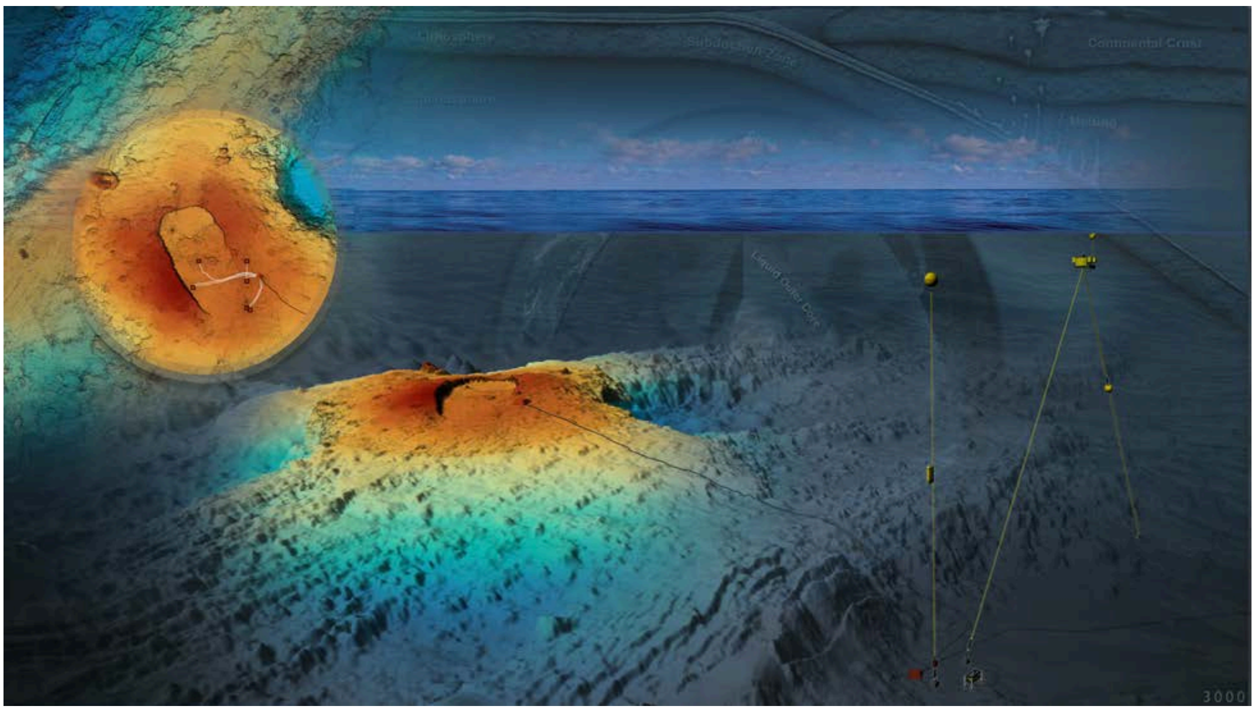
# Workshop Report

## *"Drilling into Young Oceanic Crust for Subseafloor Observations at Axial Seamount"*

October 11-13, 2017




organized by

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*1.1 Overview*

Axial Seamount is the most magmatically active submarine volcano in the northeast Pacific and has been the focus of inter-disciplinary studies for over two decades. The range of scientific interests includes volcanology, geophysical characterization and monitoring, hydrothermal vent formation and geochemistry, quantification of heat and chemical fluxes, hydrogeology, and the diversity and evolution of microbiological and animal communities. Axial Seamount erupted in January 1998, April 2011, and April 2015, and is likely to erupt again in the coming years. The site, therefore, presents a unique opportunity to study the interaction between volcanic, hydrothermal, and biological responses to magmatic and volcanic events. Primarily for these reasons, Axial Seamount was chosen as one of the key sites on the National Science Foundations' (NSF) Ocean Observatories Initiative's (OOI) cabled observatory network, the Cabled Array (CA). The Axial workshop was held to explore how ocean drilling and related studies can complement seafloor-based investigations by gaining access to the subseafloor to expand our understanding of microbiological, geophysical, hydrologic, and geochemical processes, now that the CA is fully operational with data streaming live to shore from a diverse suite of cabled instruments,. Three of the four International Ocean Discovery Program (IODP) research themes were directly addressed in this workshop, including Biosphere Frontiers, Earth Connections, and Earth in Motion. The workshop brought together a multidisciplinary group of scientists across a broad spectrum of ocean sciences and engineering to identify high priority science objectives and research opportunities that can only be achieved with ocean drilling at Axial Seamount, and to learn about state-of-the-art drilling capabilities that can be brought to bear in this mid-ocean ridge environment.

**Figure 1.** The 47 participants of the workshop at LDEO

*1.2 Axial Seamount*

Axial Seamount is located on the Juan de Fuca Ridge and rises from a water depth of ~ 2700 m to 1500 m (Fig. 2). The caldera hosts three main hydrothermal fields (ASHES, CASM, and International District), as well as myriad diffuse flow sites, some associated with eruptive fissures. Axial Seamount has been the focus of long-term studies for the last several decades because it is the most active submarine volcano in the NE Pacific, it is close to West Coast ports, and its frequent eruptions perturb the chemistry of the hydrothermal vent fields and their resident chemosynthetic-based biological communities. It has proved to be a superb site for the study of active submarine volcanism and its dynamic influences on ocean chemistry and marine ecosystems with previous eruptions in 1998, 2011, and 2015 (1, 2).

In 2014, the cabled component of NSF's Ocean Observatories Initiative, the Cabled Array, became fully operational. It is the most advanced submarine volcanic observatory in the world, designed to be operative for 25 years (3). The site is connected to shore via a ~500 km high power (8 kW) and high bandwidth (10 Gbs) fiber-optic cable (Figs. 2, 3). Two-way communication at the speed of light to seafloor instruments and instrumented water column profilers allow highly interactive rapid responses to diking events, volcanic eruptions, and earthquakes. The array provides co-registered real-time measurements of associated changes in venting and biological communities with capabilities to change data accumulation, fluid-DNA sampling rates, and camera-look angles. Instrumentation includes broadband and short-period seismometers, bottom pressure-tilt meters, in situ temperature-chemical sensors in the high temperature and diffuse flow fluids, including an in situ mass spectrometer, a fluid and microbial DNA sampler, and digital still and high definition video cameras.

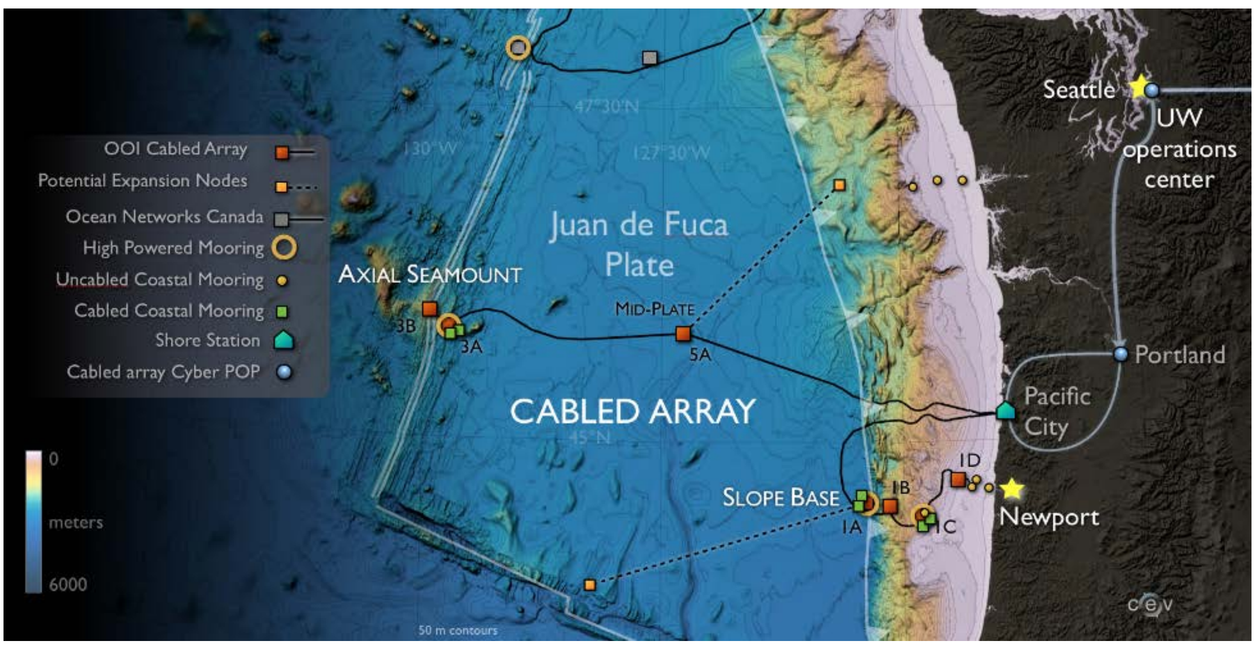

**Figure 2.** Location of the OOI Cabled Array showing the Primary Infrastructure that includes >900 km of high power and bandwidth fiber optic cables, seven primary nodes (red squares) that provide power and communications to >33,000 m of extension cables, >140 instruments, and 6 state-of-the-art moorings with instrumented wire crawlers (Credit: University of Washington).

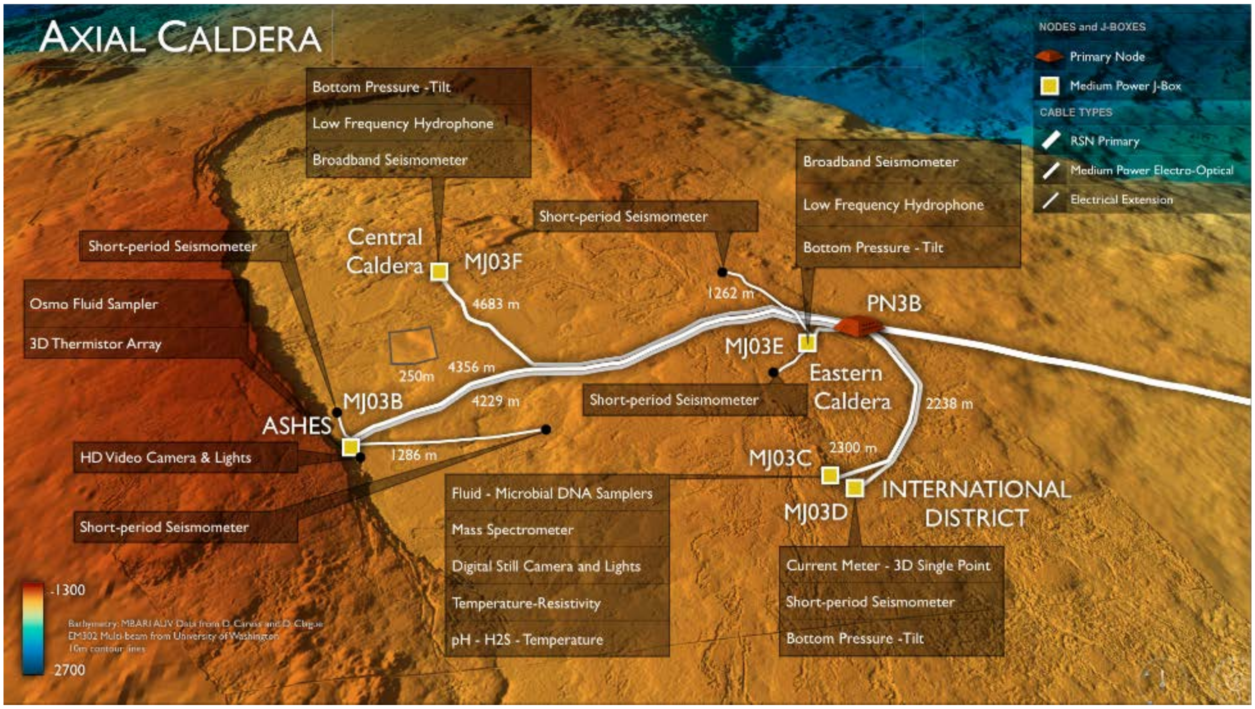


**Figure 3.** Primary and Secondary Cabled Array infrastructure now installed and operational at the summit of Axial Seamount. Primary Node PN3B provides power and bandwidth to five secondary nodes (medium-powered junction boxes) and several kilometers of extension cables that cross the caldera, providing power and communications to 21 OOI core instruments. Additional instruments (e.g. bottom-pressure tilt and CTD) instruments have been installed through additional NSF funding: The system is highly expandable. Scheduled maintenance cruises turn selected instruments and junction boxes annually (3).

The high power and bandwidth, coupled with easily daisy-chained secondary junction boxes at the summit of Axial Seamount allow for significant expansion capabilities for future infrastructure, which may include instrumented boreholes with real-time monitoring and two-way communication for perturbation experiments.

The breadth of science currently being conducted at Axial with both ship- and cable-based investigation spans microbiology, hydrology, petrology, seismology, geodynamics, macrobiology, volcanology, geochemistry, instrument testing and more. Studies at Axial Seamount have greatly expanded our understanding of microbial life in young oceanic crust (4–12), the nature of deep-sea eruptions (13–17), and the chemical evolution of vent event plumes and hydrothermal fluids over time (18–21). Multi-channel seismic surveys and active-source seismic experiments have revealed a large shallow reservoir of magma beneath the summit caldera (22–24), and time series pressure measurements combined with the seismic network now in place as part of the OOI infrastructure make Axial Seamount the only site in the world where volcanic inflation concomitant with earthquake activity and vent fluid chemistry and flow is being monitored in real time (3, 25, 26).

### *1.3 Motivation for Subseafloor Observations and the Role of Drilling*

Almost all of these exciting scientific results from Axial are from data gathered at or above the seafloor to infer processes occurring beneath the seafloor. The motivation for drilling is to provide direct access to the subseafloor to expand our understanding of subseafloor microbiological, geophysical, hydrological, and geochemical processes at Axial Seamount. For example, investigators have relied on the use of numerical models in conjunction with measurements at the seafloor to infer subseafloor properties in mid-ocean ridge environments, including the total heat flux, porosity, and permeability of the upper basement (27–32). However, numerical modeling studies can typically only provide constraints on such properties on the scale of an entire hydrothermal system, and would greatly benefit from direct measurements of the permeability and permeability structure in the upper few hundred meters below the seafloor. Ocean drilling will allow for direct measurements of the critical seismic and hydrological properties (e.g., VP, VS, permeability, and porosity) of the crust at Axial Seamount. Such information will provide needed constraints for estimates of rates of fluid, heat, and solute transport from the lithosphere to the hydrosphere at Axial. Similarly, for the last nearly three decades of work at Axial Seamount, scientists have used diffuse vents as access points to infer microbial and geochemical processes occurring in the subseafloor. These low temperature hydrothermal fluids range in temperature from 5°C to 50°C and can be analyzed and manipulated as they flow from the seafloor. However, they can only be sampled at the seafloor point of exit where they have already mixed with seawater, making inferences of subseafloor habitats, population structure, flow rates, and geochemical gradients challenging (4-12, 33-36). With seafloor drilling that includes sampling and borehole instrumentation, we will be able to directly examine in situ conditions for microbial and biogeochemical processes, including the thermal and chemical gradients in the rocks and fluids, how these might vary and evolve with seismicity or eruptions, where in the rocky matrix microbial life is distributed, and the extend and nature of microbe-mineral association signatures.

The earthquake monitoring component of the CA at the summit of Axial Seamount includes a small seismic network comprising two broadband seismometers with accelerometers, two low frequency hydrophones and five short-period seismometers. In principal the broadband seismometers extend the lower bound of frequency sensitivity of the network from 1 Hz to <0.01 Hz and thus provide a tool to search for very low frequency tremor and earthquake signals associated magma movement. In conjunction with co-located CA bottom pressure sensors, broadband seismic records can also be used for compliance studies to search for temporal changes in S-wave velocity linked to changes in the distribution of subsurface magma. However in practice, broadband sensors deployed on bare volcanic rock are poorly coupled to the seafloor at low frequencies and subject to extensive rocking noise from ocean currents. While shielding (such as was done for the CA instruments) or encasement in concrete improves the performance of seafloor installations, the deployment of at least one broadband seismometer in a shallow borehole would add substantially to the fidelity of low frequency seismic records. A reason for drilling is that penetration beneath the seafloor may allow for perturbation experiments that could include injection of fluid tracers with both downhole sensors and cabled sensors in adjacent vents. Such measurements would provide unprecedented insights into the hydrogeology within these dynamic systems that may include the connectivity of fluid pathways and microbial habitats in the subsurface with linkages to surface environments.

### *1.4 Workshop Goals*

To understand how drilling can contribute to the communities scientific understanding of subseafloor microbiology, hydrogeology, petrology, seismology, volcanology, and geochemistry at Axial Seamount, we convened a meeting October 11-13, 2017 at Lamont Doherty Earth Observatory in Palisades, New York with 47 participants to achieve the following goals:

- Review the state of knowledge of Axial Seamount spanning biology to geophysics and including existing infrastructure and experiments already underway.
- Review the results of drilling and downhole experimentation in other bare rock and/or hydrothermally active environments.
- Discuss the current state-of-the-art drilling capabilities in hard-rock environments.
- Identify and prioritize the scientific questions at Axial Seamount that are best addressed by ocean drilling and downhole instrumentation.
- Determine the best drilling strategy and downhole instrumentation to achieve the scientific objectives at Axial Seamount.
- Determine how to best integrate downhole observatories with OOI seafloor cabled observatory.
- Determine how to develop the framework for a full IODP proposal, if the decision is to move forward.

### *1.5 Workshop Participants and Agenda*

An open call for participation was implemented and an application process that included a 2-page CV and a short paragraph about why individuals wanted to participate, with particular attention to their experience with either ocean drilling or Axial Seamount, as well as general interest in getting involved with either, particularly important for early career scientists. Given the diverse scientific questions motivating the desire to drill Axial Seamount, we had national and international participants from across the ocean drilling, marine microbiology, hydrothermal vent, marine geophysics, geochemistry, seismology, volcanology and instrumentation communities. This included participants with experience at Axial Seamount, but no ocean drilling experience, as well as participants with experience drilling into hard rock or hydrothermal environments. Three experts in hard rock drilling from IODP TAMU also participated and their insights and contributions were invaluable. In addition to USSSP support, travel costs of various participants were supported by the NSF Science and Technology Center for Dark Energy Biosphere Investigations (C-DEBI), NSF OOI, IODP TAMU, and various other individual funding resources. These additional avenues of support allowed us to expand our participant list from the 30 individuals budgeted to the 47 that attended.




**Figure 4.** Upper Left, Deb Kelley, (University of Washington) introducing the participants to the Cabled Array at Axial Seamount; Upper Right, Jay Miller (Texas A&M) presenting history and future of rock drilling with IODP; Lower Left, Gretchen Fruh-Green (ETHZ-Zürich) presenting lessons learned from IODP X357.

Given the multi-disciplinary nature of the participants, a full morning was committed on the first day to broad overview talks to bring the entire group onto the same page about the state of various research topics at Axial Seamount. Beyond those scientific talks, three technical talks focused on the challenges of drilling into hard rock and new technologies now utilized by industry, various types of borehole observatories, and the potential for linking borehole observatories to a cabled observatory. In addition to these talks, there were numerous breakout sessions over the two days. The goal of these sessions was to develop a drilling plan for Axial Seamount, beginning with the driving scientific questions and priorities and moving into the experimental design and funding mechanisms. For Breakout 1 on Scientific Questions, participants were pre-assigned and a leader identified, and the discussion was “seeded” with lists of scientific questions, as detailed in the attached agenda. For all other breakouts, participants self-selected across the groups. We also included 3-minute informal lightning presentations throughout the meeting. The third morning was with the entire group and focused on discussion of drill locations and their purpose, followed by discussion and writing activities.
The participant list and agenda as executed are included below.

*1.6 Workshop Outcomes*

Similar to most multidisciplinary scientific efforts, there were many opinions on what should (or should not) be drilled at Axial and why. Myriad science priorities were identified for using drilling to advance studies and our understanding of the state, evolution, and dynamics of the Axial hydrothermal system, including determining the thermal and chemical state of the reaction zone, defining the permeability structure of the hydrothermal system and pathways for fluid flow below the seafloor, and understanding transient behavior and system response to perturbations. Significant discussions focused on the scales of hydrological connectivity in the subsurface. The importance of comparing and contrasting results from Axial drilling efforts to the few other hydrothermal systems that have been drilled was recognized, such as sulfide mounds like TAG, sedimented hydrothermal systems like Middle Valley, and soon, the active arc volcano, Brothers Seamount.

Scientific priorities specific to subseafloor microbial and geochemical processes operating at Axial Seamount were also identified, including determining the nature and extent of microbial communities and identifying the transition between biological versus abiological processes. Additional research inquiries related to velocity changes in the crust, the 3D nature of the magma chamber, and understanding the physical nature of faults and other features were prioritized. This included inquiry related to ground-truthing geophysical data by characterizing the magma-hydrothermal interface, such as determining how heterogeneous the magmatic system is through time, what the nature of the faulting at Axial is and how this relates to mid-ocean ridges and plate tectonic processes. Finally, there was interest in defining the architecture, structure and composition of zero-age upper oceanic crust, including determining the nature of the host rock, in terms of petrology, geochemistry, and physical properties, with the goal of penetrating the apparent seismic gradient zone that comprises the seismic 2A-2B boundary.

Based on the identification of these scientific priorities, two types of drill holes were identified of interest to the attendees; 1. Holes that enable observatory-based science, e.g. instrumented holes integrated with the CA for in situ experimentation (including perturbation experiments) and multi-hole observations, and 2. Those that involve collection of rock core for examining a myriad of crustal properties, ranging from microbiology to porosity to mineralogy. In some cases, one hole could be used for both, e.g. drill a hole to collect core with subsequent instrumentation. In all cases, there was a strong desire for downhole logging and rock sampling whenever possible. In addition, many participants encouraged pairing of holes to enable experiments that allow for small scale lateral continuity (or lack of it) in the geological, hydrological, and microbiological properties of the upper oceanic crust. Placing such a pair of holes near the CA would enable real-time monitoring and experimentation over time using power and communication capabilities from the OOI infrastructure. Given this desire for such observatory-based science within close proximity to the cabled observatory, a number of participants also met to identify sensors and sampling technologies to conduct in situ experiments in boreholes, with a focus on biological and geochemical instruments.

It was especially important and useful to have IODP/TAMU engineers at the workshop to help refine drilling feasibility based on driving scientific questions and objectives. Given that Axial is zero-age basaltic crust, the challenges are substantial with respect to both core recovery, particularly in the upper 15-50 meters of basement, as well as coring to considerable depth, meaning anything deeper than 100-150 meters should not be expected within the time frame of one 6-week drilling cruise. In hard rock, the greatest challenge is getting the hole started and keeping the pipe stable, as well as keeping the hole open and stable (37). In planning, there needs to be clearly identified objectives for each hole, with a plan for engineering each hole to balance how deep the hole needs to be with how much core recovery is desired. Importantly, drilling of "shallow" holes less than 150 meter depth, would be sufficient to address many of the high priority scientific questions identified, especially if instrumented. A number of new tools on the Joides Resolution (JR) focused on seafloor visualization have improved hard rock drilling, including new HD re-entry and survey cameras, new gyro compass, new fiber optic cable, and a new dual hydraulic power system. Given the different interests and challenges of working in zero age crust, there were numerous discussions about the possibility of using a seabed drill, rather than or in addition to the JR, and a number of participants with expertise on that front also provided important feedback.

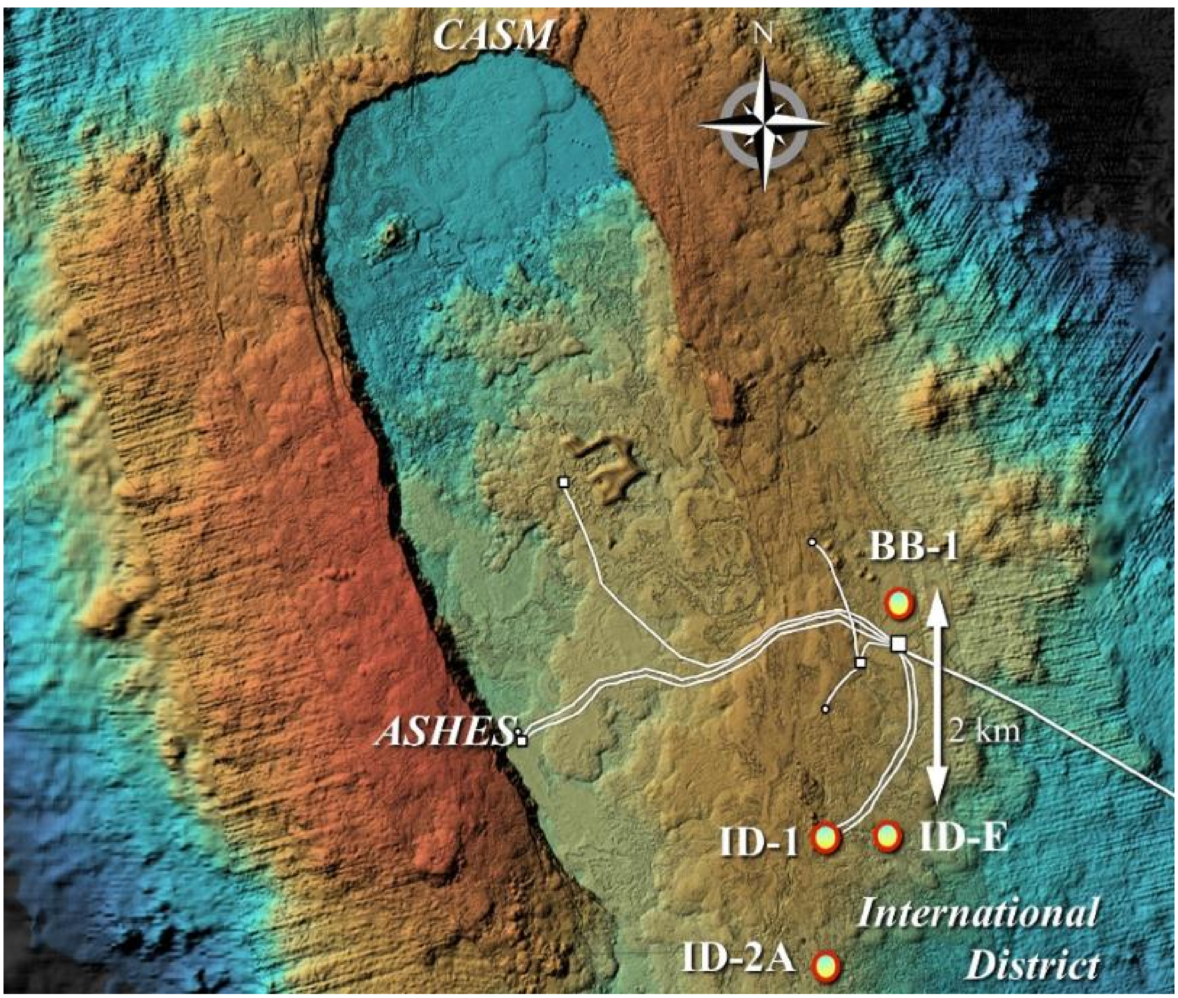

**Figure 5.** Cabled Array infrastructure at the summit of Axial Seamount in relationship to four proposed instrumented and uninstrumented drill holes at Axial Seamount.

**Table 1**. Example of 4 proposed holes for drilling Axial Seamount.

| Site | Location | Objective |
|---|---|---|
| ID-1 | Center of International District | Understand the anatomy of hydrothermal system |
| ID-E | 500 m east of 1D-1 | Investigate connectivity in the hydrothermal system over a short distance and 3-D architecture of the system |
| ID-2A | 1 km south of 1D-1 | Investigate connectivity in the hydrothermal system over a longer distance and 3-D architecture of the system. Potential location of a deeper hole seeking 2A/2B boundary. |
| BB-1 | 2 km north of ID-1 | Location in seismically active zone provides another opportunity to test conductivity over a larger length scale. Potential location of broad band seismometer. |

Beyond the challenges of drilling into zero-age oceanic crust, concerns were raised with respect to the impacts of frequent Axial eruptions on borehole infrastructure and the impacts of drilling itself on benthic animal communities. These, and other concerns, were discussed openly, and a number of plans were considered, with one example shown here. Given that Expedition 376 at Brothers Volcano will be carried out in May-June 2018, there was consensus that it would be wise to see how that expedition went before deciding how to proceed at Axial Seamount. The scientific goal of X376 is to discover key processes that distinguish submarine arc-hosted hydrothermal systems from those linked to spreading centers; this requires drilling into complicated rocky and mineral deposit substrates. A number of participants involved in X376 were at the workshop, and conversations between the Axial and Brother's groups will continue as the projects progress to make sure the lessons learned from Brother's are reflected in any future drilling Axial proposal.

Overall, there was a lot of excitement from both the national and international community in studying Axial Seamount using ocean drilling at the most advanced volcanic underwater observatory in the world, only 1.5 days from port. It is clear that there is great potential for important new scientific discoveries by coupling ocean drilling to the cabled array at Axial. The scientific motivation to drill at Axial spans diverse lines of inquiry including understanding subseafloor life, examining both the geochemical and geophysical temporal evolution of a submarine eruption, determining flow patterns and hydrogeological parameters in the subseafloor, and advancing seafloor instrumentation. Many of these scientific goals can only be addressed through ocean drilling at Axial Seamount.

### *1.7 Agenda as Executed*

**October 11, 2017**

**9:00** Welcome and Goals of Workshop: Julie Huber & Sean Solomon

**9:30** *Axial Seamount and the OOI Cabled Observatory*: Deb Kelley

**10:00** *Rock Drilling with IODP: Past and Future*: Jay Miller

**10:30** Coffee Break

**11:00** *Rock Drilling: Lessons from X357 (Atlantis Massif)*: Gretchen Früh-Green

**11:20** *Rock Drilling: Lessons from X360 (Southwest Indian Ridge)*: Jason Sylvan

**11:40** *Rock Drilling: Planning for X376 (Brothers Seamount)*: Tobias Hofig

**12:00** Q&A with all morning speakers

**12:30** Lunch Provided

**2:00** *Axial Seamount: Eruptions & Volcanology*: Bill Chadwick & Scott Nooner

**2:20** *Axial Seamount: Eruption Detection with the Cabled Array*: William Wilcock & Maya Tolstoy

**2:40** *Axial Seamount: Anatomy of the Magma Chamber*: Suzanne Carbotte

**3:00** *Axial Seamount: Petrology*: Brian Dreyer & Mike Perfit

**3:20** Coffee Break

**3:50** *Axial Seamount: Fluid Geochemistry*: Dave Butterfield

**4:10** *Axial Seamount: Microbiology*: Jim Holden & Julie Huber

**4:30** *Constraining Subseafloor Hydrogeology with Borehole Observatories*: Andy Fisher

**4:50** *Infrastructure for Borehole Observatories & Cables*: Evan Solomon

**5:10** Q&A with all afternoon speakers

**5:30** Group Dinner at LDEO

**October 12, 2017**

**9:00** Review of Day 1 Progress, Input on New Discussions, etc.

**9:15** Lightning Presentations (1 slide/3 minutes): All Participants, limit 15

**10:00** Group Discussion & Planning for Breakouts

**10:15** Coffee Break

**10:45** *Breakout #1: Scientific Priorities & Driving Questions*

What are the scientific priorities and driving questions for drilling Axial? How can your science be enhanced with drilling, e.g. science that could not be done otherwise and what might we learn?

**11:45** *Plenary #1: Scientific Priorities & Driving Questions, Review & Report*

**12:15** Lunch Provided

**1:15** *Breakout #2: Best Technologies to Achieve Scientific Priorities*

What type of instruments have you worked with or would you want for drill hole instrumentation to enhance your science at Axial? What additional instruments, measurements, or boreholes would you suggest having at Axial that would increase the scientific value of this project, pre/during/post drilling?

**2:15** *All Participants: Best Technologies to Achieve Scientific Priorities, Review & Report*

**2:45** Lightning Presentations (1 slide/3 minutes): All Participants, limit 15

**3:30** Coffee Break

**4:00** *Breakout #3: Identifying Drilling Locations, Depths, and Strategies for Moving Forward*

How can/does your science inform the placement of drill holes and drilling operations at Axial?

**5:00** *Plenary #3: Identifying Drilling Locations, Depths, and Strategies for Moving Forward, Review & Report*

**5:30** Adjourn & Dinner on your own

**October 13, 2017**

**9:00** Review of Where We Are, Outstanding Questions/Concerns & Assignment of Tasks

**9:15** *Vision for a Future Observatory at Axial Seamount*: John Delaney & Tim Crone

**9:45** *All Participants: Group discussion of a tentative plan for drilling at Axial Seamount*

**10:30** *Breakout Writing groups based on identified interest groups, e.g. seismometers, downhole instrumentation, seabed drilling, getting to the 2A/2B boundary, etc.*

**12:30** Adjourn with take away boxed lunches

## *1.8 Workshop Participants*

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