the workshop did not disagree with this.

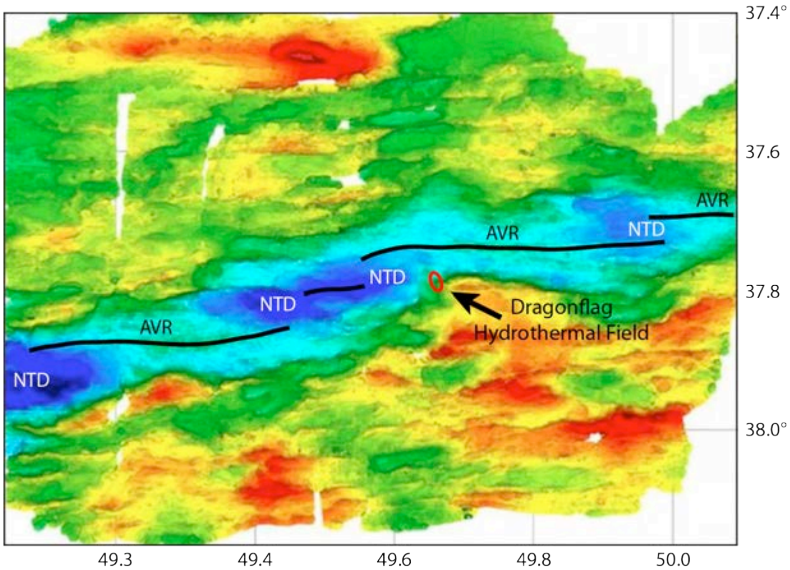

Figure 4. Dragon Flag Hydrothermal Field, Southwest Indian Ridge (Modified from Zhou (pers. comm.). Red oval indicates the vent area.

3. Dragon Flag Hydrothermal Area

The workshop extensively reviewed the biology, geology, geochemistry and geophysics of the Dragon Flag hydrothermal area, and evaluated it for hydrothermal and tectonic drilling. Included in the discussions was drilling at the 53°E Dragon Bone Amagmatic ridge segment lying across the Gallieni Transform, which juxtaposes the most magmatically robust spreading segment of the entire SW Indian Ridge against one of the least (Zhou and Dick, 2013). It is called the *Dragon Bone Segment* as unlike the *Dragon Flag Segment*, it has virtually no crust, and no known hydrothermal area – no meat on the bones at all.

The Dragon Flag hydrothermal area is situated at a detachment fault on the south wall of a magmatic segment adjacent to a non-transform discontinuity. Serpentinized mantle has been dredged from the rift valley wall above the hydrothermal site that lies in the center of the 46° to 52°E first-order supersegment between the Indomed and Gallieni Transforms. It is believed that this represents fault gouge intruded from where the detachment fault cuts mantle peridotite in the adjacent non-transform discontinuity. In form, the ridge segment hosting the Dragon Flag hydrothermal field appears to represent an excellent example of a deeply rifted spreading magmatic ridge segment with a well-developed axial volcanic ridge. Such segments represent the major style of accretion along the SW Indian Ridge, and can expose mantle peridotite on the rift valley wall and at adjacent discontinuities. So far these have received little attention in assessing accretionary processes along this or any other slow-spreading ocean ridge. In this case, based on the EMAG2 Global Magnetic Anomaly Map (Maus et al., 2009) while the ridge segment was spreading slightly asymmetrically to the south from 13 to 8.0 m.y. at ~55% to the south, this has accelerated to ~65% to the south since 8 m.y. This is consistent with a switch from symmetric to asymmetric spreading and detachment faulting, as at Dragon Flag.

In many respects, the Dragon Flag hydrothermal area closely resembles the TAG hydrothermal area on the Mid-Atlantic Ridge, having very similar tectonic setting and fluid chemistry. The differences between the TAG and Dragon Flag hydrothermal areas are important. The TAG detachment fault is long-lived (~1 Ma), and is forming an oceanic core complex. The TAG hydrothermal area is correspondingly long-lived, with many large 200 by 50-m mounds consisting of several clusters of high and low-temperature chimneys, mostly still active, while the detachment fault exposing the footwall is relatively young and has yet to evolve as a long-lived oceanic core complex. This young age and relatively simple geometry offers the opportunity to study directly the pattern of hydrothermal circulation and alteration by drilling, where at TAG, the overall pattern is more than likely obscured by overprinting earlier patterns. Dragon Flag represents the opportunity for parallel studies to the far older and complex TAG hydrothermal area, and for determining the microbial biogeography between the Atlantic and Indian Oceans to match that of the diverse macro fauna at TAG.

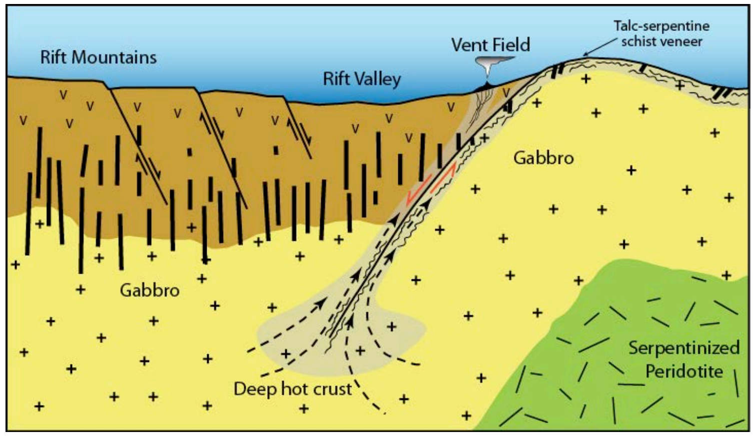

Figure 5. Cartoon of likely geometry of the Dragon Flag Hydrothermal Field

Short-lived detachment faults, exposing lower crust and mantle are common features of magmatic accretionary segments along the SW Indian Ridge. These faults have up to 2 to 3 km heave that expose diabase dikes, primitive gabbro, troctolite and dunite and peridotite. Unlike long-lived core complexes, such as Kane Megamullion, Atlantis Bank and Atlantis Massif they are believed to expose relatively little oxide gabbro or other highly differentiated plutonic rocks (Dick et al., in prep). However, the later conclusion is based on a relatively small sampling of two such faults on the Gakkel Ridge at 10°E and SWIR at 21°E, and an objective of footwall drilling at Dragon Flag would be to determine whether this is the case here too, and if that difference gives rise to differences in the nature of the hydrothermal fluids and SMS deposits.

The exposure of serpentinized peridotite on the face of the detachment fault over the gabbro massif there indicates that either there are screens of mantle peridotite within it, or that these peridotites were intruded along the detachment fault from exposures in the adjacent non-transform discontinuity. It is proposed to test this by a series of short (100-200 m) single bit holes drilled along the from the detachment fault face into the non-transform discontinuity to examine the lateral continuity of the igneous stratigraphy and the transition in magmatic environment from east to west.

Drilling at the Dragon Bone Amagmatic Segment, 300 km to the east of the Dragon Flag Hydrothermal area offers an opportunity to recover pristine mantle peridotite from high on the Marion Rise for comparison to the mantle that can be drilled in amagmatic deep regions of the eastern SW Indian Ridge, and critically to mantle rocks drilled in the Dragon Flag area. The questions to be addressed are straightforward. The Dragon Bone Segment represents an amagmatic segment high on the Marion Rise, while the amagmatic segments at the Eastern SWIR occur on some of the deepest portions of the SW Indian Ridge. At the same time, the mantle to be drilled in the Dragon Flag region has produced some of the most robust magmatism found on any ocean ridge. The question is, how does the mantle composition differ between these areas, and can the mantle compositions be related to the contrasting magmatic environments and axial depth?

The consensus of the meeting was that the Dragon Flag hydrothermal area and adjacent Dragon Bone Amagmatic Segment are of considerable interest, but the development of a full

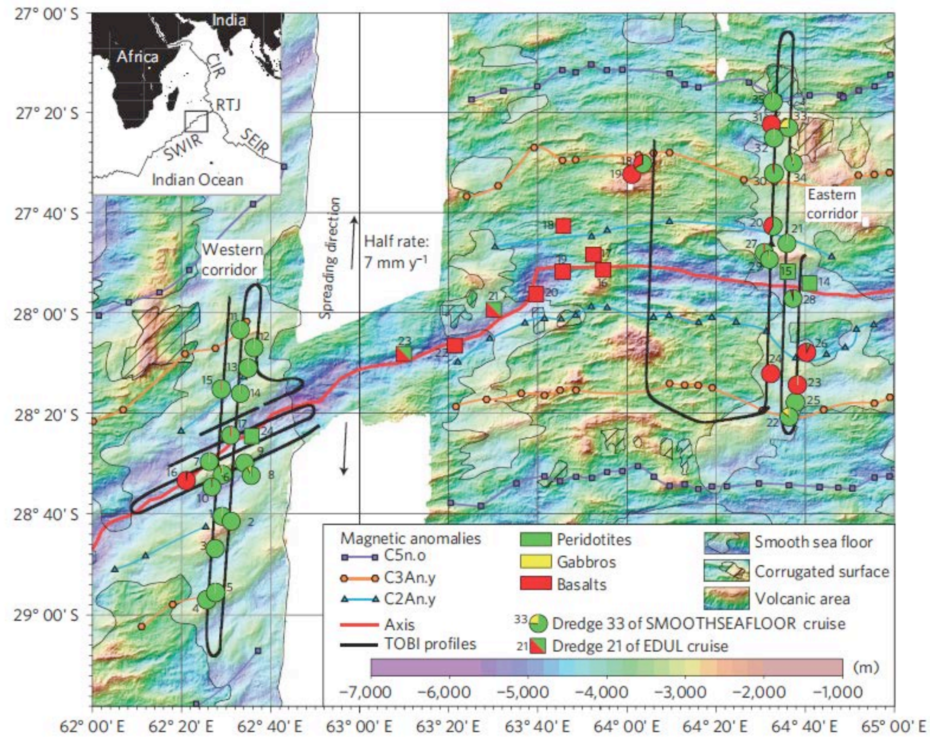

Figure 6. *Bathymetric map with the side-scan sonar tracks and dredge locations on the SW INDIAN RIDGE (Sauter et al., 2013). The proportion by weight of magmatic and mantle-derived rocks is shown as individual pie charts for each dredge station. The different types of seafloor (corrugated surfaces, volcanic and non-volcanic smooth seafloor areas) are from Cannat et al. (2006). Magnetic anomaly identifications are from Sauter et al. (2006). RTJ: Rodrigues Triple Junction; CIR: Central Indian Ridge; SEIR : Southeast Indian Ridge.*

drilling proposal requires more site survey data. In particular, AUV high-resolution micro bathymetry needs to be collected over potential drilling targets in the hydrothermal area located on the hanging wall of the detachment, and the adjacent footwall exposed in the rift-mountains. Twenty to fifty meter seabed rock drills should also be used to recover the shallow basement lithologies in both the detachment footwall and the adjacent footwall source rock.

4. Mantle Drilling in Smooth Seafloor

The proposition of drilling directly into the mantle in ‘smooth’ seafloor on the eastern SW Indian Ridge was very well received at the workshop, with a consensus that a pre-proposal would be in-order for drilling. Additional survey, however, is necessary for a full drilling proposal for the JOIDES Resolution. This includes high-resolution micro-bathymetry of selected regions and potential drill sites to better understand the character of ‘smooth’ seafloor, and its relationship to adjacent terrains.

Perhaps the most dramatic, and underreported, change in our knowledge of the Earth over the last 20 years has been the discovery that large portions of the oceans have no crust, with the mantle exposed directly to the seafloor [*Dick et al*., 2001; *Michael et al*., 2003]. The eastern SW Indian Ridge is one of the best examples, with vast regions where the seafloor is paved by mantle rock with only scattered pillow basalt flows for thousands of km^2 (Cannat et al., 2006; *Sauter et* *al*., 2013). The dominant mantle rock is lherzolite with high-alumina spinel (Seyler et al., 2003), likely representing the least modified mantle end-member source composition for mid-ocean ridge basalt. By comparison, the 53°E Dragon Bone Amagmatic Segment peridotites, another drilling target adjacent to the Dragon Flag Hydrothermal Area 1,800 km to the west, are highly-depleted harzburgites, representing residues of mantle melting at the ridge and earlier events that likely did not affect the eastern Southwest Indian mantle (Zhou & Dick, 2013).

Bathymetric and geophysical data in the easternmost part of the crust generated at the SW Indian Ridge over the past 26 Ma show that the basement presents three types of morphology. Volcanic seafloor, representing ~60% of the mapped terrains, is marked by volcanic cones and along-axis fault scarps (Cannat et al., 2006). Seafloor that lacks a volcanic upper layer is made of either corrugated domal surfaces that are the surface expressions of oceanic core complexes (~4% of the mapped terrains), or smooth seafloor expressed by long, broad and smooth ridges with no scarps. The latter represents about 37% of the mapped terrains, and is recognized as the morphological manifestation of crustal construction processes at the melt-poor end-member parts of ultraslow spreading ridges, dominated by detachment faulting with no or very little magmatic activity. Dredged samples in these smooth seafloor areas are almost exclusively serpentinized peridotites (95%), with minor gabbros and basalts (Sauter et al., 2013; Roumejon et al., 2015).

The smooth seafloor area at 64°30'-64°40' E has been recently imaged by a seismic refraction and reflection experiment (sismo-smooth cruise, R/V Marion Dufresne, 2014). It will be further surveyed at the end of 2016 with ROV dives that combine geological exploration and sampling, microbathymetry and near bottom magnetics surveys, and measurements of local microseismicity by OBS's (Bronner et al., 2014; Sauter et al, 2013).

Eventually, the 64°30'-64°40' E smooth seafloor area will have been completely surveyed, and will be an ideal target for IODP drilling. The main objectives for scientific drilling in this area will include:

- Sampling the lithospheric mantle in the magma-starved end-member of the mid-ocean ridge system and documenting its structure and composition.
- Sampling and documenting the penetration depth of hydrothermal fluids, and the mode(s) of hydrothermal circulation and serpentinization (e.g., Rouméjon et al, 2015).
- Documenting the lithological and structural architecture of the crust (as defined geophysically), and possibly sampling fresh mantle peridotites at depth that are likely reachable by conventional non-riser drilling, with a gravity-derived apparent crustal thickness ≤ 2.5 km.
- Understanding the dynamics of the faults generating the smooth seafloor, and testing the working model that predicts changing fault polarity.
- Documenting the extent and depth of geomicrobial activity in serpentinized mantle lithosphere where it is directly exposed on the seafloor.

The drilling strategy will be fully defined after the geophysical and geological surveys in the area of interest are completed. It could combine shallow coring/drilling (using seabed rock drills or single bit JR holes) to document the lithological variability, and one or several deep holes (several hundred meters) to get the necessary samples to document the variability of serpentinization processes with depth and eventually access fresh mantle peridotites.

5. Microbiology/Biogeochemistry

5.1 Introduction

The workshop brought together the broader microbiology/biogeochemistry community to review past experience on prior drilling legs, and to discuss and develop sampling strategies and collaborations for IODP Expedition 360 and for the proposed Dragon Flag Hydrothermal Area drilling. An additional goal was to educate the scientific party on the difficulties of such sampling and to explain the necessity of avoiding contamination of the cores prior to this. The overall microbiology and biogeochemistry objective is to find evidence for microbial life in the lithologies that are drilled. During the workshop Beth Orcutt (Bigelow Lab) gave an overview of knowledge about the microbiology of ocean crust and mantle. Frieder Klein (WHOI) explained the reaction pathways and hydrogen generation that occur during serpentinization of abyssal peridotite. Matt Schrenk (Michigan State U.) followed with a presentation about the connections between serpentinization, carbon, and deep microbial life. A potential deep subsurface carbon source for microorganisms is methane (and various organic compounds) generated abiotically, and Oliver Plümper (Utrecht U) explained how low-temperature nanocatalysis of abiogenic methane occurs during peridotite alteration.

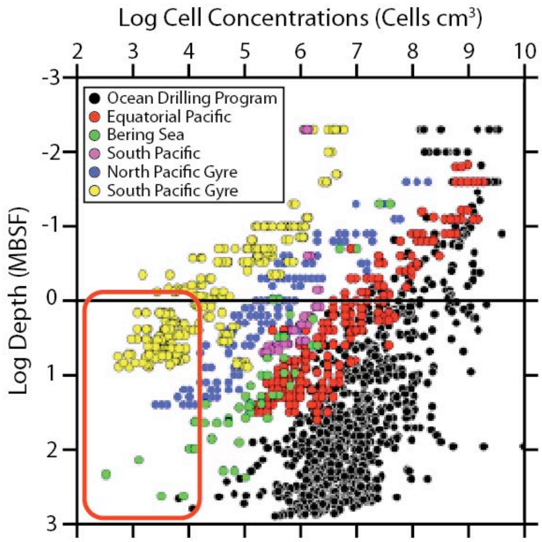

Figure 7. Cell concentrations in subsurface core samples from varied locations. Red square highlights the expected maximum cell concentrations in deeper Atlantis Bank samples. Adapted from Kallmeyer et al. (2012).

5.2. IODP Expedition 360 SloMo Drilling Phase I

5.2.1 Overview: Microbial life in the deep subsurface at Atlantis Bank will likely be at very low cell concentrations based on published cell concentrations in subsurface samples from relatively shallow core depths at various locations (Fig. 7). There are specific and significant challenges associated with working with RCB drill core samples for studies of microbial diversity and activity because the material used must be relatively contaminant-free and analyses must control for remaining contaminants. The workshop provided an opportunity to clearly explain these challenges. This was valuable because it allowed geologists who will sail on Expedition 360 to gain an appreciation for these challenges, for strategies that can be utilized by all science party members who handle the cores to minimize and control for contamination, and to understand why rapid processing of core sections is important for the microbiologists. The microbiologists and biogeochemists also refined their sampling strategies during the workshop to enhance the return of unused but still informative core material left over from sampling whole round sections dedicated to microbiology. This considerably alleviated the concerns of the geologists that key intervals or markers might be missed. David Smith (U. Rhode Island) detailed some of the challenges of working with low biomass samples and offered suggested strategies based on his extensive experience conducting microbial investigations during previous IODP expeditions. Jennifer Biddle (U. Del., presentation delivered by V. Edgcomb) offered examples from prior investigations of strategies for controlling for contamination. V. Edgcomb outlined the biological sampling objectives and anticipated strategies for sample handling and contamination control that are outlined below.

5.2.2 Serpentinization: Serpentinization can provide energy and raw materials (ferric iron, hydrogen gas) for chemosynthesis by subsurface microbiota. Where H_2 and CO_2 are present in subseafloor environments, both biotic and abiotic methane production are possible. If a deep serpentinite zone is encountered during drilling, it will be particularly interesting to investigate these samples for evidence of active microbial processes, such as methanogenesis or methane oxidation. It will be necessary to infer the conditions of serpentinization (e.g., temperature, concentrations of reduced gases, etc.) from the rock record, as it will not be possible to take in situ fluid samples during Expedition 360.

5.2.3 Biological Sampling Objectives: Microbiologists on Expedition 360 aim to collect samples for the following objectives, 1) determination of microbial biomass (cell counts), 2) determination of microbial diversity and activity based upon DNA, RNA, and lipid biomarker approaches, 3) determination of rates of selected processes (methanogenesis, sulfate reduction) using isotope incubations, 4) measures of exoenzyme activities, 5) microscopy (SEM-EDS, Raman on thin sections, and fluorescence microscopy of cells from crushed rock material), 6) enrichment cultures for bacteria, archaea, and fungi, and 7) material for analysis of carbon content by a shore-based organic geochemist. The expedition microbiologists Sylvan and Edgcomb aim to collect samples from all lithologies drilled to the extent possible without compromising the critical mission objectives. Ideally, they would like one ~10 cm whole round sample from every 10 - 20m of core retrieved. Of particular interest will be samples of olivine- and pyroxene-rich gabbro that may host serpentinization, as well as samples that show promising alteration features (presence of serpentinite, carbonate veins). Admittedly, the list of objectives is extensive for a two-person team, but efforts will be made to meet each objective as much as possible (e.g.: every sample will be processed for cell counts and DNA/RNA/lipids, but likely not every sample will be processed for exoenzymes).

Drilling will incorporate perfluoromethylcyclohexane (PFC) at 84 ml/150,000 L seawater as a contamination tracer. This tracer is easily detectable by gas chromatography (GC), and its use as a contamination control is routine now on drill legs that include sample collection for microbiological and biogeochemical analyses. David Smith discussed an alternative tracer compound currently under development, which will be investigated and evaluated prior to the cruise. Upon retrieval of a core on deck, a shipboard petrologist working with the microbiologists will conduct preliminary identification of lithologies and alteration assemblages. Samples dedicated to microbiology will then be captured in a whirl pak bag and transferred as quickly as possible to a sterile metal box within a laminar flow hood. Shipboard personnel will utilize sterile gloves and disposable masks to handle the core prior to designation of the section for microbiology, and microbiologists will continue this for handling the designated microbiology

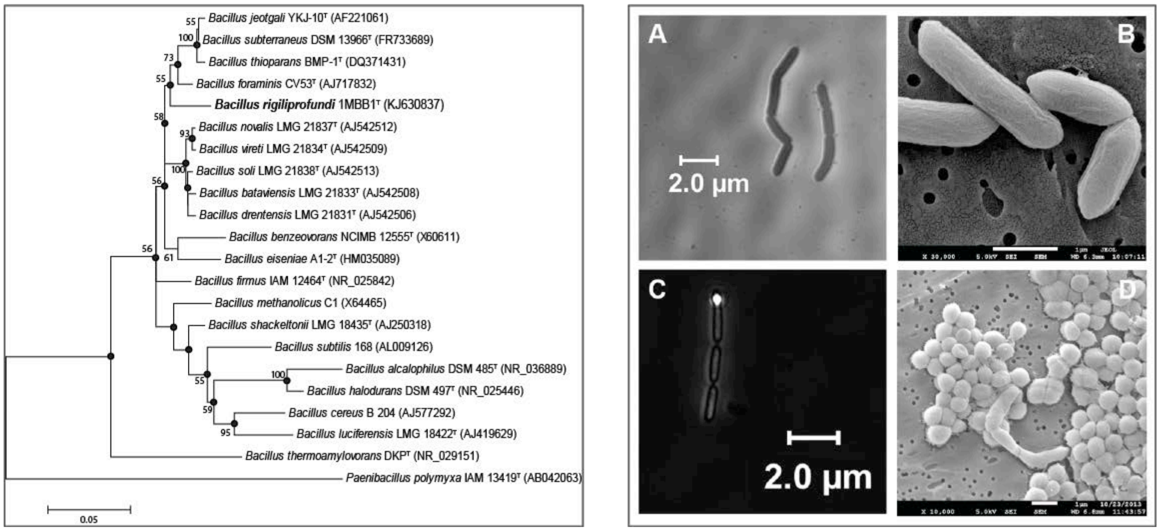

Figure 8. *Bacillus rigiliprofundi*, a new species isolated from 392 mbsf . Adapted from Sylvan et al. 2015.

sample. The exterior of the core section will be flamed inside a sterile metal box to remove most of the PFC (and contaminating microbes coming from drill fluids). Removal of PFC (a proxy for contaminating microbes) will be confirmed by shipboard GC analysis. The microbiologists will use a drill with a hollow bit to remove material from the remaining clean core sample using 3 x 2 cm hollow drill bits and/or rock chisels for downstream analyses. The remaining material will then be returned to the core liner for archiving and further description by the scientific party. All core plugs will be photo-documented. A thin section billet from each sample will be submitted for thin section preparation on board the ship (2/day on average). It is particularly important to downstream data interpretation that thin section preparations are made for each biogeochemical sample.

Samples for DNA and lipid biomarker analyses will be stored at -80°C, and samples for RNA work may also be first placed in RNAlater prior to storage at -80°C. Not all rock material for RNA analyses from each sample will be stored in RNAlater in case there are unanticipated problematic interactions between this high-salt preservative and sample material. Crushed rock will be preserved immediately in 4% paraformaldehyde and/or stained with SYBR green (a live stain) for visualization of living cells. Cells will be separated from crushed rock using centrifugation through Nycodenz (protocol used by J. Sylvan on subseafloor volcanic rocks) post-cruise. Analysis of exoenzyme activity onboard the ship will utilize fluorometric substrates and a microplate reader provided by Sylvan. Enrichment cultures will be established on board ship for microorganisms present in samples, with the hope that novel microbiota will be recovered. Novel microorganisms have been recovered previously using approaches that will be used on Expedition 360 (e.g., Sylvan et al. 2015, Fig. 8). These efforts will utilize a wide range of media, and any growth will be photo-documented. Enrichments using stable isotopes to measure methane production or sulfate reduction will be analyzed post-cruise. Prioritization of samples for post-cruise analyses will be established based on analysis of prepared thin sections by a shore-based participant using SEM-EDS and confocal Raman spectroscopy to locate potential microbial hot spots, carbonaceous concretions, and presence of organic molecules such as lipids, amino acids, and proteins. The most promising samples will be selected for detailed lipid analyses at

Washington University, and DNA and RNA-based studies at the Woods Hole Oceanographic Institution, and microscopy at the University of Brittany.

5.3 Dragon Flag Hydrothermal Area

There was much discussion of potential drill sites in the Dragon Flag area during the second half of the workshop. Hydrothermal vent microbial communities are shaped by the interplay of sharp environmental gradients that include temperature and availability of different carbon and energy sources. If a series of relatively shallow (<200m) drill holes is planned at Dragon Flag, these would provide an excellent opportunity for examining fluid movements across that detachment fault area and through hydrothermal features, how local fluid dynamics impact the geochemistry of the environment as fluids pass through different subsurface lithologies, and the resulting impacts on microbial communities and processes. In particular, it would be interesting to know how subseafloor boiling influences the partitioning of different electron carriers such as hydrogen sulfide, which may exist in the vapor phase, and iron, which may exist in brines. If serpentinization is an active process at Dragon Flag, this site would be an excellent one for understanding how this process affects deep biosphere communities and carbon cycling, and if serpentinization can support an active microbial community. With a series of shallow holes in the Dragon Flag area, and if bore hole chemistry data can be gathered from this series of holes, it will be possible to better understand how proximity to active venting, faulting, different lithologies (and sediments, if they are present), and hydrological regimes shapes available carbon and energy sources available to microbial communities. Additionally, the rates of key processes that impact subseafloor carbon and other major nutrient cycling (e.g., carbon fixation) can be measured. It will be important to distinguish biotic from abiotic organic synthesis and the relative importance of autotrophy using carbon and non-carbon energy sources. In addition to microbiology and biogeochemistry experiments planned for Expedition 360, the work plan could include microbiological study of near surface microbiology in close vicinity to hydrothermal features, including examinations of macrofauna and microbial eukaryotes and their associations (trophic relationships and symbioses) with Bacteria and Archaea using culture-based approaches, microscopy, and a suite of molecular approaches. These include metagenomics to examine community genetic potential, metatranscriptomics to examine community transcribed genes, single-cell genomics, DNA- and RNA-based quantitative PCR to look at expression of key genes of selected processes, fluorescent *in situ* hybridization and epifluorescence microscopy to enumerate target microbial populations and to visualize symbioses, incubation studies using stable isotopes to measure rates of key processes, and possibly Raman spectroscopy to visualize activities and chemical composition of selected cells. Additionally, at Dragon Flag it should be possible to collect more detailed organic biogeochemistry data on *in-situ* fluids to aid interpretation of microbiology data. This can be accomplished by deploying borehole instrumentation to collect *in-situ* fluids for characterization.

6. Post-Drilling Site Surveys at Atlantis Bank

6.1 Background

One of the main objectives of SloMo is to test the hypothesis that at some tectonic settings formed at slow and ultra-slow spreading rates, the Moho is a serpentinization front rather than a lithological boundary. A main driver for testing this hypothesis at Atlantis Bank are the results of the only seismic survey conducted to date in this area: a 1994 survey lead by scientists at University of Cambridge. The 1994 seismic survey consisted of 2D seismic reflection imaging using a short, 8-channel 800-m-long hydrophone streamer for sediment thickness, and an 10-element airgun array source with a total volume of 71 L (4,333 cubic inches), triggered every100 m shot. It also included 3 wide-angle seismic profiles instrumented with sparsely spaced (~20 km) 9 ocean bottom hydrophones (OBHs) (Fig. 9), a standard design in academic mid-ocean ridge research in the early 1990s.

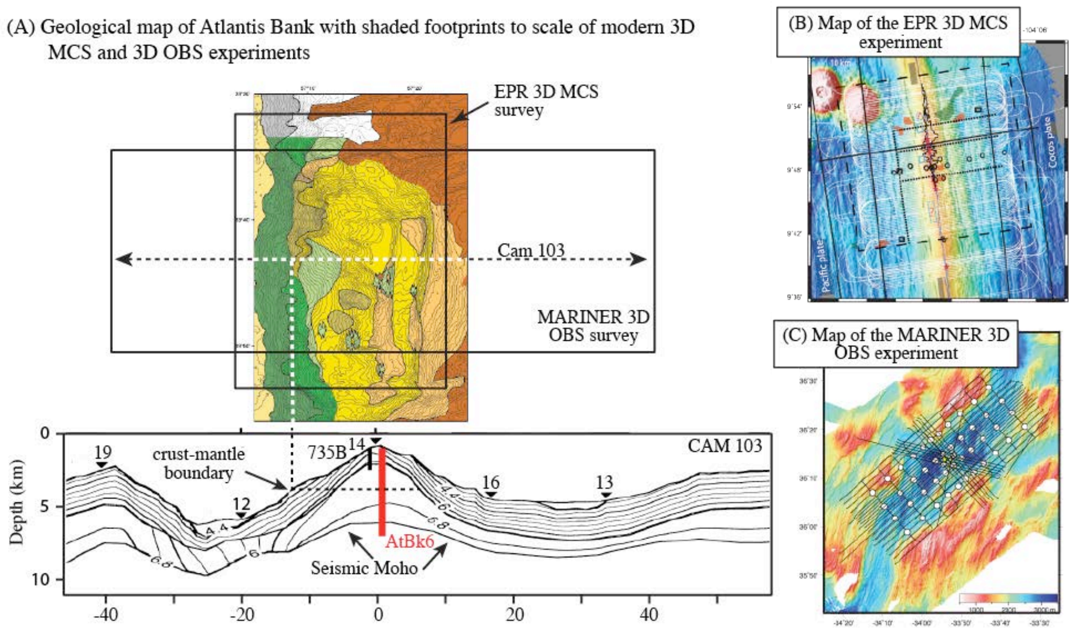

Figure 9. A) Geological map of Atlantis Bank (top, Dick et al., 2015), and its seismic structure (bottom, Muller et al., 2001). Dashed lines show the position of seismic Line CAM 103. Boxed areas show the footprints of (B) the EPR 3D MCS experiment of Aghaei et al. (2014), and (C) Canales et al. (2013). Heavy black line shows the position and depth of Hole 735B, while the heavy red line shows the planned position and depth of Hole AtBk6 after Phase II drilling by the riser drill ship Chikyu.

Because of the rapid shot repetition rate, OBH data are noisy at the larger source-receiver offsets needed for deep velocity modeling, and first arrivals are typically observable out to ~30 km source-receiver offsets, which allowed modeling the seismic velocity structure within the upper 4-5 km of Atlantis Bank. Records from the two OBHs located on the top of Atlantis Bank show somewhat ambiguous triplication from the Moho (PmP) at 20 km offsets; these arrivals were used to determine depth to Moho beneath the flanks of Atlantis Massif. Results have been published in [*Minshull et al.*, 1998; *Muller et al.*, 2000; *Muller et al.*, 1997], and can be summarized as: The seismically-defined "crust" beneath Atlantis Bank consists of a 2.0-2.5 km thick layer 2 and a 1-2 km thick layer 3. Based on gravity and geochemical modeling, the lower

2-3 km of this 4-5-km-thick seismic "crust" are interpreted as serpentinized peridotites, thus implying that the wide-angle seismic reflections (PmP) defining the Moho correspond to a serpentinization front.

6.2 Geological Targets for Seismic Imaging

The long-wavelength features of the 1994 CAM models are consistent with gravity modeling, and thus Moho depth is probably accurate to ±1 km vertically. However lateral resolution is severely limited due to the experimental geometry, and seismic velocities and vertical gradients in the lower crust have elevated uncertainties to a level that allows multiple geological interpretations. For these reasons, the objectives of SloMo can only be truly met with new seismic models/images that resolve the internal structure of Atlantis Bank at scales comparable to those of surface geology and drilling observations. In addition, modern seismic surveys will help placing drilling results in a global context to better assess their global significance. The two most relevant geological observations that should guide seismic imaging are (Fig. 9a):

- Shinkai Dives 466 and 458 have documented the location of the lithological crust/mantle boundary, outcropping along the western wall of the transform valley at depths of 4500 m and 4650 m, respectively (Baines et al., 2003).
- ODP Hole 735B on the top of Atlantis Bank, which cored 1500 m of gabbro (Dick et al., 2000).

Needless to say, future seismic imaging should also enclose, in addition to the above targets, upcoming deep-penetration drill site AtBk6.

6.3 Modern Survey Examples as Reference Guides

Academic mid-ocean ridge seismic research has advanced tremendously in the last two decades, and the community has now access to the technologies and imaging algorithms that make meeting the SloMo objectives highly feasible. The workshop presented 3 examples of modern seismic research in mid-ocean ridge settings that have some similarities with Atlantis Bank, either because of tectonic setting and/or in scientific objectives. These modern surveys and their results should serve as reference guides for future studies at Atlantis Bank.

6.3.1. *High-Resolution Seismic Imaging of a Gabbroic Section at Atlantis Massif, MAR*. This presentation reported the latest results obtained from applying advanced seismic imaging techniques to 2D multichannel seismic (MCS) data collected with a 6-km-long, 480-channel streamer (2001 *RV M. Ewing* cruise EW0102) across Atlantis Massif on the Mid-Atlantic Ridge. Advanced seismic imaging included SOBE downward continuation (Synthetic Ocean Bottom Experiment) and traveltime tomography (Henig, 2012), full waveform inversion (FWI), and reverse-time migration (RTM) [*Harding et al.,* in prep]. FWI velocity models closely match the down hole velocity profiles, and clearly delineate the boundaries of the gabbroic body drilled in IODP Hole U1309D and the detachment damage zone. RTM images show different reflectivity signatures in the Southern Ridge, where serpentine is believed to form a larger fraction of the subsurface lithology, compared to the gabbroic Central Dome, which is largely seismic transparent. Seismic reflections beneath the Central Dome at 2.5-3 km depth observed in the RTM images may correspond to the bottom of the drilled gabbro body.

6.3.2 *3D MCS Imaging of Moho at the EPR*. This presentation reported results from the first academic 3D multi-streamer MCS survey conducted in a mid-ocean ridge environment (2008 *RV M. Langseth* cruise MGL0812 (Mutter, 2009)). Data were acquired with four, 6-km-long streamers spaced 150 m apart in a 714 km^2 area centered at 9°48'N over the East Pacific Rise (Fig. 9b). 3D Post-stack time migrated (Aghaei, 2014) and 3D pre-stack depth migrated [*Nedimović et al*., in prep.] volumes show spectacular images of both, axial and off-axis crustal melt lenses, and Moho reflections across >90% of the ~16 x 28 km^2 imaged area. Moho is shown to vary spatially in character, from impulsive, to shingled, to diffusive, indicating local variations in the structure and perhaps the nature of the crust-mantle transition zone.

6.3.3 *MARINER: A Multi-disciplinary Geophysical Study of a Non-Transform Discontinuity and Ultramafic Massif, MAR-Rainbow Area*. This presentation reported initial results from a 2013 multidisciplinary geophysical experiment conducted across the Rainbow are in the Mid-Atlantic Ridge (*RV M. Langseth* cruise MGL1305). The experiment included seafloor acoustic, gravity, and magnetic field mapping (Paulatto et al., 2015), a 3D active-source wide-angle seismic tomography experiment using 4-component ocean bottom seismometers (OBSs) (Fig. 9c), 2D MCS profiles using an 8-km-long, 636-channel streamer, and a 9-month OBS deployment for local seismicity monitoring (Canales, 2013). The initial 3D seismic velocity volume show large lateral variations in Vp largely associated with rift valley faulting and the Rainbow ultramafic massif [*Arai, Dunn, et al*., in prep]. The 3D velocity volume was used for pre-stack depth migration of the MCS profiles, allowing imaging of deep-penetrating faults and other crustal reflectors in a complex area [*Canales et al.,* in prep] where more conventional imaging approaches (e.g., post-stack migration) fail to adequately image the targeted structures.

6.4 Recommendations

- **Critical Seismic Surveys:** The workshop participants agreed that the complexity of Atlantis Bank area (i.e., large topography variations, rapid lateral variations in seafloor geology) and the challenges of conducting seismic surveys in the southern oceans (weather, strong currents) absolutely require a combination of 3D MCS and high-resolution 3D wide-angle surveys if one is expected to image the internal structure of Atlantis at scales comparable to those of surface geology and drilling observations. 3D Wide-angle data acquired with closely spaced OBSs (≤4 km) and a dense distribution of sources to provide complete and homogeneous azimuthal distribution of source-receiver pairs can provide the accurate velocity and anisotropy structure (via traveltime and full waveform tomography) needed for 3D pre-stack depth migration of an MCS volume. The properly migrated MCS volume should then reveal the sharp contacts associated with faults and lithological units.

- **2D MCS Reconnaissance:** One important aspect that was discussed was the need of 2D MCS reconnaissance prior to any 3D MCS survey. The main advantage of acquiring 2D MCS profiles would be to assess the quality of MCS imaging and determine seismic targets that would guide the design of a future 3D survey. However arguments can be made that 2D profiles may not be that useful in this setting, and could even be detrimental in justifying a 3D MCS survey. For example, lack of clear reflections in 2D images could be used as argument for not conducting a more expensive 3D survey. Lack of clear reflections in 2D images could arise from factors that would actually be mitigated or corrected in a 3D survey. Among these potential factors are: (1) Ocean currents. Expected strong surface currents would degrade the quality of 2D images, unless the profiles are run parallel to currents. However ocean currents' direction does not necessarily coincide with the strike of geological and bathymetry structures that should determine the orientation of 2D profiles for optimal imaging. (2) Seismic anisotropy. Anisotropic fabrics at the Moho transition zone can make the quality of seismic imaging of the Moho very sensitive to the orientation of 2D profiles.

- **OBS Deployment Challenges:** It was suggested that deploying OBSs in the deepest areas of Atlantis II transform valley (>5,500 m) and the steep slopes on the flanks of Atlantis Bank may require the use of remote-operated vehicles or tethering for some instruments.

- **Modeling:** It was suggested that designing a 3D-MCS experiment would benefit from a synthetic section based on a realistic geological cross-section Atlantis Bank as well as on the information available form seismic imaging at Atlantis Massif. In addition, modeling of gravity-derived crustal thickness including 3D density variations, asymmetric spreading could help designing both OBS and MCS surveys.

- **Conjugate Crust:** A secondary priority was to survey the lithosphere conjugate to Atlantis Bank. It was suggested that if 2D MCS reconnaissance work were to be conducted, that would be an ideal opportunity to do some work in the conjugate side.

- **Down hole Seismometers and Hole-to-Hole Seismics:** These high-resolution experiments can add a great deal of information locally in the vicinity of the drill holes. Their feasibility and logistics can probably be better assessed once drilling is completed after Expedition 360 Leg 1.

- **Microseismic study:** A local seismicity monitoring could be a good way of obtaining Vp/Vs information, which is important for distinguishing lithologies that have overlapping Vp.

6.5 Non-Seismic Geophysical Surveys

High-resolution microbathymetry using AUV's and underway near-bottom geophysics (i.e., magnetics) surveys over Atlantis platform are of critical importance. This would be key to interpreting the internal structure of Atlantis Bank, such as the likely orientation of major faults and their relationships to proposed stratigraphic boundaries from drilling and seismic surveys.

Controlled-source electromagnetics (EM) could help to detect serpentinization, but is not considered as a big priority.

6.6 International Collaboration

The recommended seismic surveys are ambitious and expensive. International collaboration can spread the costs and allow pooling resources and instrumentations. For example, a 3D OBS tomography experiment that acquires data at sufficiently dense lateral sampling for waveform tomography studies will require more than 100 OBSs. Such large number is at the limit of current US national facilities (OBSIP), but it easily achievable by combining instruments from different countries such UK, France, and Germany, and in particular Japan (JAMSTEC, who operates one of the largest active-source OBS pool (~150 OBS). For 3D MCS the only platform available in academia is the US RV M. Langseth. Since it is an expensive ship, any 2D work that is deemed necessary prior to a 3D MCS survey would be better conducted in other ships of opportunity that routinely survey the southern oceans, such as the French vessel *Marion du Fresne* in conjunction with IFREMER MCS equipment. Other nations such as Japan of Britain could also take the lead in 2D reconnaissance work. For ROV deployment of OBSs, UK participants mentioned a low-cost ROV that has been used before for such operations. Finally participant nations could assist in the deployment of high-cost vessels such as RV Marcus Langseth, by paying for fuel rather than general operational costs.

6.7 Dragon Flag Survey Area.

Dragon Flag area has been surveyed with 3D OBS tomography, but not seismic reflection. Developing a competitive drilling proposal at Dragon Flag segment will require at the minimum 2D seismic reflection profiles that can image the shallow structure beneath the hydrothermal deposits (achievable with a relatively short streamer of 2-km and high-resolution source) as well as the deeper structure of the detachment fault (which would require larger-aperture streamer for deep imaging in a setting of large lateral velocity contrasts, such as 6 km or the 8-km-streamer of RV Marcus Langseth).

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US - CHINA IODP Joint Drilling Workshop
USSAC/IODP China
May 13th to 17th, 2015

Scientific Drilling in the Indian Ocean Crust and Mantle

Agenda

Day 1 Wednesday 13th

08:30 – 08:40 Henry Dick: *Introduction and Workshop Objectives*

Atlantis Bank Site Survey Data and Prior Results

08:40 – 09:10 Mathilde Cannat – *the SW Indian Ridge*

09:10 – 09:40 Jian Lin: *Evolution of the SW Indian Ridge: Hotspot-ridge Interaction, Ridge Segmentation and Crustal Accretion*

09:40 -10:10 Mike Cheadle: *Regional Tectonic Setting of Atlantis Bank*

10:10 – 10:30 Break

10:30 – 11:00 Henry Dick: *The Origin and Emplacement, of Atlantis Bank*

11:00 – 11:30 Tim Minshull: *Seismic Constraints on Crustal Structure at Atlantis Bank*, VIA SKYPE

11:30 – 12:00 M. Tivey: *Magnetic Survey of Atlantis Bank*

12:00 – 12:30 Chris MacLeod: *Local-scale Geology of Atlantis Bank: Constraints from Seabed Drilling*

12:30 – 13:30 Lunch (Buffet Clark top floor)

13:30 – 14:00 Jack Casey: *Correlation Between Core From Leg 179 Hole 1105A and Hole 735B Atlantis Bank, SW Indian Ridge*

14:00 - 14:30 Jim Natland: *Results of Prior Exploration at Atlantis II Bank*

14:30 – 15:00 Deans, Jeremy; *Reoriented High Temperature Fabrics and Textures at Atlantis Bank, SW INDIAN RIDGE: Magmatic Emplacement and Lower Crustal Flow*

15:00 – 15:30 Koepke, Juergen; *Hydrothermal Activity Triggering Partial Melting in Gabbros from Slow-spreading Ridges*

15:30 – 15:50 Break

15:50 – 16:20 Sanfilippo, Alessio; *Troctolites from the Crust Mantle Boundary, Why Should We Go So Deep?*

16:20 – 16:50 Rioux, Matthew; *High-precision ID-TIMS U-Pb Dating of Zircons from Plutonic Crust from ODP Holes 735B and 1105A, Atlantis Bank, SW Indian Ridge*

16:50 – 17:20 Beth Orcutt: *What is known about Microbiology of Ocean Crust and Mantle*

17:30 – 18:30 Reception (Top Floor Clark Laboratory)

18:30 Conference Dinner (Top Floor Clark Laboratory)

Day 2 Thursday 14th

8:30 – 9:00 Frieder Klein: *Reaction Pathways and Hydrogen Generation During Serpentinization of Seafloor Serpentinite*.

9:00 – 9:30 Matt Shrenk: *Serpentinization, Carbon, and Deep Life*

9:30 – 10:00 Pluemper, Oliver; *Low-temperature Nanocatalysis of Abiogenic Methane during Peridotite Alteration*

10:00 – 10:20 Break

10:20 – 10:50 Johnson, Kevin; *Carbonation Reaction Experiments on Olivine-rich Basalt*

10:50 – 11:20 David Smith: *Challenges and Strategies for biogeochemical Sampling*

11:20 – 11:50 Jennifer Biddle (V. Edgcomb) *Challenges of working with low biomass samples*

Drilling Objectives

11:50 – 12:10 Virginia Edgcomb* *Biological Drilling Objectives*

12:10 – 12:30 Benoit Ildefonse*: *What are the Igneous Drilling Objectives*

12:30 – 13:30 Lunch (Buffet Clark top floor)

13:30 – 13:40 Bobbie John*: *What are the Tectonic Objectives of drilling*

13:40 – 13:50 Dave Goldberg: *Down Hole Logging*

Model Site Surveys for SloMo Phase 1

13:50 – 14:20 Alastair Harding: *High-resolution Seismic Imaging of a Gabbroic Section at Atlantis Massif, MAR*

14:20– 14:50 Mladen Nedimovic: *3D MCS Imaging of Moho at the EPR*

14:50 – 15:20 Rob Dunn: *MARINER: A Multi-disciplinary Geophysical Study of a Non-transform Discontinuity and Ultramafic Massif, MAR - Rainbow Area*

15:20 – 15:40 Break

Hole Siting

15:40 – 16:30 Peter Blum: *Prior Drilling at Sites 735 and 1105 and Engineering a Deep Hole*

16:30 – 17:00 Guerin, Gilles; *Logging a Deep Hole in the Ocean Crust and Mantle*

17:00 – 17:30 Henry Dick* *Siting Hole AtBk 1*

Dinner: Participants will be provided with a list of Falmouth Restaurants

Day 3 (Friday 15th)

8:30 – 9:00 Chris MacLeod*: *Down-Hole Logging Plan*

9:00 – 9:30 Virginia Edgecomb*: *Biological Sampling*

Survey Siting

9:30 – 10:00 Pablo Canales* *SloMo Phase 1 Site Surveys*

10:00 – 10:20 Break

10:20 – 10:50 Pablo Canales* *SloMo Phase 1 Site Surveys* -continued

***Discussion leader with short presentation**

Science Planning

10:50 – 11:10 Benoit Ildefonse*: *Shore Based Studies & Access to Samples*

Contributed Talks

11:10 – 12:10 Mathilde Cannat, **Drilling Proposal**: *The Easternmost SW Indian Ridge: A Melt-poor Natural Laboratory for the Study of Ridge Processes*

12:10 – 12:30 Changgui Gao: *Melt Extraction and Mantle Source at the SW Indian Ridge Dragon Bone Amagmatic Segment on the Marion Rise*

12:30 – 13:30 Lunch (Buffet Clark top floor)

13:30 – 14:00 Marguerite Godard: *Mantle Processes and Composition of the Oceanic Crust: Lessons from Drilling at Atlantis Massif and Hess Deep*

14:00 – 14:30 Eric Ferre: *Using Fabrics to Quantify Rheological Coupling at the Oceanic Crust-mantle Boundary*

14:30 – 15:00 Tomoaki Morishita: *Gondwanaland-mantle Beneath the Central Indian Ridge*

15:00 – 15:30 Nebel, Oliver; *In-situ Formation of Indian Mantle in Global Subduction Zones*

15:30 – 15:50 Break

Dragon Flag Hydrothermal Site

15:50 – 16:00 Huaiyang Zhou: *Introduction and Workshop Objectives for the Dragon Flag Drilling Proposal*

16:00 – 16:30 John Chen: *Seismic Constraints on SW Indian Ridge Crustal Architecture from 46°-52°E*

16:30 – 17:30 Mathilde Cannat & Daniel Sauter: *Geochemical and Tectonic Evolution of the 46°-52°E Segment*

18:00 Lobster Bake, Fenno Estate Lawn

Day 4 (Saturday 16th)

8:30– 9:00 Huaiyang Zhou: *The Dragon Flag Hydrothermal Area*

9:00 – 9:30 Yang Qun Hui: *Geochemistry of the Dragon Flag Vent Fluids*

10:00 – 10:30 Susan Humphris: *Results of ODP Drilling in the TAG*

9:30- 10:00 Xiang Zeng: Biological Communities at the Dragon Flag Hydrothermal Field

10:00 – 10:20 Break

10:20 – 10:50 Maurice Tivey: Maurice Tivey: *Reduced Crustal Magnetization beneath Relic Hydrothermal Mounds, TAG Hydrothermal Mounds, Mid-Atlantic Ridge*

10:50 – 11:20: Fernando Barriga: *Manus Basin Hydrothermal Drilling*

11:20 – 11:50 Pablo Canales: *Crustal Architecture and Fault Geometry at the TAG Hydrothermal Field*

Hole Siting

11:50 – 12:30 IODP/TAMU/BRG: *Engineering for and Logging at Hydrothermal Drilling*

12:30 – 13:30 Lunch Break

13:30 – 14:00 Huaiyang Zhou: *Preliminary Drilling Plan for the Dragon Flag Hydrothermal Area*

14:00 – 14:30 Henry Dick*: *Tectonic Drilling Objectives at the Dragon Flag Hydrothermal Area*

14:30 – 15:00 Wolfgang Bach*: *Biogeochemical Objectives at the Dragon Flag Hydrothermal Area*

15:00 – 15:30 Susan Humphris* *Discussion of the Dragon Flag Hydrothermal Area Potential Drill Sites*.

15:30 – 16:00 Ciazela, Jakub; *Why Primary Copper Enrichment Could Be Expected at the Moho Transition Zone?*

18:00 – 19:30 (June 16th) Barbecue for organizing committee, report volunteers hosted by Henry & Winifred Dick at Coonamessett Bog, Hatchville.

Day 5 (Sunday)

8:30 – 9:00 Pastries & Coffee

09:00 – 09:30: Steering committee and volunteers meet to organize writing assignments.

09:30 – 12:30 Writing

12:30: Pizza lunch provided.

13:30 – 15:30 Writing

15:30 – 16:00 Wrap up group session.

Submitted Abstracts

Fernando Barriga, University of Lisbon: Manus Basin Hydrothermal Drilling

We report on difficulties and unexpected results of drilling Pacmanus, Papua New Guinea (ODP Leg 193; Binns et al, 2007). The leg was designed for drilling hard rock and massive sulfides but, in addition to this, we found all stages of wall rock alteration. We sailed with the ODP routine paraphernalia for hard rock and the (at the time) new Advanced Diamond Core Barrel (ADCB) and Hard-Rock Reentry System (HRRS).

Every effort was attempted, with the equipment available, but we met moderate success only, at two sites: 1188 Snowcap (diffuse vent area) and 1189 Roman Ruins (high temperature site). We cored a total of 736 metres with recovery of 79 metres of core (10.7% recovery). The maximum depth attained was 387 mbsf. We cased extensively (~230m), largely in Snowcap.

In a leg full of surprises, the least expected drilling operation took place in Roman Ruins. Under about 30m of fresh rhyodacite, we penetrated almost 86.9 metres in 8 hours (to a depth of 117.9m), including all necessary operations, with penetrations up to seconds/meter, and recovering ~1% of the drilled interval (small fragments of massive sulfides and deeply altered volcanic rock, abundantly cemented and partly replaced by anhydrite/gypsum and quartz). Logging While Drilling resistivity data produced variable textures of conductive material in a high resistivity matrix in a "salt and pepper" pattern.

Collectively, the above data suggest that the rock is very incoherent, probably mud with many trapped pockets of fluid. In detail, a number of possibilities are conceivable. It appears likely that the original volcanic sequence is being replaced by sulfide-anhydrite-silica assemblages, largely incoherent, with altered rhyodacite remnants. Pacmanus may a present-day analogue to a giant massive sulfide deposit in the process of formation (Barriga et al., 2004).

Barriga, F.J.A.S., Binns, R.A., Miller, D.J., and Shipboard Party, 2004. Leg 193: the third dimension of a felsic-hosted, massive sulphide hydrothermal system in a back-arc basin (PACMANUS, Papua New Guinea). 32nd Int. Geol. Congr., Florence, August 2004, T26.01

Binns, R.A., Barriga, F.J.A.S., and Miller, D.J., 2007. Leg 193 synthesis: anatomy of an active felsic-hosted hydrothermal system, eastern Manus Basin, Papua New Guinea. In Barriga, F.J.A.S., Binns, R.A., Miller, D.J., and Herzig, P.M. (Eds.), Proc. ODP, Sci. Results, 193: College Station, TX (Ocean Drilling Program), 1–71, doi:10.2973/odp.proc.sr.193.201.2007

Jennifer Biddle, University of Delaware: Challenges of working with low biomass samples

The goal of drilling an extremely deep borehole yields excitement for the deep biosphere community, as we currently aren't sure where the lower limit for life is in the deep biosphere. It seems that temperature has the greatest control on the allowance of biological activity and signatures, and 120 degrees C may be the isotherm that prevents life from continuing in the subsurface. On the way to this temperature, biomass may increase or decrease, depending on the available energy. This talk will concentrate on strategies to cope with the possibility of low biomass samples, and what challenges may lie ahead for deep biosphere research at this site.

Peter Blum and Steve Midgley, International Ocean Discovery Program, JOIDES Resolution Science Operator: Operational approach to Atlantis Bank (SW Indian Ridge) drilling, IODP Expedition 360

IODP Expedition 360, SW Indian Ridge Lower Crust and Moho (30 November 2015 - 30 January 2016) is scheduled to drill and core the first part of a deep hole into the Atlantis Bank that will eventually penetrate the Moho estimated at ~5.5 km depth. Riserless drilling operations are targeting a depth of ~3 km (multi-leg Phase I), with Expedition 360 expected to complete at least 1300 m depth at proposed site AtBk-6 in 700 m water depth. A riser vessel will be required to drill and core to the ultimate target at 5.5 km (multi-leg Phase II).

Two major holes were drilled previously in the top of Atlantis Bank: Hole 735B on Ocean Drilling Program Legs 118 (1987) and 176 (1997); and Hole 1105A on ODP Leg 179 (1998). Hole 735B is located ~3.5 km SW of target site AtBk-6, at the southwest corner of the flat surface of the Atlantis Bank platform, at 731 m water depth. It was cored to a total of 1508 m below seafloor, with 87% core recovery, all in gabbro ~11 Ma in age. Unfortunately, drill string failure near the end of Leg 176 left hundreds of meters of tubulars in the hole that could not be retrieved, leaving that hole unusable for deepening. Hole 1105A is located ~2 km S-SW of AtBk-6, in the center of the platform, at 703 m water depth. It was cored to 158 m below sea floor while waiting for supplies, with 83% recovery, also in gabbro.

The two main engineering objectives during the 42 operational days of Expedition 360 are to (1) establish a re-entry system that will support more than 30 bit runs (using the average of ~100 m per bit run on Leg 176 between 504 and 1508 mbsf); and (2) to drill and core as deep as possible in the available time.

Hole 735B deployed a re-entry system based on a hard-rock guide base (HRGB) that should keep the drill bit in place while establishing the pilot hole. Images taken through the re-entry cone of the HRGB by the ROPOS cruise in 1998 showed at least three intersecting holes at the seafloor, supporting more anecdotal suspicions that the HRGB is not a useful way of establishing a hole on a bare rock surface because it is not anchored in any way to the sea floor.

The primary approach to establishing a re-entry system during Expedition 360 will be a drill-in casing, whereby an assembly of 14 m of 13.375 casing and a free-fall funnel are drilled into the surface gabbro using a 12.25 in tri-cone bit ahead of an underreamer that widens the hole. We will have two types of underreamers available: (i) a bicentric “wobble bit” type and (ii) an arm type (with arms set to 15.375 in.). Once the casing is in place, the drill pipe with casing running tool is released from the assembly and retrieved. Two types of release tools will be available: (i) a newly developed hydraulic release tool that should minimize the risk of rotating the drill-in assembly in the hole; and (ii) a mechanical system based on pipe rotation that has been used in the past. The entire re-entry system installation process, including cementing the casing in place, is estimated to take ~2.6 days.

The drill-in casing approach has been used in five holes so far (Expeditions 352, 354, and 355), mostly into hundreds of meters of sediment. Only 5 m of igneous rock were penetrated with this system (Hole U1439B). The relative ease of gabbro coring during Legs 118, 176 and 179 promises success with the drill-in casing on Expedition 360. Should problems be encountered, alternative assemblies and deployment methods can be employed as well.

As for objective 2, to drill and core as deep as possible in the available time, two operational decisions will have to be made.

(A) We could open the hole to 12.5" diameter and run 10 3/4" casing string to ~200 m. A smooth, cased conduit in the upper part of the hole might help getting the cuttings from deep in the hole flushed out to the sea floor without degrading that part of the hole profile or taking an excessive amount of time. However, setting the casing would take up to 4 days (equivalent to up to 130 m penetration, based on Leg 176) and it is speculative to predict whether the upper hole will be or become fractured or out of shape.

(B) We could drill ahead without coring for one or more bit runs (~100 m penetration per bit run) in stratigraphic sections estimated by scientists to have already been recovered in Hole 735B. Drilling vs. coring ~100 m would save in the order of 1 day, which could be used to advance ~30-50 m deeper instead.

J. Pablo Canales, WHOI: Seismicity and Crustal Architecture Beneath the TAG Hydrothermal Field

The Trans-Atlantic Geotraverse (TAG) hydrothermal field on the Mid-Atlantic Ridge is considered a case example of basalt-hosted high-temperature hydrothermal system at slow spreading ridges. It is one of the largest sulfide hydrothermal deposits found to date on the seafloor, and includes several inactive hydrothermal deposits and an active mound discharging fluids at temperatures up to 360 °C. While the fluid temperatures indicate that hydrothermal fluids extract heat from crystallizing magma bodies, the formation of such massive deposit has been related to tectonic activity along a long-lived detachment fault. Drilling, geological and geophysical observations during the last 2 decades have provide invaluable constraints on seafloor structures, lithologies, and sub-surface structure and dynamics of this system and its enclosing spreading segment, and have paved the way for understanding other massive sulfide deposits found along the global mid-ocean ridge system.

In this presentation I will provide an overview of geophysical observations and their interpretations that have been carried out in the TAG segment, primarily those arising from the 2003-2004 STAG experiment. This experiment showed that microearthquakes in the TAG segment form a ~15 km long, dome-shaped, detachment fault surface that penetrates to depths greater than 7 km below the seafloor on a steeply dipping (~70°) interface. Seismic structure is highly asymmetric across the fault interface, suggesting that the footwall rolls over to a shallow dip of ~20° at a depth of ~3 km. Two-dimensional and three-dimensional P-wave velocity models show that the detachment footwall is composed primarily of rocks with high seismic velocities typical of lower crustal gabbros and partially serpentinized peridotites at depth as shallow as 1 km. The seismic models also contain a velocity anomaly 1.5–3.5 km beneath the active TAG hydrothermal mound characterized by relatively reduced P-wave velocities. The origin of this anomaly is unknown (elevated temperature and partial melt, serpentinized ultramafic rocks, or a highly fissured zone due to extensional stresses are all plausible mechanisms), but strongly suggests that hydrothermal circulation is present within the detachment footwall. At shallow levels, very small microearthquakes cluster within a narrow depth interval (50-125 m below seafloor) on the south and west flanks of the active mound, and are thought to result from reaction-driven fracturing events caused by anhydrite deposition in the secondary circulation system of the hydrothermal mound.

Mathilde Cannat, CNRS-IPGP: The Southwest Indian Ridge

This presentation provides an overview of spreading geometry and spreading rates along-axis the Southwest Indian Ridge, at present-day and in the past. It then presents several proxies for the degree of mantle melting and the melt supply to the ridge axis, addressing the long debated question of the respective roles of spreading rate, lithosphere thickness, mantle fertility and mantle temperature on mid-ocean ridges melt supply. What is the « normal » melt production of an ultraslow ridge?

Mathilde Cannat, CNRS-IPGP: Geochemical and Tectonic Evolution of the 46°-52°E Segment

This presentation builds largely on the work of Mendel et al. (G-cubed, 2003) and Sauter et al. (GJI, 2009). It provides an overview of the geochemical and tectonic context of the ridge axis between 49° and 52°E (ridge segments numbered 26 to 29 in Cannat et al., JGR 1999), where an extensive seismic refraction experiment has recently been carried out, and where the Dragon Flag hydrothermal black smokers field has been discovered. The regional axial depths, mantle Bouguer anomaly values, geochemical proxies for the extent of partial melting and tomographic models along the Southwest Indian Ridge (SWIR) all concur in indicating the presence of thicker crust between the Indomed and Gallieni transform faults (46°-52°E) relative to the neighboring ridge sections. Off-axis, topographic and gravity anomaly maps display pronounced outward facing topographic and gravimetric gradients that mark the outer edges of two shallow off-axis domains on the African and Antarctic plates. These anomalously shallow and thick crust off-axis domains can be interpreted as the relicts of a volcanic plateau that formed due to a sudden increase of the magma supply. This event of enhanced magmatism started in the central part of the Indomed to Gallieni ridge region and then propagated along axis to the east and probably also to the west. It did not cross the Gallieni and Indomed TFs suggesting that large offsets can curtail or even block along-axis mantle flow. The corresponding gravity anomaly suggests excess crustal thickness of the order of 1.7 km, relative to older seafloor. Magnetic anomalies suggest that this event occurred between ~8 (magnetic anomaly C4n) and ~11 Ma (magnetic anomaly C5n). Axial valley relief suggest that this enhanced magmatism is presently waning along most of the 46°-52°E region, except in ridge segment # 27, where the most recent seafloor remains anomalously shallow.

Mathilde Cannat, CNRS-IPGP: The easternmost SW Indian Ridge: a melt-poor natural laboratory for the study of ridge processes

It is now generally accepted that about 25% of the seafloor formed at slow spreading mid-ocean ridges, and a good proportion of the ocean-continent transitional domains at divergent margins, are emplaced in the footwall of exhumation faults (also called detachments). The tectonic, magmatic and hydrothermal processes associated with this exhumation (from mantle upwelling and melting in the sub-axial asthenosphere, to serpentinization and volcanic intrusions in the shallow sub-seafloor domains) are therefore part of the fundamental processes of plate tectonics.

The Mid Atlantic Ridge represents the most general case of accretion at slow spreading ridges. Exhumation there is accompanied by abundant magmatism (magmas are intrusive in the exhumed peridotites, they are injected and crystallize in fault zones and their hydrothermal alteration products facilitate deformation). The easternmost SW Indian Ridge is an exceptional and complementary end-member, which allows the study of hydrothermal and tectonic consequences of nearly amagmatic exhumation. This end-member is a plausible analog for the formation of the continent-ocean transition at many divergent continental margins. This natural laboratory offers several targets for future IODP drilling.

Jack Casey, University of Houston: Correlation Between Core From Leg 179 Hole 1105A and Hole 735B Atlantis Bank, SW Indian Ridge

Oxide-free olivine gabbro and gabbro and oxide olivine gabbro and gabbro make up the bulk of the gabbroic suite recovered from Ocean Drilling Program (ODP) Leg 179 Hole 1105A, which lies ~1.2 km away from Hole 735B on the eastern transverse ridge of the Atlantis II Fracture Zone, Southwest Indian Ridge. The rocks recovered during Leg 179 show striking similarities to rocks recovered from the uppermost 500 m of Hole 735B during ODP Leg 118. The rocks of the Atlantis platform were likely unroofed as part of the footwall block of a large detachment fault on the inside corner of the intersection of the Southwest Indian Ridge and the Atlantis II Transform at ~11.5 Ma. Lithologic, geochemical, and structural stratigraphy of the section has been analyzed in detail. Down hole lithologic variation allowed division of the core into 141 lithologic intervals and 4 main units subdivided on the basis of predominance of oxide gabbroic vs. oxide-free gabbroic rocks. Analyses of whole-rock chemistry, mineral chemistry, microstructure, and modes of over 200 samples clearly show that the gabbroic rocks are of cumulate origin. These studies also indicate that geochemistry results correlate well with down hole magnetic susceptibility and Formation MicroScanner (FMS) resistivity measurements and images. FMS images show rocks with a well-layered structure and significant numbers of fine-scale mappable layer contacts or compositional contrasts. Down hole cryptic mineral and whole-rock chemical variations depict both "normal" and inverse fine-scale variations on a scale of 10 m to <2 m with significant compositional variation over a short distance within the 143-m section sampled. A Mg# shift in whole-rock or Fo contents of olivine of as much as 20–30 units over a few meters of section is not atypical of the extreme variation in down hole plots. The products of the earliest stages of basaltic differentiation are not represented by any cumulates, as the maximum Fo content was Fo78. The extent of fractionation represented by the gabbroic rocks and scarce granophyres in the section, however, is much greater than that represented in the Atlantis II basalts. The abundance of oxide gabbros is similar to that in Hole 735B, Unit IV, which is tentatively correlated as a similar unit or facies with the oxide gabbroic units of Hole 1105A. Oxide phases are generally present in the most fractionated gabbroic rocks and lacking in more primitive gabbroic rocks, and there is a definite progression of oxide abundance as, for example, the Mg# of clinopyroxene falls below 73–75. Coprecipitation of oxide at such early Mg#s cannot be modeled by perfect fractional crystallization. Evolved melt migration or in situ boundary layer fractionation could offer explanations for the complex juxtaposition of oxide- and non oxide-bearing more primitive gabbroic rocks. The geochemical signal may, in part, be disrupted by the presence of mylonitic shear zones, which strike east-west and dip both to the south and north, but predominantly to the south away from the northern rift valley where they formed. Down hole deformation textures indicate increasing average strain and crystal-plastic deformation in units that contain oxides. Oxide-rich zones may represent zones of rheologic weakness in the cumulate section along which mylonitic and foliated gabbroic shear zones nucleate in the solid state at high temperature, or the oxide may be a symptom of former melt-rich zones and hyper solidus flow, as predicted during study of Hole 735B.

Michael J. Cheadle, Barbara E. John, University of Wyoming, A. Graham Bines, Neftek Petroleum Consultants, Joshua J. Schwartz, California Sate University, Northridge: Regional Tectonic Setting of Atlantis Bank

Atlantis Bank is an oceanic core complex on the Antarctic Plate ~100km south of the axial valley of the ultraslow-spreading SW Indian Ridge (SWIR), between the Atlantis II Transform fault at ~57°05′E and a fracture zone associated with a non-transform discontinuity at ~57°40′E. It is an ~40km by 20km bathymetric high, elongate in the N–S direction that has a wave-cut platform that shallows to 690m depth. With almost 3km of anomalous elevation, Atlantis Bank forms the northernmost peak of a 130km long transform parallel transverse ridge whose anomalous uplift averages 1.5km. Atlantis Bank formed between ~13.2 to 10.6 Ma, and the detachment fault bounding Atlantis Bank slipped at a rate of 14.1+1.8/-1.5km/Myr. At this time, the full-spreading rate of the SWIR increased from the average of 14km/Myr to ~17km/Myr for ~2.3Myr, and so ~80% of the plate-motion was accommodated by detachment faulting. Consequently the detachment fault effectively became the plate boundary between the Antarctic and Somalian Plates. The majority of the extension in the upper lithosphere was accommodated by detachment faulting with only 20% of the extension accommodated by magmatic diking. The detachment fault likely rooted in a zone of magmatic accretion in the lower–middle lithosphere below which extension was primarily accommodated by magmatic intrusion, and ductile deformation and upwelling of mantle.

Atlantis Bank likely formed as a consequence of changes in plate spreading rate and direction. At 40Ma, a ~35^o clockwise rotation in plate spreading direction increased the overall obliquity of the SWIR to the plate-spreading direction, leading to second order (~75km wide) ridge segmentation. Subsequently, asymmetric spreading and the growth of large transform faults (e.g. the Atlantis II Transform Fault) at the expense of adjacent spreading parallel ridge offsets led to the rotation of the 450km wide first order spreading segments to become more orthogonal to spreading. The initiation of oceanic detachment faulting at Atlantis Bank was likely influenced by a combination of kinematic factors; specifically i) the asymmetric spreading associated with this long-lived evolution of the plate-boundary geometry, ii) the short-lived regional increase in full-spreading rate, and iii) Atlantis Bank's proximity to the growing and weak Atlantis II Transform fault, which was undergoing transtension following a second ~10^o anti-clockwise rotation in plate-spreading direction ~20Ma. Locally increased magmatism may also have played a role.

The anomalous uplift of Atlantis Bank was also likely due to a combination of factors including: i) flexural uplift of up to 800m due to detachment faulting, ii) additional flexural uplift of up to 1200m following the period of transtension on the Atlantis II Transform Fault due to the second change in spreading direction at ~20Ma, and iii) likely off axis magmatism ~2.5Myr after initial crystallization/formation of the Bank.

Y John Chen, Peking University: Seismic Constraints on SW Indian Ridge Crustal Architecture from 46°-52°E

The oceanic crust is formed by a combination of magmatic and tectonic processes at mid-ocean spreading centers. Under ultraslow spreading environment, however, observations of thin crust and mantle-derived peridotites on the seafloor suggests that a large portion of crust at ultraslow spreading ridges is formed mainly by tectonic processes, with little or absence of magmatism. Using three-dimensional seismic tomography at an ultraslow spreading Southwest Indian Ridge segment at 50.47°E, we discovered an extremely magmatic accretion of the oceanic crust. Our results reveal a low velocity anomaly (-0.6 km/s) at 4-8 km depth beneath the seafloor in the lower crust suggesting the presence of partial melt, which is accompanied by an unusually thick crust (~9.5 km), the thickest ever observed along mid-ocean ridges. We also observe a strong along-axis variation in crustal thickness from 9.5 to 4 km within 30-50 km distance, requiring a highly focused melt delivery from the mantle. We conclude that the extremely magmatic accretion is due to localized melt flow towards the center of the segment, which was enhanced by the significant along-axis variation in lithosphere thickness at the ultraslow spreading Southwest Indian Ridge.

Jakub Ciazela, Adam Mickiewicz University, Juergen Koepke, Leibniz University Hanover, Roman Botcharnikov, Adam Mickiewicz University, Henry Dick, Woods Hole Oceanographic Institution, Andrzej Muszynski, Adam Mickiewicz University, Thomas Kuhn, Leibiz University Hanover: Why primary copper enrichment could be expected at the Moho level?

Highly increased chalcophile element concentrations in harzburgites which underwent interaction with MORB melts in comparison to normal abyssal harzburgites have been observed from the Kane Megamullion oceanic core complex (OCC; Mid-Atlantic Ridge, 23°30’ N; Ciazela et al. 2014). Ciazela et al. 2015 quantified the Cu enrichment based on the bulk rock analyses of plagioclase peridotites and a contact zone between mafic vein and hosting mantle, obtaining a four times higher concentration in the former and a nine times higher concentration in the latter with respect to unaffected spinel harzburgites (36 ppm Cu). Here, we provide a hypothesis for this enrichment, based on the S determination of bulk samples, and the in situ microscopy and electron microprobe (EMPA) analyses of two contact zones between mafic veins and host peridotites.

We determined the S concentrations in six mantle samples from the Kane Megamullion oceanic core complex that interacted with mafic melt. The Cu and S concentrations correlate well (r=0.95) for this set of the samples. This implies that sulfides are the main phases concentrating Cu and probably other chalcophile elements. Moreover, we investigated by in-situ methods two thin sections containing peridotites that exhibit distinct contact zones (8 and 15 mm wide) adjacent to gabbroic veins. By using reflected light microscopy, we have estimated the density of large (>40 μm) sulfides in the contact zones that is ~3.3 grains/cm2, whereas it is only ~0.3 grains/cm2 in the background peridotite. No large sulfide occurs in the gabbro vein. A similar analysis for the medium (10-40 μm) sulfides shows they are more common but similarly distributed, with densities of ~6.0 grains/cm2, ~1.5 grains/cm2 and ~0.7 grains/cm2, respectively. Subsequently, we performed the EMPA mapping of selected areas (1 cm2) crossing the contact zones in both thin sections. Based on S distribution in the given areas, we have discovered that the density of small (<10 μm) sulfides overcomes the density of large and medium sulfides, and the main crystallization front of the sulfides is ~ 3 mm wide, and is located on the margins of the contact zones adjacent to the mafic veins. A similar pattern of sulfide distribution was observed in an experiment performed under high pressure (2 kbar) and high temperature (1150 °C) in an internally heated pressure vessel, using a sulfur-saturated basaltic melt which was filled in an capsule of olivine (olivine from San Carlos; Fo. 90). Most of sulfides (~90%) in the experimental product crystallized at the contact of the basaltic glass adjacent to olivine capsule material.

The narrow sulfide crystallization fronts observed in the two thin section represent an example of a small-scale melt/rock interaction at the margins of local melt channels transporting MORB-type melt during its ascent through the lithospheric mantle. However, we suppose that this process may also operate on a broader scale, considering that the Cu concentration in 14 dunites from the Kane Megamullion area is 118 ± 17 ppm Cu (1σ; Ciazela et al. 2014), which is four times higher than that found in the associated spinel harzburgites. Dunites are usually formed Page 11 of 38 due to reaction of mantle and MORB melts during their ascent through the lithosphere. That this processes may be of broader significance is indicated from observations in the Samail ophiolite in the Sultanate Oman. Here, some dunites, preferentially found in the up to several hundred meter thick Moho transitions zone, are associated with ancient copper deposits. At least 12 sites of ancient Cu excavations have been found throughout this zone (Boudier, personal communication). Although Cu has partially been redeposited in secondary processes, the data from our study and the characteristic distribution of the ancient mining sites imply that the first stage of Cu enrichment could be a primary magmatic process. The upcoming SlowMo project gives us a unique opportunity to verify this hypothesis.

Ciazela, J., Dick, H., Koepke, J., Kuhn, T., Muszynski, A., & Kubiak., M., 2014. Mantle-crust differentiation of chalcophile elements in the oceanic lithosphere. Abstract V31B-4756 presented at AGU Fall Meeting, San Francisco, Calif., 15-19 Dec.

Ciazela, J., Dick, H., Koepke, J., Botcharnikov, R., Kuhn, T. & Muszynski, A., 2015. Cu refertilization of harzburgites by melt percolation. Geophysical Research Abstracts 17, 1044.

Jeremy Deans, Texas Tech University: High temperature fabrics and textures at Atlantis Bank, SW INDIAN RIDGE: A window into the lower oceanic crust

Current models of slow-spreading ridges assume that magmatic and crystal plastic fabrics recorded the onset of extension by a large scale, normal sense detachment shear zone. However, there are no existing geometrical constraints on the geographic orientation of high temperature fabrics. We present new microstructural data and geographically-reoriented fabric results from two slow-spreading oceanic core complexes to a) further constrain the onset of detachment shearing and magma emplacement, and b) constrain formation processes of the lower oceanic crust. High temperature fabrics were re-oriented to the ridge reference frame by correlating structural measurements of fractures in the core (and, therefore, fabrics in the core) and fractures in the borehole wall identified using the Formation MicroScanner (FMS) logging tool. Four ODP/IODP Holes at core complexes meet the necessary requirements to reorient high temperature fabrics: Holes 735B and 1105A from Atlantis Bank, SW INDIAN RIDGE and 1309B and 1309D from Atlantis Massif, MAR.

The Atlantis Bank and Atlantis Massif are bathymetric highs with lower crustal and upper mantle rocks exposed by a currently low angle detachment fault. Both complexes have been sampled by ODP/IODP drilling, submersible dives, and dredging. The Atlantis Bank was drilled by three ODP Legs over two holes, Holes 735B is 1.5 km deep and 1105A is 160 m deep. Both Holes recovered ~90% with rocks ranging from olivine gabbro to oxide gabbros. The Atlantis Massif was drilled by two IODP Legs with two main holes, Holes 1309B is 102 meters deep and 1309D is 1.4 km deep with recoveries of ~50% and ~75% respectively. The rocks recovered range from troctolite to oxide gabbro. All rock types recovered at both complexes have magmatic and crystal plastic fabrics. Fabrics were reoriented in Hole 735B over the interval of 90-600 mbsf and in Hole 1309D over the interval 98-380 mbsf by Morris et al. (2009).

The reorientation results suggest that the fabrics at Atlantis Bank and Atlantis Massif have no systematic orientation at any depth and/or with fabric intensity. This is in contrast to the prediction that all deformation recorded by high temperature fabrics were caused by detachment shearing. This result must be reconciled with the presence of other complications, such as, mylonites at depths greater than a km below the detachment surface; the deformed greenschist grade detachment zone; and rotations of the complexes on the order of 45o below the Curie temperature (e.g., Garces and Gee, 2007). Considering these results paired with textural observations (e.g., undulose olivine in an undeformed sample) suggests that the lower oceanic crust was built over time with most of the fabrics at depth forming either due to emplacement processes (e.g., ballooning) and/or rheologic contrasts between units. Higher temperature deformation was distributed throughout the crust until lower temperature, when extension was localized to form the detachment shear zone.

Henry J. B. Dick, Woods Hole Oceanographic Institution: The Origin and Emplacement of Atlantis Bank

Atlantis Bank (Fig. 2) is located in the southern rift mountains of the SW Indian Ridge (~14 mm/yr). It borders the 200-km offset Atlantis II Transform, ~80 km south of the ridge axis in ~10.7 to 14.5 Ma old crust. The bank represents the most magmatically robust formation of an oceanic core complex known to date. The pre-detachment crustal section, including the original carapace of pillow lavas and sheeted dikes, appears to have been ~4-6 km thick (Dick et al., 2000). The SW Indian Ridge is in many ways transitional between slow-spreading ridges like the Mid-Atlantic Ridge and the Gakkel Ridge, illustrating the importance of magma supply as opposed to spreading rate in determining local ridge morphology. While much of the SW Indian Ridge exhibits radically different tectonics from the mid-Atlantic Ridge; due in part to its highly oblique trend to the plate spreading direction, Atlantis Bank lies in a section that more closely resembles typical Mid-Atlantic Ridge geomorphology consisting of near orthogonal spreading segments and transforms.

The Atlantis Bank Oceanic Core Complex consists of a ~40 km long by 30 km wide dome rising from ~5700-m depth at the base of the transform wall to ~700-m depth, where there is a 18 km2 wave cut platform, before dropping down to ~4,300 m on its eastern flank. It is an enormous single-domed core complex representing continuous extrusion of gabbro onto the seafloor for 3.7 m.y on a plutonic growth fault (oceanic low-angle detachment fault). Post-detachment North-South normal faulting, uplifted Atlantis Bank to as much as 1-km above sea level (Palmiotto et al., 2013) during a 12 m.y. period of transtension initiated by a 10° change in spreading direction around 19.5 Ma, creating an ocean island prior to subsiding to its present depth (Baines et al., 2003; Dick et al., 1991}. Partially serpentinized massive mantle peridotites have been sampled below massive gabbro along the western wall of the core complex for some 36 km, which lies some 5-6 km above the Moho determined by Minshull and co-workers (Muller et al., 2000; Muller et al., 1997).

The original smooth undulating detachment fault surface is preserved over large regions of the bank. The fault damage zone and underlying gabbros are well exposed by the high-angle normal faulting on the eastern side of the complex, in headwalls of large landslips on the western flank, and on the wave cut platform on the top of the bank. Sampling on the detachment fault surface and in the damage zone in the underlying footwall shows that it consists largely of foliated oxide gabbro interspersed with deformed and undeformed olivine gabbro enclaves and amphibolites lying parallel to the detachment footwall. Locally there is well-preserved chloritized and weathered fault gouge formed in the brittle regime in less eroded areas. Talc-serpentine schists are found on the footwall overlying the gabbro, and appear to represent a discontinuous remnant of serpentinite intruded along the detachment fault from the transform, then exposed by uplift into the rift-mountains.

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Robert Dunn, University of Hawaii: MARINER: A multi-disciplinary geophysical study of a non-transform discontinuity and ultramafic massif, MAR - Rainbow Area

The MARINER experiment was designed to examine the relationship between tectonic rifting, heat/melt supply, and oceanic core complex formation along the Mid-Atlantic Ridge, 36˚N, the site of the Rainbow core complex and hydrothermal system. The experiment consisted of a 3D active-source seismic tomography experiment using ocean bottom seismographs (OBS), a multi-channel seismic experiment, a 9-month OBS seismicity study, and seafloor acoustic, gravity field, and magnetic field mapping. The study covered four segments of the MAR and was centered at Rainbow. For the tomography experiment, we deployed 46 OBS in a grid pattern and shot twenty-six seismic lines using the Langseth's 36-element source. Seismic imaging shows that across regions of the study area not including Rainbow, the crust is about 4 km thick on average and is composed of an upper shallow surface layer about 2 km thick with very low P-wave velocities, indicative of a densely cracked and porous region, and a lower layer of material consistent with a gabbroic lower crust. The transition from crust to mantle is gradual. Beneath the ridge axes there is scant evidence for the high-temperature and melt containing regions found along faster spreading ridges. Beneath the Rainbow massif, the low-velocity surface layer is thinner and relatively higher-velocity than elsewhere, consistent with a densely cracked and altered layer of mixed ultramafic and gabbroic material. Seismic wave speeds beneath the surface layer rapidly increase to mantle-like values. These observations are consistent with the massif having a mostly unaltered mantle core. Along the ridge axes neighboring the Rainbow massif, seafloor spreading produces widely spaced large-offset faults in addition to closer-spaced smaller faults. The seismic tomography images reveal undulations in crustal structure and thickness in these areas that closely correspond to the spacing of the major faults and appear to be large rotated crustal blocks, with Rainbow being an extreme version of this pattern. Seismic anisotropy is observed in the low-velocity surface layer, where it can arise from stress-aligned cracks and hydrofracturing. Images of anisotropy reveal a broad semi-circular region of heavily cracked lithosphere surrounding the Rainbow massif that focuses upwards to a narrow chimney below the Rainbow vent field, potentially indicating the recharge and discharge zones for hydrothermal circulation. Patterns of seismicity correlate with this high-anisotropy region. There is no significant high-temperature region or magmatic system beneath Rainbow. Instead, the heat source for the vents may be small shallow melt lenses intruded below the massif. A great strength of the MARINER study is its multi-component nature and the joint interpretation of the different datasets that greatly enhance our understanding of the system as a whole. The MARINER study can serve as a model for a future similar study at the SW Indian Ridge drilling site.

Dr. Virginia Edgcomb, Woods Hole Oceanographic Institution, Biological Drilling Objectives

Two microbiologists designated to participate on Expedition 360, Jason Sylvan and Virginia Edgcomb will focus their efforts on collection of samples appropriate for downstream biogeochemical studies of microbial communities within lithologies encountered during drilling. These lithologies may include olivine-rich gabbros hosting serpentinization. Microbiota in such samples are interesting for understanding life below the seafloor, as well as exobiology and origin of life questions. We will aim for collection of samples from all lithologies recovered, and our priority will be to collect contamination-free rocks for determination of biomass, diversity, activity, and selected metabolic rates for the microbial communities found within those rocks. Our sampling goals and anticipated approaches will be briefly outlined, leaving time for feedback from Workshop participants on these, as well as input as to how we might best serve the broader community of researchers interested in potentially pursing additional biogeochemical investigations using samples that we process and preserve for post-cruise studies.

Eric Ferre, Southern Illinois University: Using fabrics to quantify rheological coupling at the oceanic crust-mantle boundary

The Plate Tectonics theory assumes a strong rheological coupling between the two mechanical layers that form the oceanic lithosphere. Yet, some lower crust gabbros exhibit a surprisingly strong fabric (e.g., anisotropy of magnetic susceptibility) of ambiguous origin. Here, I will review a few case studies highlighting the nature of these magmatic and solid-state fabrics as well as genetic hypotheses. Also, the lattice-preferred orientation (LPO) of uppermost oceanic mantle peridotites appears, in some cases, stronger than predicted. These combined observations favor a clutch rheological model in which strain localizes along the crust-mantle boundary. I will discuss the evidence supporting this model and explain how the SW Indian Ridge might be an ideal location to test this unconventional tectonic clutch hypothesis.

Changgui Gao, WHOI: Melt Extraction and Mantle Source at the SW Indian Ridge Dragon Bone Amagmatic Segment on the Marion Rise

This work examines the trace and major element compositions of spatially associated basalts, gabbros and peridotites from a single amagmatic ridge segment at 53°E east on the ultraslow spreading SW Indian Ridge. This provides a unique perspective on mantle source composition, as well as on melting and melt extraction, consistent with an earlier geologic model for support of the Marion Axial Rise by buoyant upper mantle rather than a hot fertile mantle plume (Zhou & Dick, 2013). The Dragon Bone basalts, except for large U and Pb spikes, have similar patterns to normal depleted middle ocean ridge basalts. The shape of the rare earth element patterns do not match those predicted for the pre-alteration Dragon Bone peridotite compositions, but can be modeled by about 5 to 10% non-modal batch equilibrium melting of a DMM source. Highly variable Fe8.0 contents are likely the result of plagioclase and olivine phenocryst accumulation. The Na8.0 contents lie at the low end for SW Indian Ridge basalts, consistent with a location high up the Marion Rise, and the refractory composition of the spatially associated peridotites.

The peridotites are clinopyroxene-poor harzburgites. Most samples, however, show higher than expected incompatible element abundances, some with positive Ce and Eu anomalies. This is attributed to variable hydrogenous manganese contamination, refertilization by basaltic melts, and/or hydrothermal fluids. Spinel chromium numbers, however, lie in the middle of the range for abyssal peridotites. Thus, the composition of the Dragon Bone peridotites would seem to lie within the range of normal abyssal uppermost mantle. Their low calcium and alumina whole rock compositions, however, indicate a pyroxene-poor mantle source composition very different and less fertile than those for primitive upper mantle or DMM.

The least contaminated Dragon Bone peridotites were best modeled by fractional melting. This requires ~ 7% fractional melting in the garnet stability field, followed by an additional ~12.5 to 13.5% in the spinel stability field of a DMM and primitive upper mantle source, respectively. For peridotites exposed in an amagmatic ridge segment, such extensive melting suggests that they were previously depleted by an earlier event predating the ridge event. Given their pyroxene-poor composition, the latter was likely a hydrous melting event, as wet melting depletes pyroxene faster than dry. Thus, the garnet-field event likely occurred during the formation of an arc terrain and the assembly of Gondwana. Following breakup at ~184

Ma, the underlying previously depleted Gondwanan mantle then became the source for SW Indian Ridge volcanism.

Marguerite Godard, Géosciences Montpellier: Mantle processes and composition of the oceanic crust: Lessons from drilling at Atlantis Massif and Hess Deep

The oceanic crust is the magmatic product of adiabatic melting of the upwelling mantle at oceanic spreading ridges. It's varying architecture along slow to fast spreading centers, from heterogeneous to layered, reveals the impact of mantle magma fluxes but also of tectonics and hydrothermal cooling on the genesis of the oceanic crust. These coupled mechanisms could possibly affect the bulk composition of the crust. Over the last decades, several drilling expeditions allowed to sample sections of the gabbroic slow spread crust (IODP Site U1309; Atlantis Massif, Mid-Atlantic Ridge) as well as fast spread crust (IODP Site U1415, Hess Deep). Bulk rock analyses of drilled samples are used to calculate bulk crust compositions at these sites and discuss magma plumbing systems and the possible impact of melt transport and melt-rock interaction processes in these different tectonic environments on the composition of the oceanic crust.

Dave Goldberg, Natalia V. Zakharova, Lamont-Doherty Earth Observatory, Borehole Research Group: Advances in downhole logging for ocean crustal studies

Recently, significant advancements in downhole logging technology, far beyond the previous standard, are now possible on IODP expeditions. New measurements of particular interest to crustal studies include: nuclear magnetic resonance (NMR) logging for direct measurement of pore structure and bulk permeability, wireline formation testing (MDT) to measure formation pressure and recover in situ fluid samples, and improved formation electrical imaging (FMI) with twice the borehole coverage for better core orientation and fracture detection. These measurements have never been acquired in the ocean crust and could greatly improve our understanding of the structural context and nature of fluid exchange in this environment. To use these tools however, a larger-diameter (6.675") drill pipe conduit must be deployed from the rig floor and a seafloor funnel must be lowered for re-entry into the borehole. In water depths of 3000 m, these activities require approximately 1.25 days of additional logging operations time. New rig floor handling equipment was acquired from Blohm & Voss, GmbH and tested on the JOIDES Resolution in 2014. Using these state-of-the-art technologies during future IODP expeditions will undoubtedly provide new data to test models of the deformation, the structure of the oceanic crust, and the nature of fluid exchanges between the crust and the ocean.

Gilles Guerin, Lamont-Doherty Earth Observatory, Borehole Research Group: Logging a Deep Hole in the Ocean Crust and Mantle

One of the challenges of deep crustal drilling is the elevated temperature that can be encountered in the process of reaching the target depths. The intense pumping of surface water during drilling, used primarily to remove the cuttings, keeps the borehole temperature within reasonable range for the coring tools. However, as soon as drilling and circulation stop, temperature at the bottom of the hole starts recovering towards the formation temperature. While full recovery of the borehole water to thermal equilibrium with the formation can take up to several years, temperature in the deepest part of the hole can rapidly exceed the range of many logging tools. Most logging tools used in scientific ocean drilling can't withstand temperatures above 150C, and some of them have even lower operating range. Depending on the depth of the hole, on the formation temperature and on the number of logging deployments, it becomes necessary to develop strategies to be able to acquire the most critical measurements. Several remediation strategies have been used in the past than can help achieve the objectives of any future deep hole.

Alistair Harding, Scripps Institution of Oceanography: High-resolution Seismic Imaging of a Gabbroic Section at Atlantis Massif, MAR

Oceanic core complexes are an attractive target for high resolution imaging with the refraction arrivals of multichannel seismic (MCS) data. Their relatively shallow depth means that continuous, dense refraction coverage to depths of 1-2 km below the seafloor can be achieved with a 6km-long-streamer, and this dense coverage can be used as the basis for full waveform inversion (FWI) to produce accurate velocity models. Conventional travel-time tomography models based on OBS refraction coverage can resolve the average velocity structure but not the finer scale details. Streamer tomography, by using 1-2 order of magnitude more travel times from the MCS data, improves resolution of the upper crust, but only waveform inversion fully determine the large vertical and horizontal velocity gradients. The FWI models resolve the detachment damage zone at the surface of the footwall, as well as steep shallow contacts between gabbros and serpentinized peridotite.

Atlantis Massif is an attractive location to compare and ground truth the FWI models as it has been the site of a wide variety of seismic experiments, including standard and on-bottom OBS refraction, as well as vertical seismic profiling and down hole sonic measurements at IODP Hole 1309D, which extends 1.4 km into the Central Dome of the Massif. The FWI models closely match both the on bottom data and the down hole velocity profiles, and indicate that a two zone structure of detachment related damage can be extrapolated across the gabbroic Central Dome.

The FWI models by resolving the upper 1-2 km of crustal structure at Atlantis Massif have captured most of the large velocity variations and thus can be used as the basis for prestack depth migration. We will present & discuss depth migrated images of the MCS lines from Atlantis Massif, which indicate that the thickness of the gabbroic core of the Central Dome is 2.5-3 km.

Julie Huber, Marine Biological Laboratory: Using CORK observatories to sample subseafloor life in cold, hydrologically active oceanic crust

The cold, basalt-hosted, oceanic crustal aquifer is one of the largest ecosystems on Earth, yet little is known about its indigenous microorganisms. Recently installed subseafloor observatories on the western flank of the Mid-Atlantic Ridge penetrate hundreds of meters into the crust and provide an unprecedented opportunity to investigate microbial life in this understudied realm. Here, we present the first description of an active microbial community in fluids from the oxic crustal aquifer beneath North Pond, a ~200-m-thick sediment-filled basin overlying relatively young basaltic crust (8 Ma). Surprisingly, the major geochemical constituents in the formation fluids showed little differentiation from deep seawater. Moreover, microbial biomass in fluids from multiple depth horizons of the subseafloor observatory was similar to deep seawater (ca. 1 x 104 cells•ml-1) and dominated by Proteobacteria. However, 16S rRNA Illumina sequencing showed that while there was considerable overlap in the identity of taxa in the formation fluids and in the bottom seawater, the relative abundances of different groups reveal a distinct formation fluid bacterial community structure, which included Colwellia, Acidiferrobacter, and Sulfurimonas, likely seeded from deep seawater, basaltic rocks, and marine sediment, respectively. Finally, incubations of basaltic formation fluids with 13C-labeled bicarbonate or acetate at 5°C and 25°C revealed that potential rates of autotrophy could exceed those of heterotrophy by an order of magnitude. Collectively, these data reveal that while both heterotrophic and autotrophic microbes are present in cold, oxygenated aquifers, this environment may be selective for autotrophic lifestyles due to the scarcity of organic carbon.

Susan Humphris, Woods Hole Oceanographic Institution: Results of ODP Drilling in the TAG

In 1994, ODP Leg 158 drilled the TAG active hydrothermal mound at 26°08'N on the Mid-Atlantic Ridge – one of the largest sites of high-temperature hydrothermal activity and mineralization found to date on the seafloor. The objective of the expedition was to drill through the hydrothermal deposits and into the underlying stockwork down to a depth of at least 500 m. Drilling the sulfide mound proved technically challenging: the holes were unstable with frequent cave-ins, the cuttings were difficult to remove requiring frequent heavy mud sweeps, and the sulfide sands tended to clog the tools. This resulted in a series of 17 short holes being drilled in the 150-m diameter hydrothermal mound, with one hole to 125 mbsf reaching into the upper part of the underlying stockwork. Poor core recovery (ranging from <1 to 63%, with an average of 12%) meant that a great deal of textural, structural, and boundary information was not recovered. Despite this, the expedition was extremely successful and the internal anatomy of a seafloor hydrothermal deposit was revealed for the first time. The TAG active mound exhibits a classic volcanogenic massive sulfide (VMS) structure of a stockwork zone connecting to a sulfide lens. One of the most striking features of the entire section is the dominance of breccias composed of mixtures of clasts of various types (e.g.: sulfide, silicified wall rock) that formed by different processes at different depths. Construction of the deposit is interpreted to be episodic, and involves a combination of sulfide accumulation at the seafloor, significant subsurface entrainment of seawater and precipitation of anhydrite (and pyrite and chalcopyrite), and hydrothermal replacement, mineralization, and zone refinement during periods of activity. This is followed by collapse due to dissolution of anhydrite, mass wasting, and brecciation during periods of inactivity. Overall, ODP Leg 158 demonstrated that, despite the many technical challenges encountered during drilling the TAG active mound, major scientific advances can be made drilling into seafloor hydrothermal

systems.

Kevin Johnson, University of Hawaii: Carbonation Reaction Experiments on Olivine-rich Basalt

Secondary carbonation reactions involving igneous minerals and CO2-rich fluids are common in nature, but are optimized under specific P-T-X and redox conditions. By studying the conditions that optimize the kinetics of these reactions we can utilize these natural alteration processes to stably store anthropogenic carbon dioxide in deep geologic formations on geologic timescales. Basalt formations, which are globally widespread, are currently being considered as a long-term CO2 storage option. Because fossil fuel combustion streams often contain other detrimental gases (e.g., SO2, NOx, CO), it is also important to consider gases that could be co-injected with CO2. At depths greater than 800 m, these CO2 gas mixtures will reside as hydrous supercritical fluids in contact with the basalt reservoir rocks. Here we examine reaction products resulting from exposing Hawaiian olivine-rich basalts (picrites) to water equilibrated with super critical CO2 (scCO2), water bearing scCO2, and mixtures containing gaseous sulfur compounds. Hawaiian basalts in this study were fresh, vesicular, and olivine-rich (20+vol% olivine). Basalts, both crushed and in large pieces, were exposed to hydrous scCO2 fluid or water equilibrated with scCO2, for 80 to 550 days at 100 bar and 50°-100°C. Basalts exposed to pure scCO2 showed the least reactivity. Water equilibrated with supercritical scCO2 and reacted with olivine grains for 550 days formed discrete circular carbonate coatings on the olivine grain surfaces. In mixed gas experiments, the olivine surface was significantly altered in just 80 days after exposure to wet scCO2 containing 1% SO2. The most reactive basalt components were olivine grains, with surfaces dominated by cracks and precipitates of Mg-S compounds. Chemistry determined by SEM-EDS indicated the cracked surface was depleted in Mg and rich in Si. Minor amounts of sulfur were detected in this leached layer as well. Exposed olivine interiors were found to have the original olivine chemistry. Surface precipitates associated with the olivine crystals include hexahydrite (MgSO4•6H2O), magnesium thiosulfate hydrate (MgS2O3•6H2O), along with three different hydrated sulfite phases. These types of experiments illustrate the potential that basalt formations hold for long-term storage of CO2 and the importance of understanding supercritical phase chemical reactions involved in geologic carbon sequestration.

Frieder Klein, WHOI: Reaction pathways and hydrogen generation during serpentinization of seafloor serpentinite

Serpentinization of olivine-rich rocks is a widespread process in seafloor environments with important implications for microorganisms of the deep biosphere. Key to our understanding of geosphere-biosphere interactions in serpentinization systems is the generation of hydrogen. Hydrogen production varies as a function of protolith composition, temperature, and dissolution kinetics of primary minerals. The latter is poorly understood but appears to have a fundamental impact on reaction pathways, particularly the formation of brucite, magnetite, and hydrogen. The rate of serpentinization, and thus hydrogen generation, is not only a function of temperature, it is also largely impacted by hydrodynamic factors such as changes in permeability. Evidence from hydrothermal experiments indicates that the permeability decreases substantially after short periods of time. As a consequence, reaction progress becomes increasingly diffusion-controlled unless fracturing occurs to create new fluid pathways. Fracturing of serpentinite due to thermal contraction, tectonic forces and/or volume expansion (reaction-driven fracturing) may therefore play a key role in the rate of hydrogen supply for microorganisms and abiotic organic synthesis in subseafloor environments.

Juergen Koepke, Leibniz University Hannover: Hydrothermal activity triggering partial melting in gabbros from slow-spreading ridges

In more than 100 gabbros showing typical late-stage crystallization including pargasitic amphibole from MAR (Mid-Atlantic Ridge) and SWIR (SW Indian Ridge) we found microstructures suggesting that hydrous partial melting reactions proceeded. The petrographical record of the underlying reaction is expressed by plagioclase strongly enriched in anorthite formed in zones along grain boundaries coexisting with pargasite ± orthopyroxene. The composition of the new An-rich plagioclase is strongly impoverished in incompatible trace elements excluding a model that these An-rich zones were precipitated by late, hydrous evolved melts. In-situ analysis of such zones of An-rich plagioclases at the grain boundaries using femtosecond LA-ICP-MS evidenced that the water-rich fluids are seawater-derived, suggesting a model that hydrothermal activity/circulation within the deep oceanic crust may trigger hydrous partial melting.

Since only some percent of the gabbroic host rock undergo hydrous partial melting, while the majority of the rock remains unchanged, the amounts of melts generated are very small. For the fate of the generated melts, which were never observed to be frozen in-situ, there are two possibilities: (1) The felsic melts generated in a ductile regime may segregate / migrate into zones with less-pronounced deformation where they may crystallize and form typical trondhjemitic veins. (2) Small amounts of melt could be dissolved in the water-rich fluid migrating on grain boundaries and transported away.

In order to understand the principle reaction mechanism of hydrous partial melting of gabbro in detail, we performed water-saturated partial melting experiments with mm-sized blocks of unmodified olivine gabbro ("microrocks") as starting material using an internally heated pressure vessel. The use of a coarse-grained starting material allows us to study the principle reaction mechanism of hydrous partial melting of oceanic gabbro in detail. One significant textural feature of the discontinuous hydrous partial melting reaction is that the reaction products form two different domains dislocated from each other: (1) the formation of anorthite-rich zones on plagioclase/plagioclase grain boundaries, and (2) interstitial growth of orthopyroxene and amphibole around primary mafic minerals. The same systematics we observed in the natural gabbros from MAR and SW INDIAN RIDGE: The grain boundaries between primary plagioclases are characterized by zones of anorthite-rich plagioclase, while the mafic primary minerals show reactive rims of "interstitial" pargasitic amphibole and orthopyroxene. The observed features imply a model on hydrothermal activity at very high temperatures (850–950°C), proceeding on grain boundaries within the deep oceanic crust without any crack system, a prerequisite in current models for enabling hydrothermal circulation.

Jian Lin, Woods Hole Oceanographic Inst., Jennifer Georgen, Old Dominion University, Tao Zhang, Second Inst. of Oceanography, Hangzhou China: Evolution of the SW Indian Ridge: Hotspot-ridge interaction, ridge segmentation, and crustal accretion

The ultra-slow Southwest Indian Ridge (SWIR) dominates the floor of the southwestern Indian Ocean, extending a total length of 7,700 km from the Bouvet to the Rodrigues triple junction and spreading at full rates of 14-18 mm/yr. The SWIR represents the longest section of ultra-slow spreading ridge in the world. A series of NE- to N-trending fracture zones (FZs) offset the SWIR; the most prominent is the 750-km-long Andrew Bain FZ that divides the axis into two almost equidistant sections. A broad topographic swell, defined to the north by the Madagascar Ridge and to the south by the Del Cano Rise, uplifts the central SWIR. As a result of concerted international efforts, almost the entirety of the SWIR axis has been mapped by multibeam bathymetry sonar. The SWIR exhibits extreme diversity in ridge segmentation geometry and off-axis evolution, volcanic crustal accretion styles, and tectonic deformation patterns.

1) Interaction of the Marion hotspot with the SWIR: Most topographic highs in the central SWIR are related to the Marion hotspot and its interaction with the SWIR. The activities of the Marion hotspot can be divided into three main phases: Interaction with the paleo-Rodrigues triple junction (73.6–68.5 Ma), interaction with the SWIR (68.5-42.7 Ma), and intra-plate volcanism (42.7–0 Ma). These three phases correspond to the formation of the eastern, central, and western parts of the Del Cano Rise, respectively. The propagation of the Marion hotspot effect along the paleo-ridge of the SWIR is thought to be restricted by transform faults, and its attenuation correlated to the geometry of transform faults. The excess magmatic flux generated was greater when the Marion hotspot approached the RTJ and SWIR than when the hotspot was far away from the SWIR.

2) Ridge segmentation geometry and off-axis evolution: In non-hotspot-influenced sections of the SWIR, two general patterns of ridge segmentation are observed. The first pattern is characterized by relatively stable, long-lived segmentation defined by large-offset transform faults, orthogonal ridge segments, and non-transform offsets (NTOs). The second style of segmentation comprises unstable, short-lived segments

bounded by small-offset NTOs. In areas with stable segmentation patterns, off-axis topography associated with orthogonal segments can be traced for long distances along the flow lines, indicating that magmatic centers have been very stable in location. In contrast, regions with short-lived segmentation are characterized by very discontinuous off-axis tectonic fabric along spreading flow lines.

3) Volcanic crustal accretion styles: Three distinct volcanic crustal accretion styles are observed along the SWIR. The first crustal accretion style consists of amagmatic zones characterized by oblique spreading, thin crust inferred from gravity data, exposed upper mantle rocks on the ocean floor, few or no volcanic edifices, low ridge-axis magnetization indicating the lack of a basaltic layer, and extremely low effective spreading rates. At the other end of the spectrum are zones of highly focused volcanism. These segments of robust magmatism are distinguished by relatively shallow depths at the ridge segment center, as well as by large along-axis gradients in bathymetric relief and mantle Bouguer anomaly. Between these two end-member cases are SWIR segments that reflect the style of volcanic crustal accretion along the slow-spreading Mid-Atlantic Ridge (MAR), with similar axial volcanic ridge volumes, morphology of volcanic edifices, and mantle Bouguer anomaly amplitudes.

4) Tectonic deformation patterns: A very wide range of rift valley depths and widths have been observed along the SWIR, reflecting major variability in lithospheric structure and deformation style. Such extreme variability in rift morphology could result from long-lived mantle temperature anomalies (e.g., due to the Bouvet and Marion hotspots) affecting multi-segment sections of the SWIR axis and/or from time-dependent magmatic/amagmatic episodicity within individual ridge segments. Well-defined inside-corner tectonic corridors have been observed adjacent to several major FZs along the SWIR. Many of these uplifted inside-corners have a blocky morphologic appearance similar to those observed along the inside-corner corridors of the slow-spreading MAR. Where gravity data are available, these SWIR inside-corner corridors are shown to be associated with relatively thin crust, again similar to the MAR. Examples of "megamullion" low-angle detachment fault features have been observed on the SWIR.

Chris MacLeod, Cardiff University: Local-scale Geology of Atlantis Bank: Constraints from Seabed Drilling

The 35km^2 flat-topped platform of Atlantis Bank is the shallowest portion of the transverse ridge that lies on the eastern side of the Atlantis II fracture zone at 57°E on the Southwest Indian Ridge. Knowledge of the geology of the surface and flanks of Atlantis Bank comes from several site survey cruises that complement the sub-surface results of ODP drilling (legs 118, 176 and 179). Local-scale constraint comes principally from data collected during RRS James Clark Ross cruise JR31. On this cruise we acquired video imagery and near-bottom magnetics from ROV surveys of the platform surface, and constructed a high-resolution bathymetric map of the summit region using ship borne narrow-beam echo sounder data. Broad scale sampling of the transverse ridge and flanks of the massif by dredging was complemented by a detailed shallow coring program on the platform surface. Using robotic seabed rock drills constructed by the British Geological Survey (BGS) we collected 42 short (1–5m-long) hard-rock cores from Atlantis Bank, some of which (acquired using BGS's 'BRIDGE' rock drill) were fully geographically oriented.

Andrew McCaig, Leeds University, and Sofya Titarenko: Thermal evolution of hot and cold detachment faults

Two of the best-studied oceanic core complexes are the Atlantis Bank on the SW INDIAN RIDGE and the Atlantis Massif on the MAR; both will be revisited by IODP in 2015. Both are similar lithologically in that deep ODP/IODP drill holes have penetrated mainly gabbroic rocks, but have different deformation histories. ODP Hole 735b in the Atlantis Bank is famous for its high temperature mylonite zones, deformed at 800-950 °C, while high temperature mylonites are almost absent in IODP Hole U1309D in the Atlantis Massif. Another difference is the presence of about 50% diabase intrusions chilling against fault rocks in the upper 120m at Site U1309. This suggests that the detachment first localized and then exhumed a dyke-gabbro transition in slow spread detachment-mode crust, with a very different geometry to fast spreading ridges.

We investigate circumstances in which these different deformation histories could originate through thermal and hydrothermal modeling using Comsol Multiphysics. In the case of the Atlantis Massif, the cooling history recorded in published thermochronometric data (U-Pb zircon, U-Th-He zircon, multicomponent magnetic remanences) can be matched well in models where hydrothermal circulation occurs in the hanging wall of the detachment fault during exhumation. We also use a new calculation of present-day heat flow into the base of the Massif using 3-D modeling (based on the thermal profile recorded in IODP Expedition 340T) to establish an end-point for 2-D exhumation models. In the case of the Atlantis Bank, the slower initial cooling history can be matched using conductive exhumation models without hydrothermal circulation. The difference probably lies in the distribution of magma during the initiation of detachment faulting, with the Atlantis Bank requiring a much more magma-rich starting configuration.

Tim Minshull, University of Southampton: Seismic constraints on crustal structure at Atlantis Bank

The first modern seismic surveys of the SW Indian Ridge axis were conducted aboard RRS Discovery in 1994, on the ridge axis at 66E and at the Atlantis II Fracture Zone. The latter survey involved the deployment and recovery of eight ocean bottom hydrophones (OBHs) on profiles along and across Atlantis Bank in the vicinity of Ocean Drilling Program Hole 735B, with an average spacing of 20 km. Shots were fired at 40 s (c. 100 m) intervals from a ten-gun, 71 L tuned airgun array. These shots were also recorded on an eight-channel hydrophone streamer with 100 m group interval. The streamer data were used to map sediment thickness and do not reliably image features within basement. The shot interval was chosen as a compromise between longer intervals, that would have provided cleaner OBH data, and the shorter interval required to allow stacking of streamer data. OBH data were recorded on digitally encoded analogue tape. These data show strong scattering from the hard seabed and water-column noise obscures first arrivals beyond about 20 km, but the data quality is sufficient to provide strong constraints on crustal thickness and velocity structure. Away from Atlantis Bank, the crust consists of a 2 km thick high-velocity-gradient oceanic Layer 2 and a 1-2 km thick low-velocity gradient Layer 3 that thins toward a non-transform discontinuity east of the fracture zone. The transform valley has a 2.5 km thick crust with anomalously low velocities interpreted to consist largely of highly serpentinised mantle rocks. The seismically defined crust is thickest beneath the borehole, despite the presence of a thinner oceanic Layer 2 and the absence of upper crustal rocks; here the seismically defined lower crust may contain 2-3 km of partially serpentinised mantle. Reconciliation of these seismic constraints with those from gravity data depends critically on the gravity signature of mantle thermal structure.

Tomoaki Morishita, Kanazawa University: Gondwanaland-mantle Beneath the Central Indian Ridge

Heterogeneities of magma source beneath mid-ocean ridges have been mainly investigated with chemical compositions of volcanic rocks. Abyssal peridotites directory recovered from the mid-ocean ridges are important proof of the oceanic mantle. Os isotopic compositions of some abyssal peridotites recovered from Mid-Ocean ridge systems have suggested the existence of ancient mantle that suffered from melt extraction at more than billion years ago. The distribution, composition, and length scale of the mantle heterogeneities and their origins are, however, not clear yet. We recovered orthopyroxene-rich rocks, i.e., relatively silica-rich ultramafic rock compared to normal olivine-rich abyssal peridotites, from a knoll along the Central Indian Mid-Ocean Ridge. I show petrological characteristics and Os isotopic compositions of these samples. The orthopyroxene-rich rocks have petrological characteristics similar to those of subduction-induced metasomatized peridotites, rather than typical abyssal peridotites. The Os-isotopic compositions support their origin as subduction-induced metasomatized peridotites, probably formed at the Gondwanaland margin or during the formation of the Gondwanaland. I conclude that the Gondwanaland mantle material is mixed with the ascending athenospheric mantle beneath the Central Indian Ridge and is now emerged from the Mid-Ocean Ridges.

James H. Natland, RSMAS University of Miami: Results of Prior Drilling at Atlantis II Bank

Two sites 1.2 km apart were drilled into gabbros atop Atlantis II Bank, Southwest Indian Ridge, during ODP Legs 118/176 (Site 735) and 179 (Site 1105). Both had >80% recovery, and provided an unprecedented look at the structure and development of plutonic ocean crust at a slowly spreading ridge.

The cores demonstrate simultaneous operation of magmatic differentiation, strong shear deformation, and metamorphic processes. Late-stage silicate melts (which crystallized to oxide gabbros and tonalite/trondhjemite felsic veins), coursed through more primitive olivine gabbro in veins, gashes, seams and intergranular porosity structure as the entire mass was being unroofed from a rift valley floor, uplifted and exhumed to form a core complex at Atlantis II Bank. Deformation produced porphyroclastic, gneissic and even mylonitic fabrics in the core, much of it associated with seams of oxide gabbro. At Hole 735B, over 500 seams of oxide gabbro, some with 5-30% combined ilmenite and magnetite, most from a few cm to m thick, and one composite body nearly 40m thick, are dispersed up and down the section. Several m-thick bodies of oxide gabbro were cored at Hole 1105A, but none are as thick as the main oxide gabbro at Hole 735B. The balance of the long section at Hole 735B consists of three main masses of olivine gabbro and troctolite, totaling >1150m thick. The upper two of these are systematically more differentiated upward, whereas the third and thickest is more uniform. The relatively primitive rocks comprise >500 intervals with igneous, not deformational, contacts, each representing a small intrusive body. Few rocks exhibit igneous layering. The three bodies may represent partially overlapping magmatic intrusive centers that developed as spreading widened the floor of the ancient rift valley, before uplift, unroofing and extended differentiation occurred.

Geothermometry of pyroxenes and oxide minerals suggest that recrystallization occurred between ~1000-700° C, most of it beneath the rift-valley floor while some melt was still present. Conditions then were hydrous, since magmatic amphibole is intergrown with ilmenite-magnetite intergrowths. Deformation fabric dips toward the present rift valley. Subsolidus recrystallization down to ~400°-<100°C, together with formation of secondary amphibole, then occurred, at first rapidly, then more slowly for another ~4 million years (John et al., 2004).

The rocks are a vivid example of what Bowen (1920) termed “differentiation by deformation” (the synkinematic differentiation of Dick et al., 2000), in which the residual melt porosity of rocks is almost completely removed by compaction, squeezing and shear. Development of granulite-like deformational fabric was essential to igneous differentiation, and is a common feature of fracture-zone gabbros. Gravity-driven crystal settling or flotation, igneous layering, and reduction of intergranular porosity structure by crystal overgrowth, the central tenets of cumulate theory, are thus insignificant processes at slowly-spreading ridges, where no large or small magma chambers have ever been detected by seismic techniques. Differentiation by deformation is thus the major mechanism driving the crystallization, consolidation and development of the general lithostratigraphy of gabbroic rock beneath more than half of the ocean crust and a third of the surface of the planet.

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Oliver Nebel, Monash University, Melbourne, Australia: In-situ formation of Indian Mantle in global subduction zones

The isotopic signatures of Sr-Nd-Pb-Hf-Os in mid-ocean ridge basalts (MORB) in the Indian Ocean are clearly distinct compared with their Atlantic/Pacific (A/P) counterparts. The origin of this isotopic distinction has been a matter of debate since its discovery by Dupré and Allègre (1983). Current models advocate: (i) delamination of ancient, negatively buoyant lower crust/lithosphere from a supercontinent; (ii) contamination of A/P-style mantle with plumes (the original association with the DUPAL anomaly); or (iii) long-term overprint by a subduction component (SC) surrounding a former supercontinent. The sum of various stable and radiogenic isotope proxies appears to support a delamination scenario, but alternatives, or the combination of the aforementioned scenarios, are possible. Irrespective of the origin of the Indian mantle domain, isotopic signatures similar to those of Indian MORB and hot spots are observed in arc/back-arc systems associated with western Pacific subduction zones. These isotope signatures have been regarded as unequivocally derived from Indian-type mantle, and accordingly used to trace eastward flow of that type of mantle.

Here we show the majority of igneous rocks associated with subduction zone systems mimic Indian-type mantle in Pb isotope space, but are distinct in Hf-Nd isotope co-variations. We suggest isotopic signatures believed to be derived from Indian mantle in subduction zones are the result of medium-term subduction overprint of evolving A/P-type mantle wedges. This feature results from the relative mobility of U-Pb>Sm-Nd>Lu-Hf in subducted slab-derived components and Th/U (k) fractionation in the mantle wedge.

Elevation of k in the wedge from 2.6 (MORB) to about 6-12 can account for the shift in Pb isotope space over a duration of ca. 50-100 My; "decoupling" of Hf-Nd isotopes reflect the subduction component vs mantle wedge contribution. More generally, "Pseudo-Indian mantle" is noted as common in subduction zones globally, and not limited to the western Pacific, supporting the in-situ generation of isotope signatures akin to Indian mantle. Radiogenic ingrowth in modified wedge mantle requires shallow storage of affected parts of the mantle wedge over tens to hundreds of millions of years. Convection models support the feasibility of this scenario, provided that wedge rheology is modified through hydration (as is required by Th addition) in, at least, a small region of the wedge center. We argue that most if not all Indian-mantle signatures in global subduction zones are not related to the actual Indian mantle domain and associated geotectonic models employing this proxy in subduction zones need revision.

In turn, similar processes may be responsible for isotope oddities in the actual Indian mantle domain.

Dr. Mladen Nedimovic, Dalhousie University: 3D MCS Reflection Imaging of Moho at the East Pacific Rise

Multichannel seismic (MCS) reflection imaging of the oceanic crust, including the Moho discontinuity, started in the late 1970s and continued to this date. The earliest studies were 2D surveys across the East Pacific Rise (EPR). The first pseudo-3D MCS survey was carried out in 1997, also across the EPR. Long (>=6 km) hydrophone streamer 2D MCS surveying of the oceanic crust became the norm approximately at the turn of the 21st century. This was followed in 2008 by the first detailed multi-source and multi-streamer 3D MCS surveys across the EPR. The goal of this presentation is to first briefly introduce Moho reflection imaging through time. This will be followed by a more detailed presentation of the Moho reflection imaging results from the 2008 3D EPR survey. The reflection images from this work show the oceanic seismic Moho mapped at detail, sharpness and continuity not previously possible.

Beth Orcutt, Bigelow Laboratory for Ocean Sciences: What is Known about Microbiology of Ocean Crust and Mantle

During Integrated Ocean Drilling Program Expeditions 327 and 336, several new subsurface borehole observatories were installed in oceanic crust, with a primary motivation to access the deep biosphere in these poorly understood environments. These new observatories have enabled unprecedented opportunities to collect high-quality samples for microbiological analysis, including metagenomic and single cell genomic investigations of the unique microbial communities living "on the rocks." This presentation will provide an overview of what we have learned from analyzing the cored rocks, and how that compares to our observations from observatory experiments and samples. This presentation will discuss the implications of these findings for understanding life in the deep biosphere and for planning future drilling and observatory research.

Oliver Pluemper, Department of Earth Sciences, Utrecht University: Low-temperature Nanocatalysis of Abiogenic Methane during Peridotite Alteration

Mantle peridotite alteration can catalyze abiogenic hydrocarbon formation, particularly CH4. This gas sustains the deep biosphere, promotes gas hydrate formation, and may form gas reservoirs. Although CH4 synthesis in known to occur in the presence of metal alloys or chromite during serpentinization at T>200 °C, little is known about the potential for massive CH4 catalysis at low-temperatures. Here, we present first results of our investigations into the natural catalyst within the massive, low-temperature (~50 °C1) CH4 seep at the Chimaera site, Tekirova ophiolite, Turkey. CH4 has been used at this site for >2000 years and the original reservoir is estimated to be thousands to millions of cubic meters making it the Earth's largest onshore abiogenic CH4 seep. Our investigations show that the serpentinites are massively enriched in chromite. Using micro-analytics we show that chromite alters to a mesoporous network of nanocrystalline spinel phases. We argue that the crystallographic preferred pore wall orientation, high surface area, and trace metal content of these spinel phases facilitates low-T CH4 synthesis with significant production capacities over timescales of several hundred to thousands of years. Using paleo-tectonic reconstructions we estimate the total amount of CH4 production since ophiolite emplacement.

1. Etiope et al. 2011, EPSL, 310(1-2), 96-104.

Matthew Rioux, University of California, Santa Barbara, Michael J. Cheadle, University of Wyoming, Barbara E. John, University of Wyoming, Samuel A. Bowring, Massachusetts Institute of Technology: High-precision ID-TIMS U-Pb dating of zircons from plutonic crust from ODP Holes 735B and 1105A, Atlantis Bank, SW Indian Ridge

High precision ID-TIMS U-Pb zircon dates from ODP Holes 735B and 1105A provide new constraints on the timescales and processes of crustal accretion at Atlantis Bank, SW Indian Ridge. We have dated 21 samples from depths of 26–1430 mbsf. The studied samples are from each of the three main intrusive series, and include oxide gabbros, disseminated oxide gabbros, and diorite, tonalite and granodiorite dikes/veins. Single grain TIMS 206Pb/238U date uncertainties for most analyses range from ± 0.01–0.2 Ma and weighted mean 206Pb/238U date uncertainties range from ± 0.004–0.07 Ma, providing precise constraints on the timing and duration of magmatism.

Th-corrected single grain 206Pb/238U dates from individual samples generally define single populations, with limited evidence for xenocrystic older zircons, consistent with rapid zircon crystallization relative to the analytical uncertainties. Weighted mean 206Pb/238U dates from Hole 735B become progressively younger with increased depth in the core. Dates from intrusive series 1 range from 12.10 to 11.99 Ma; dates from intrusive series 2 ranges from 11.97 Ma to 11.92 Ma; and dates from intrusive series 3 range from 11.93 to 11.90 Ma. Three samples from Hole 1105A have weighted mean dates of ~11.96 Ma.

Two hypotheses to explain the distribution of dates are: 1. The sampled crust was formed by progressively deeper magmatism over an interval of 210 ± 30 ka; or 2. Assuming steady state thermal conditions during crustal accretion, the shape of the age-depth profile in Hole 735B records crystallization along the boundary of the mush zone as defined by the 700–850ºC isotherm.

Four of the dated samples contain ~200–600 ka older xenocrystic zircons. The xenocrystic zircons may reflect assimilation of older gabbros that crystallized within the mantle below the ridge (Schwartz et al., 2006), or assimilation of older gabbro from the northern side of the ridge, which is likely to be almost stationary with respect to the detachment fault footwall due to extreme asymmetric spreading (Baines et al., 2008).

Further high-precision dating of rocks recovered during Expedition 360 has the potential to differentiate between the hypotheses presented above and provide a four dimensional view of crustal accretion.

Alessio Sanfilippo, Università di Pavia: Troctolites from the crust mantle boundary, why should we go so deep?

Studies on chemically primitive lower crustal rocks (olivine-rich troctolites) suggest that hybridized mantle material can be locally embayed within the lower oceanic crust in form of hybrid troctolites. These hybrid rocks are considered to originate through interactions between the shallow mantle and melts migrating through it. Common models of formation require a two-stage process, entailing dunitization, partial dissolution of olivine and crystallization of new magmatic phases. In this contribution, we questioned this idea, showing that textural and chemical inheritances of the pre-existing mantle are preserved in olivine-rich troctolites worldwide. Hybrid troctolites may thus form through the direct overprint of the pre-existing mantle, sustained by recent experimental studies and numerical simulations. If our idea is correct, we expect hybrid troctolites to be more diffused at the crust-mantle transition in slow spreading environments. Here extensive interaction within a thick thermal boundary layer may facilitate conversion of the shallow oceanic mantle into hybrid crustal rocks.

We discuss the possible role of such melt-mantle interaction processes on the composition of the lower oceanic crust and MORB, examining two study cases. On the basis of thermodynamic calculations, we show that the assimilation of mantle peridotites into a migrating melt may explain the steep clinopyroxene Mg#[Mg/(Mg+Fe)] versus plagioclase anorthite correlation of a troctolite-gabbro sample suite from the Godzilla Megamullion (Philippine sea). Then, we examine the Os isotope composition of the troctolites from the Central Indian Ridge. We propose that the melt-mantle reactions that formed these rocks produced melts with radiogenic Os compositions, discussing the isotopic variability of MORB under a melt-rock reaction perspective.

Our investigations indicate that melt-mantle reactions may have a profound effect in defining the composition of the lower oceanic crust and of the basalts erupted on the seafloor. A more thorough characterization of the rocks forming the crust-mantle transition is thereby necessary to i) have a complete picture of the compositional variability of the parental melts extracted from the mantle, and ii) understand how these melts evolve prior to be erupted on the seafloor as MORB.

Matt Schrenk, Michigan State University: Serpentinization, Carbon, and Deep Life

Serpentinizing ultramafic rocks are conduits for the exchange of carbon and energy between the deep Earth and the surface environment. The growth and activity of microbial communities hosted within serpentinites may play important roles in controlling the composition and mobility of carbon-bearing compounds. However due to a complex interplay of carbon sources and sinks and a paucity of data on the microorganisms associated with serpentinites, the significance of microbial processes has proven difficult to constrain. Concerted studies have allowed us to begin to define the identity and functional potential of microbial communities associated with serpentinizing ophiolites, their energy sources, and their impacts upon carbon speciation. Taxonomic data indicate that Betaproteobacteria predominate at shallower oxic/anoxic interfaces, whereas anaerobic taxa within the order Clostridiales are abundant in deeper, more anoxic regions of the serpentinites. Metagenomic and functional genomic analyses support and expand upon these observations, documenting evidence of both hydrogen oxidation and hydrogen production through fermentation of organic matter, and in some cases for sulfur red-ox transformations. Additionally, these studies provide evidence for aerobic carbon monoxide assimilation and carbon fixation via the Calvin cycle and the acetyl CoA pathway. Surprisingly, to date evidence of archaeal methanogens has been very rare within the habitats sampled. These data provide important targets for quantification of subsurface biogeochemical processes and their impact upon the characteristics of circulating fluids and their host rocks.

Maurice A. Tivey, Woods Hole Oceanographic Institution: High-Resolution Magnetic Studies of Atlantis Bank, South West Indian Ridge

Atlantis Bank located on the southern flank of the South West Indian Ridge at 32°S / 57°E on the eastern side of the Atlantis II transform fault is now recognized as an oceanic core complex that exposes lower crust at the seafloor. Several legs of the Ocean Drilling Program (Holes 735B and 1105A) reveal a ~1500 meter section of coherently and reversely magnetized gabbroic ocean crust. The mean stable magnetic inclination is 71° approximately 20° steeper than the geocentric dipole inclination of -51° expected for this southern hemisphere latitude. This implies 20° of back tilt, significantly less than is typical for OCC rotation found in other locales. In 1998, as part of a site survey of the 700 m deep Atlantis Bank for ODP Leg 176, a detailed near-bottom magnetic survey and remotely operated drilling program was carried out using the Canadian ROV ROPOS and the British Geological survey (BGS) drill and BRIDGE oriented rock drill. Ten fully oriented cores and 12 additional BGS cores were sampled across the top of Atlantis Bank. The mean inclination of 69.3° and declination 179.4° for the oriented cores support the reversely magnetized nature of the crust at Atlantis Bank. However, in addition to the reversely magnetized samples there is a zone of normal polarity sampled by the drill core on the northern part of Atlantis Bank. Two near bottom deep tow magnetic profiles and several on bottom ROV magnetic profiles document that a small positive anomaly is located in this general vicinity. The anomalies correlate with the sea surface magnetic profile coverage and correlate with the short chron C5r.2n (11.592 to 11.657) based on the 2012 astronomically-tuned geomagnetic timescale (Gradstein et al., 2012). The magnetic anomaly shows a slight southward shift in the magnetic boundary relative to the seafloor boundaries inferred from seafloor drilling. This implies a southward dip to the magnetic horizon, consistent with the concept of a cooling isotherm in the gabbroic section (i.e. a dip away from the spreading axis). Hole 735B does not have any normal polarity down hole, so this horizon must dip either below the hole or is truncated laterally or is down-dropped by a transform parallel fault. The best-fit dip to the magnetic horizon is approximately 17° or greater (if not to intersect 735B). When the 20° of tilt is restored to the section, the dip of the magnetized body is near horizontal. For this to be the case, then the gabbroic section may have cooled below the Curie isotherm of magnetite (580°C) quite late in the formation and evolution of the core complex.

Maurice A. Tivey, Woods Hole Oceanographic Institution: TAG Magnetics

The TAG hydrothermal area found on the slow spreading Mid-Atlantic Ridge at 26N is marked by a sea surface magnetic low located over the eastern rift valley wall. Original speculation by Peter Rona on the source of the anomaly suggested that the hydrothermal system itself was responsible for this anomaly. Following the discovery of the high temperature vent site, nearby relict mounds and diffuse activity, a detailed magnetic studies by submersible found a very localized magnetic anomaly over the active mound and nearby mounds. A subsequent near bottom towed sidescan sonar survey that included magnetics revealed a broader anomaly low that can be tied to the surface anomaly observation. Submersible and side scan observations of the eastern wall showed a faulting geometry that lead to the exposure of lower crustal rocks east of the TAG active mound and corresponds to the location of a near bottom magnetic low. The magnetic low can be explained by crustal thinning caused by 4 km of horizontal extension along a low angle normal detachment fault. The combination of these observations suggested at the time that this was a proto- oceanic core complex with the TAG vent system being located on the basaltic hanging wall. This view was subsequently confirmed by a detailed seismic survey that imaged the detachment fault at depth. It is now clear that over the past several hundred thousand years, movement on the detachment fault has episodically increased the permeability of the hanging wall and reactivated the overlying TAG hydrothermal systems. Significant vents like TAG found associated with the long-term detachment faults near seafloor spreading centers are probably more ubiquitous than previously thought and could result in a longer history of activity and mineral deposition than previously thought.

Qunhui Yang, Huaiyang Zhou, and Fuwu Ji, State Key Laboratory for Marine Geology, Tongji University: Geochemistry of hydrothermal vent fluids at the dragon hydrothermal field in the Southwest Indian Ocean Ridge

Here we report the first result of shipboard and shore based analyses of four hydrothermal vent fluids collected at the dragon hydrothermal field in the Southwest Indian Ocean Ridge. Two of hydrothermal vent fluids exhibit high temperature of 371°C and 365°C, pH of 3.679 and 3.577(25°C), high chlorinity of 611.6 and 614.5mM, high H_2S of 9.24 and 9.16 mM, methane of 0.387 and 0.364 mM, hydrogen of 0.201 and 0.154 mM. Although the two high hydrothermal vent fluids were sampled from the S zone and M zone hydrothermal site which are about 500m apart, respectively, the uniformity in end member major, minor, trace element concentrations and gas contents suggests that these two fluids originate from the same deep source. The chloride concentration (465 mM) of the other two low temperature hydrothermal vent fluids is lower than the background seawater(540 mM) indicating that these fluid are affected by phase separation. The ammonium concentrations of the four hydrothermal fluids are much higher than the background seawater and the most of the unsedimented mid-ocean-ridge hydrothermal system except the Endeavour segment of the Juan de Fuca Ridge, show its positive correlation with vent temperature up to 90.3 uM.

Xiang Zeng, Ljing Jiang, Zongze Shao, Third Institute of Oceanography, SOA and Huiluo Cao and Peiyuan Qian, Hong Kong University of Science and Technology: Biological Communities at the Dragon Flag Hydrothermal Field

Limited biological especially microbiological studies on the SWIR have been conducted. During recently Chinese cruise (cruise DY125-20, cruiseDY125-30, cruise DY125-34, cruise DY125-35), we found that Dragon flag vents field(49°S) has higher vents fauna species diversity than other hydrothermal fields including mussels, gastropods(including scaly-foot;) shrimps, crabs, anemones and barnacles. The diversity may be caused by geochemical composition and bacterial symbioses; and novel fauna species are identifying in the process.Besides, the metagenomes of hydrothermal chimneys were pyrosequenced to elucidate the associated microbial sulfur cycle. A taxonomic summary of known genes revealed a few dominant bacteria that participate in microbial sulfur cycle, especially the Delta-proteobacterial sulfate-reducing organisms. The studied metagenomes contained very abundant genes related to the sulfur oxidation and reduction. This study provides insight regarding major microbial metabolic activities driven by the sulfur cycle in low-temperature hydrothermal chimneys on an ultraslow mid-ocean ridge. Many novel microbial species including sulfur-oxidizing bacteria and sulfate-reducing bacteria were also isolated.

Minghui Zhao, South China Sea Institute of Oceanology, Chinese Academy of Sciences: Crustal structure and Fault Geometry at the Dragon Flag Hydrothermal Field

The southwest Indian Ridge (SWIR) is an ultraslow spreading end-member of mid-ocean ridge system, with the obliquity of the ridge axis, the presence or absence of transform and non-transform discontinuities, exposed mantle peridotites, etc. It is a key area to studying interplay among magmatism, tectonics, and hydrothermal circulation. The 3D seismic survey for the first time was carried out at the SWIR during DY115-21 global cruise from January to March in 2010. We use airgun shots recorded by twenty ocean bottom seismometers (OBSs) to generate a 3D P-wave tomographic velocity model of the segment 28 (37°50′S). The seismic velocity structures show strong asymmetry across the ridge axis. A corrugated oceanic core complex (OCC) on the southern flank is characterized by high velocity and thin crustal thickness. Hydrothermal activities at the Dragon Flag vent are closely associated with the detachment fault which providing a pathway for hydrothermal convection. The detachment fault could be constrained by the boundary between low and high velocity perturbation. The lateral variations of velocity model along the axis are dominantly controlled by thickness changes in the lower crust, which due to focusing of magma at segment center. A low-velocity anomaly in the eastern side beneath the active hydrothermal vent, maybe acts as heat source to sustain long-term hydrothermal circulation. We proposed 4 wells near the vent to test the mechanism of Dragon Flag vent and improving the understanding of hydrothermal processes. We also proposed 3 wells in the domain of OCC to discover the deformation and anisotropy in the footwall of OCCs.

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Huaiyang Zhou, State Key Laboratory for Marine Geology, Tongji University: Regional Geology of active Dragon Hydrothermal Field, Southwest Indian Ridge

The Dragon Flag active hydrothermal field (49.6° E) is located on an inside-corner high on the southern wall of the present-day rift valley of ultra-slow spreading SWIR segment 28. It consists of three active hydrothermal zones (South, Middle and North zones) in a trend of NNW for a length of about 1000m. The extensively surveyed South Zone of the Dragon Flag field is about 120 m across at a depth of 2760 m. In the South zone, there occur amount of active and inactive sulfide chimneys, small sulfide mounds and large area of diffuse flows or low temperature Fe-Si oxides/hydroxides precipitates. Several chimneys are more than 20 m in height. Some chimney samples have mineral assemblage of pyrite, marcasite, and sphalerite etc. in their outer portions and chalcopyrite etc. in the conduits. Measured highest temperature of vent fluids is about 370ºC.

All three hydrothermal zones are surrounded by basalts. However, about 800-1500 m southeast of vent Zone S, serpentinites, quartz-chlorite veins as well as dead sulfides were collected by TV-grab or dredge. It is postulated that the combined development of a major detachment with its upper volcanic part and lower igneous part as well as hydrothermal activities represent a genetic end-member in modern seafloor spreading and hydrothermal category.

Huaiyang Zhou, State Key Laboratory for Marine Geology, Tongji University, and Henry JB Dick, Woods Hole Oceanographic Institution: Preliminary Drilling Plan for the Dragon Flag Hydrothermal Area and the Dragon Bone Amagmatic Segment

The Dragon Flag hydrothermal field (49.6°E), consisting of three active and inactive chimney clusters, is situated at a detachment fault on the south wall of a magmatic segment adjacent to a non-transform discontinuity. Compared with TAG in the Atlantic mid-oceanic Ridge, absent of sulfide mounds in additional to venting fluids chemistry in the Dragon Flag hydrothermal filed is probably much younger.

Serpentinized schists are dredged at the detachment fault. It is believed that this represents fault gouge intruded from where the detachment fault cuts mantle peridotite in the adjacent non-transform discontinuity. In form, the ridge segment hosting the Dragon Flag hydrothermal field appears to represent an excellent example of a deeply rifted spreading magmatic ridge segment with a well-developed axial volcanic ridge.

Dragon Flag should be the opportunity for parallel studies to the far older and complex TAG hydrothermal area, and for determining the microbial biogeography between the Atlantic and Indian Oceans to match that of the diverse macro fauna at TAG.

53°E amagmatic segment (Zhou and Dick, 2013), called the Dragon Bone Segment as unlike the Dragon Flag Segment, has virtually no crust and no known hydrothermal activity– no meat on the bones, 300 km to the east of the Dragon Flag Hydrothermal area offers another drilling opportunity to recover pristine mantle peridotite from high on the Marion Rise for comparison to the mantle that can be drilled in amagmatic deep regions of the eastern SW Indian Ridge, and critically to mantle rocks drilled in the Dragon Flag area.