Axial Seamount – Restless, Wired and Occupied:

A Conceptual Overview of Resident AUV Operations and Technologies

Dana Manalang
Applied Physics Lab
University of Washington
Seattle, WA
manalang@uw.edu

John R. Delaney
School of Oceanography
University of Washington
Seattle, WA
jdelaney@uw.edu

***Abstract*—The Ocean Observatories Initiative Cabled Array has provided an unprecedented real-time window on the dynamics of Axial Volcano since fall 2014. In April and May of 2015, for the first time, researchers on shore were able to monitor an eruption event as it happened. The seismic, deformation and acoustic signals sent to shore were analyzed to determine the precise locations of diking events, followed hours later by acoustic impulses corresponding to lava expulsion from the seafloor. Although these locations informed follow-up Autonomous Underwater Vehicle (AUV) mapping expeditions which produced high resolution bathymetry, to date, the evolution of an eruptive event and its immediate impact on the surrounding ecosystem have not been observed. Although the 70,000 km-long mid ocean ridge (MOR) must generate many hundreds of powerful, transient events every year, they have never been characterized as they form.**

We envision a Resident AUV with in situ charging and data download capabilities, shore-based mission control, and an array of bottom-mounted acoustic positioning beacons that can concurrently be used as a multi-hop sensor network. This system will provide unprecedented observing capabilities before, during, and after the next eruption and formation of the highly energetic eruptive (mega) plume. AUV capabilities will include high-resolution bathymetry, high definition video and still imagery, and 3-D water chemistry and microbial sampling throughout the water column, while the acoustic array will monitor horizontal and vertical deformation.

Keywords—AUV, Axial, MOR, Cabled Array, OOI, acoustic network, optical communication, docking, Resident AUV, wireless power transfer

I. Introduction

The Mid-Ocean Ridge (MOR) system extends around the world as a highly active 70,000 km-long submarine volcanic mountain chain present in every ocean basin. It is continuously spreading apart, adding new seafloor material to existing plates along this global volcanic center. While most of the oceanic crust on earth is generated by eruptions along the MOR system, interactions between the submarine volcanic activity and overlying oceanic ecosystems are poorly understood owing to their remote locations beneath one to four kilometers of seawater. As a consequence, MOR eruptions are rarely observed and their immediate effects on overlying marine ecosystems have never been assessed as the process is unfolding during and shortly after the eruption when the plume is most potent. Tracking the long-term behavior of even a small section of this powerful planetary-scale submarine volcanic feature would contribute substantially to our understanding of a host of complex oceanic processes triggered by the many energetic, but short-lived MOR eruptions. There is some evidence that these plume-eddy features are similar to the much better known phenomena of Meddies [1,2].

Axial Seamount (Fig. 1) is a highly active MOR volcano located along the Juan de Fuca (JdF) spreading center between the Pacific and JdF tectonic plates. It represents the intersection of a segment of the Mid-ocean Ridge system with the present location of the Cobb-Eickelberg Seamount Chain or Hot Spot. As such, Axial Volcano stands well above the surrounding seafloor, and the ridge crest, owing to the excess magma supply from the Hot Spot. Because Axial is situated astride the spreading center, its two sides are spreading apart from one another at about six centimeters a year.

Axial is now uniquely instrumented and connected to the internet via a network of electro-optical cables extending nearly 400 km from Pacific City, OR, with extension cables distributed across the floor of the Axial Caldera. This network was recently installed as an essential component of the National Science Foundation's Ocean Observatories Initiative (OOI) Infrastructure Construction Phase (OOI Web site). It now provides real-time, interactive network connectivity and power between shore-side researchers and educators and data streaming from tens of seafloor and water-column sensor packages located on and near Axial Seamount.

In late April, 2015, the Axial sensor suite captured the seismicity, deformation, and temperature changes associated with a much-anticipated Axial eruption occurring within, and to the north of, the central caldera (green outlines in Fig. 1). The caldera is 3 km x 7 km depression in the 1500 m deep summit of this volcano. For the first time in history, a highly active submarine portion of the global MOR system has been turned into a permanent-presence, natural lab allowing scientists and educators to have direct access to the myriad processes operating along this type of planetary-scale Mid-Ocean Ridge System. This unique access offers the opportunity to make use of the unprecedented electrical power and nearly unlimited bandwidth in the form of a remote, real time, experimental laboratory to study the complex interactions of oceanic crustal formation with the physical,

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chemical, and biological systems that comprise many marine ecosystems above. The processes of such active volcanoes involve both energetic, transient eruptions, as well as the longer-term injection of exotic microbes, crustal-derived trace element chemistry (e.g. Fe), and excess thermal energy, as they are dissipated into the surrounding regional oceanic ecologies.

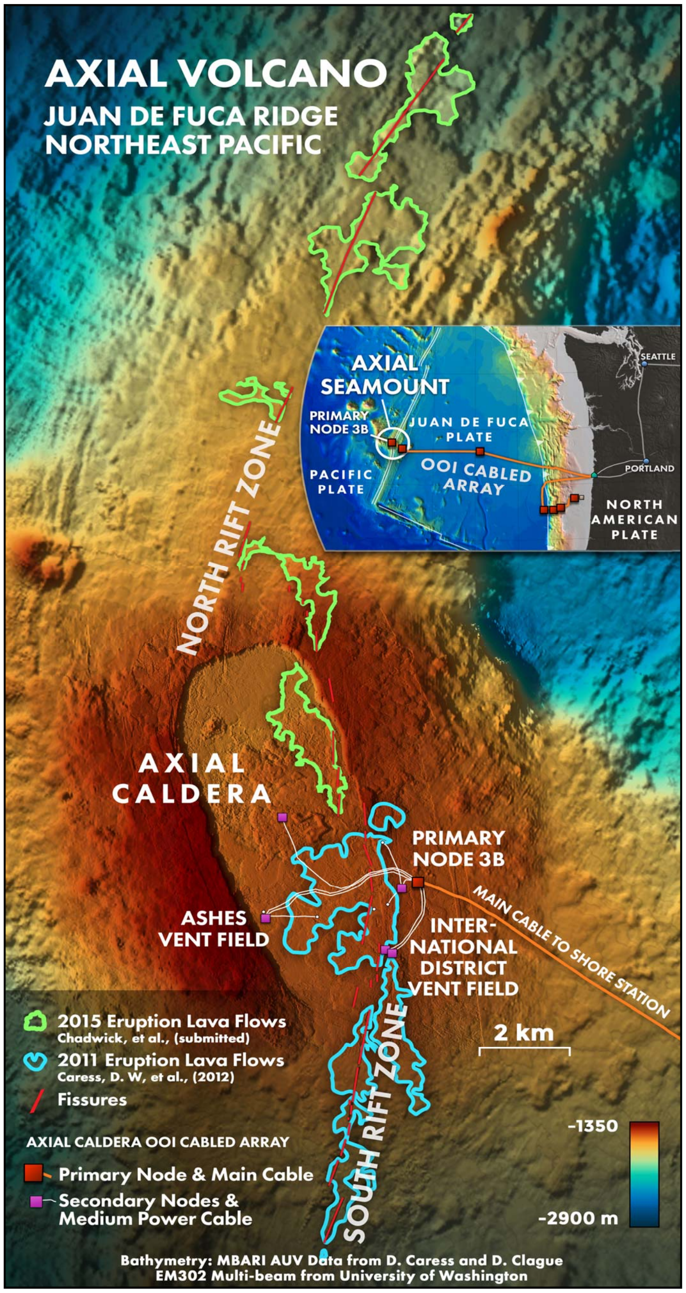

Fig. 1. Axial Volcano is small hot spot volcano situated atop the Juan de Fuca Ridge about 400 km west of the coast of Oregon. It is both wired and restless in that the OOI electro-optical cable from Pacific City is linked to a host of instruments inside the caldera and on the eastern flank of the seamount. Lava flows from two eruptions in the past 5 years are shown in colored outlines. We believe that this volcano is the perfect opportunity to deploy a "Resident" Autonomous Underwater Vehicle to constantly study the evolving physical, chemical and biological conditions in, on, and above this representative of the planetary scale Mid-Ocean Ridge System.

Although real-time data tracking of the eruption in 2015 enabled scientists to localize the events and plan response cruises, it was still months before ships could be rescheduled to survey and sample the processes operative during the eruption. Particularly disappointing was the inability of a substantial scientific community to access, quantify, and sample the dynamic, microbe-laden event-plumes, or "mega-plumes", injected into the overlying ocean during the eruption. Most of the water-column effects of this powerful, transient phenomenon were dissipated by the time the first scientific cruises investigated the region 3.5 to 4.5 months after the April event.

To date, no mega-plume has been examined during and immediately after formation, although the submarine portion of the MOR must generate many hundreds of such transient events every year, they have never been documented, quantified or even characterized as they form, evolve, and interact with normal oceanic systems, then dissipate somehow into the surrounding ocean as they migrate away from the source as Coriolis-influenced eddies. What their regional and global impacts are historically, or might be in the present climate change environment, is simply unconstrained by any data.

The difficulties our community has in responding in a sufficiently timely manner to allow submarine MOR eruptions to be fully characterized from the outset, arises from our inability to obtain foreknowledge of when and where volcanoes under the sea may erupt. Also, because most academic research vessels are committed many months, to several years, in advance and because planning for cruises is complex and time-consuming, it is clear that rerouting a ship, and an onboard Remotely Operated Vehicle (ROV), also scheduled well in advance, for an immediate eruption response cruise is simply not "in the cards".

However, we believe that there are now significant solutions to this dilemma, brought about by technological advancements on several fronts. The first is the existence of a fiber-optic network that can not only determine what is happening on a MOR system, but can determine where the major events are taking place. With that certainty in both timing and location, the power and real-time connectivity of the cabled system also enables several next generation approaches to be strategically and tactically implemented in a timely and adaptive response to such eruptive events. In the best case, an autonomous underwater vehicle (AUV) could be permanently deployed, in residence, on top of Axial Seamount with the option of interacting with a hardwired docking station connected directly to the cable, allowing batteries to be charged wirelessly and high volumes of data transmitted between AUV and shore via optical modem in near real time. The concept of this type of system is developed below, along with a fully integrated, and complementary, acoustic vehicle navigation system which will function simultaneously as a data network and horizontal-ranging geodetic system.

II. Proposed System

Developing a complete picture of how the subseafloor interacts with the overlying water column requires augmentation of existing cabled infrastructure by systems capable of:

1. Quantifying the energy, chemical, and microbial fluxes between the seafloor and water column during a volcanic eruption;
2. Characterizing, in real-time, the formation, evolution, and dissipation of eruptive plumes;
3. Tracking the evolution of seafloor features between and during eruption events; and
4. Monitoring biological populations on the seafloor and in the overlying water column.

During eruptions, which may last from days to weeks, particulate-rich and microbially-charged, thermally buoyant effluent are released, rising approximately 600 to 1000 meters above the seafloor as they coalesce into coherent plumes and large neutrally buoyant eddies, driven by Coriolis effects, along a particular pycnocline. Lava flow boundaries measured through bathymetric surveys following eruptions in 2011 [3] and 2015 [4] show that lava formation, and likely plume formation, are not localized to a single site within the caldera, but may be distributed over the surface area of a flow and perhaps the eruptive fissure itself. However, through the triangulation of seismic signals received from the cabled array, eruption locations may be determined in real-time. Therefore, the ideal system to fulfill the objectives listed above must be highly adaptable, such that it can perform multiple measurements and sensing tasks both near the seafloor and up in the water column over the entire caldera and volcanic summit, while rapidly responding to retasking signals from shore as the situation evolves in real-time.

To meet these requirements, we propose a "Resident" Autonomous Underwater Vehicle (AUV) system (Fig. 2) coupled with an acoustic array designed for navigation, ranging, and data-routing. A control/communications node and vehicle charging station will be connected directly to the cable, thereby establishing a gateway between the wireless components and the cabled infrastructure. Through this gateway, operators on shore will be able to interact with deployed vehicles and acoustic nodes in near-real time. Each individually-addressable component will be accessible, even when operating many kilometers from the gateway, through multi-hop acoustic networking. The envisioned system leverages technological advances in acoustic wireless sensor networks, AUV systems, wireless power transfer, and optical communications to deliver unprecedented long-term remote resident robotic operations.

A. *Acoustic Navigation, Ranging and Communications Network*

Acoustic transponders are regularly used in the ocean as navigation and ranging beacons, and as low-bandwidth data links. Many modern acoustic devices combine these functions in a single unit. Despite the challenges of limited sound propagation speed (in comparison to radio frequency signals on land), and acoustic rays refracting upward from the seafloor, Freitag et al demonstrated reliable acoustic communications at 2 km spacing between nodes mounted near the seafloor and transferring data to the MARS cabled

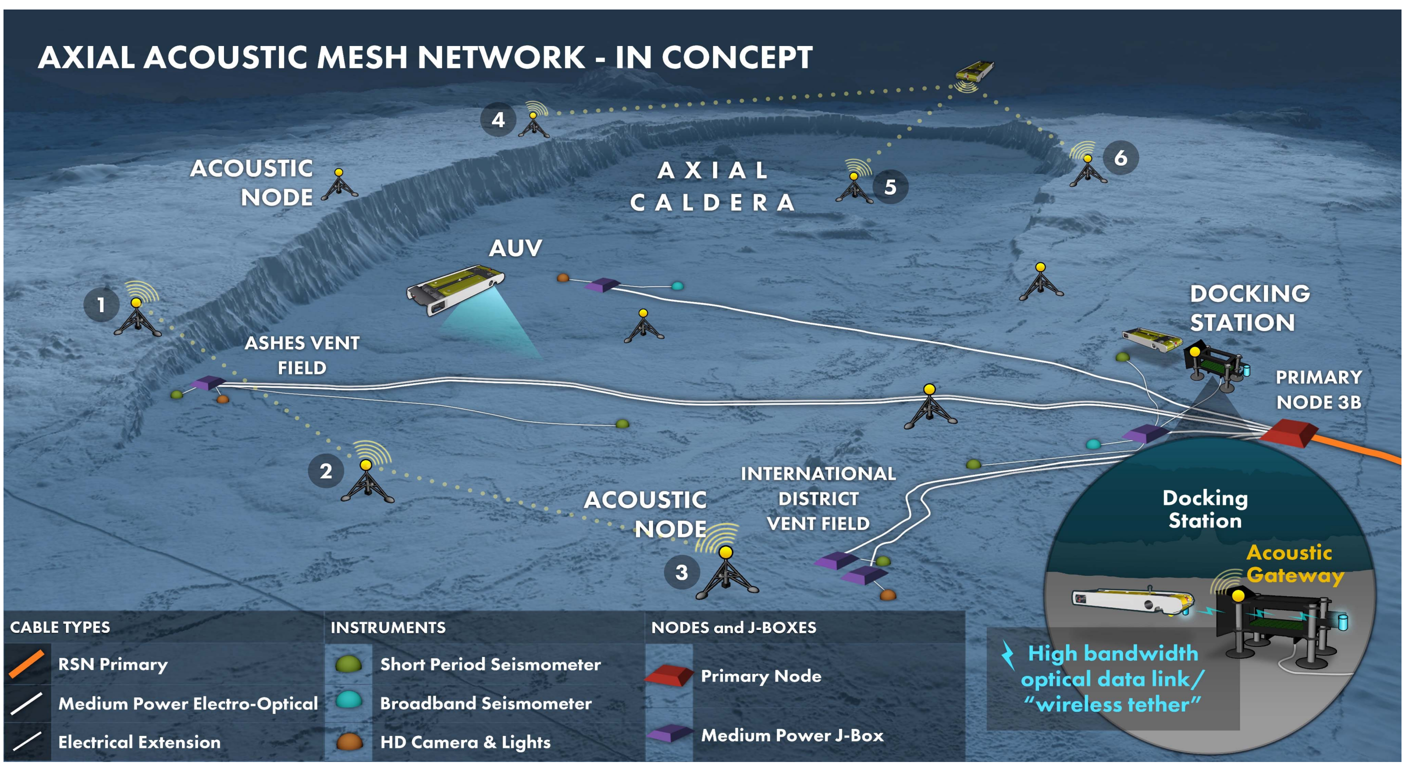

Fig. 2. Notional representation of AUVs operating at Axial caldera, with acoustic nodes in place as navigation beacons, horizontal ranging sensors, and data routers. A docking station is connected to the cabled infrastructure. Each acoustic node is capable of determining precision horizontal ranges to its neighboring nodes (e.g. node 2 ranges to nodes 1 and 3), providing a geodetic array to monitor spreading across the rift zones. The same acoustic transponders will act as navigation nodes for AUVs operating over the caldera and nearby vicinity (e.g. nodes 4, 5 and 6 provide navigation information to an AUV at the north end of the caldera).

observatory [5]. In multiple other studies, network protocols, descended from RF and cellular applications, have been modeled and implemented in ocean applications [6,7].

In the proposed Axial network, at least one acoustic gateway node will be connected, at the docking station, to the cabled infrastructure. At 2 km spacing, an array of 10 wireless nodes would adequately span the 7km x 3 km caldera, with each node able to "talk" to one or more of its nearest neighbors. Each acoustic node will be capable of routing incoming data "telegrams" toward the cabled gateway to be subsequently transmitted ashore through the electro-optical cable.

The Axial acoustic network serves multiple purposes. It is:

1. An AUV navigation array: As an AUV navigates the caldera it will maintain accurate location awareness through position information transmitted to it by acoustic nodes.
2. A real time two-way communications interface: As AUV operations progress several kilometers away from cabled infrastructure, the AUV will periodically report its location to the nearest acoustic node, which will propagate that data towards the gateway, giving remote operators real-time feedback on AUV operations. In response to an event detection on the cabled infrastructure, the acoustic network will broadcast a re-tasking message, sent from shore, to remote AUVs. Without this capability, it could be many hours before an AUV might return to the dock from a mission.
3. A seafloor deformation detection array: Accurate horizontal ranging between acoustic nodes coupled with integrated pressure sensors will be used to detect centimeter-scale or smaller deformations in the seafloor. This technique was demonstrated by Chadwick in 2000 [8], and can be enhanced by using the Resident AUV to precisely measure sound velocity between node pairs. Changes in seafloor venting patterns that may influence sound speed may also be detected and disambiguated from horizontal deformations by this method.
4. A flexible means of laboratory expansion: Once deployed, the acoustic network will provide a means of adding low bandwidth sensors and instrumentation to Axial Seamount without the need for running new cables. Each added nodes provides increased acoustic link redundancy to the network.

Underwater fixed/mobile networks have been demonstrated and used for a variety of applications, including under ice research [9] and military systems [10]. Unlike pure ad hoc networks, where each node has knowledge only of itself and its nearest neighbors, a "headed" network, with a single point of data collection at the gateway, allows for a global view of network. This enables efficient routing assignments to be managed from shore and modified as the network evolves.

B. *Resident AUV*

AUVs have played an increasingly important role in Mid-Ocean Ridge Science. On Axial volcano, multiple high resolution AUV surveys have been performed by the MBARI Mapping AUV (Dorado) over the last decade [11,12], effectively identifying eruptive fissures and characterizing new lava flows. Prior to the installation of the OOI cabled array, these campaign-style expeditions provided a primary means of determining that an eruptive event had actually occurred, but because these capable platforms arrived on the scene long after the volcanic plume was dissipated, operations to date have been unable to characterize the evolution of the oceanic portion of the eruptive event and it's immediate impact on the surrounding marine ecosystems.

Stationing a Resident AUV on Axial provides "new eyes" with which to view and explore transient MOR events as they happen. Coupled with a cabled docking station and acoustic network that functions as both a long baseline navigation array and a communications network, the AUV will be able to conduct seafloor mapping as well as data collection throughout the water column with accurate positioning and the ability to transmit and receive on-the-fly information and re-tasking to and from shore-based operators.

The AUV will periodically report its position through the network to operators on shore. In order to carry out its objectives, it will regularly transit near the seafloor for video documentation or sonar imaging, and within the water column, from 500m to 1600m water depth, to measure a variety of water properties. The Axial Resident AUV payload could be similar to other research and mapping class AUVs, such as WHOI's Sentry AUV and MBARI's Dorado class AUVs.

The following list represents a likely set of on-board science and engineering sensors:

Science Sensors	*Engineering Sensors*
Multibeam Sonar	Inertial Navigation System (INS)
Sidescan and Sub-bottom Sonar	Doppler Velocity Log (DVL)
High definition Video Camera	Sound Velocity Sensor
Conductivity, Temperature, Depth (CTD)	Depth Sensor
Dissolved Oxygen sensor	Attitude Sensor (pitch/roll/yaw)
Eh sensor	Forward-looking sonar (obstacle avoidance)
Methane sensor	Acoustic Modem/Navigation Beacon
Turbidity Meter	Optical Modem

The Resident AUV system will operate in one of two modes: baseline mode or event response mode. In baseline mode, the AUV will conduct regular mapping, imagery collection, and water column missions. At the leisurely pace of less than two 10-hr missions per week, the AUV could complete a high-resolution bathymetric survey of the entire caldera every two months and have plenty of time to spare for water-column work, video collection, and horizontal sound velocity profiles to improve ranging by the acoustic nodes. Between missions, the AUV will return to its docking station to wirelessly recharge its batteries and to optically upload data to be transmitted, via cable, to shore.

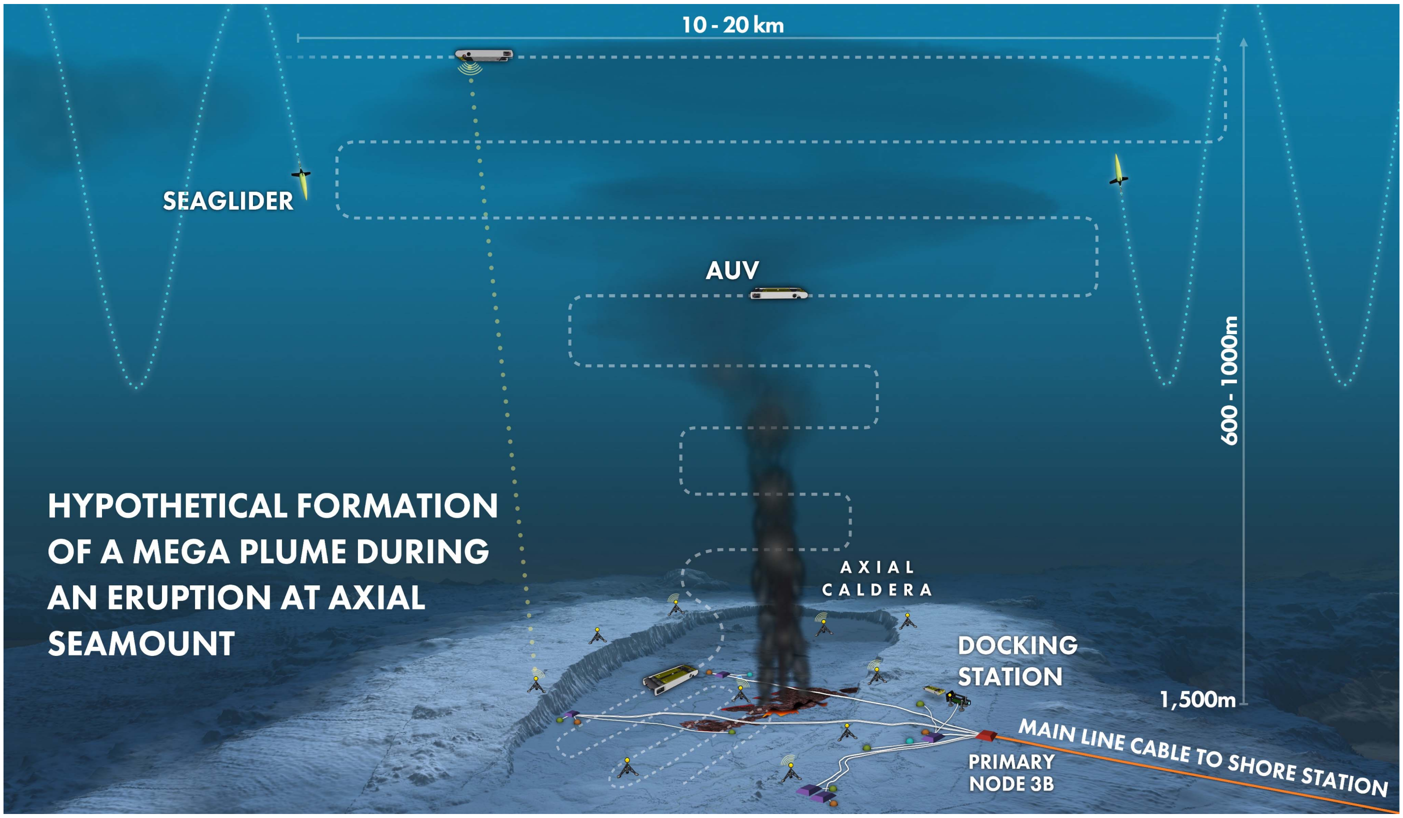

Fig. 3. Coincident with the onset of significantly increased earthquake swarms and with settling of the seafloor within the caldera detected by cabled sensor arrays, the generation of an eruptive plume is likely to originate near the actual lava eruptive site as depicted here in an artist's conception of the event. The significant thermally driven buoyancy flux results in a plume rise height of as much as 1,000 meters above the seafloor. The cabled system can empower a Resident AUV to be programmed for either routine or specific missions depending on the activity of the volcano. Complex AUV track lines can continuously define the boundaries and the characteristics of the plume as it is forming and evolving through time, by being able to recognize the plume boundaries and act upon that recognition to change its path. The notional gliders would be complementary to the work of the AUV, helping to simultaneously define the plume within the broader context of the surrounding oceanic ecosystem.

When not conducting one of its primary scientific missions, the AUV will perform inspections and servicing of other installed equipment. For example, an AUV might transit to an acoustic node reporting that it has a low battery and a large amount of stored data that is impractical to send over the acoustic link. Acting as a power and data agent, the AUV would use its own stored energy to recharge the node while simultaneously uploading stored data for transfer to the gateway.

The operational tempo of the AUV will significantly ramp up with the first detection of an eruption event, likely to occur through real-time analysis of cabled seismic data. If the AUV is currently operating away from the dock, the acoustic network will be used to send a basic set of re-tasking commands. Throughout the eruption event, the AUV will operate continuously to monitor the eruptive plume and dynamic seafloor, stopping only for battery charging and simultaneous data upload. Data aggregated on shore from cabled components and the AUV will provide inputs into missions created 'on-the-fly' to observe the evolution of the eruptive event.

Fig. 3 depicts AUV operations both within the eruptive plume and near the seafloor. Complementing the Resident AUV observations, autonomous gliders would provide further tracking of the plume's signature as it dissipates, and begins to migrate away from the eruption site.

Because the volcanic plume is buoyant at the seafloor and rises through the water column, spreading as it rises, precision navigation and vertical stability control will be required of the AUV. Most mapping AUV systems rely on an on-board Inertial Navigation System (INS) to maintain position awareness, but even the most accurate laser ring gyro INS systems can drift without corrections from auxiliary systems, like the Doppler Velocity Log (DVL), GPS or shipboard USBL. Subsurface, there are no GPS signals and once the AUV rises up 100-200m off of the seafloor, DVL beams can no longer track the bottom. However, with an array of fixed nodes at known locations, the AUV can use Long Baseline techniques to maintain sub-meter navigation accuracy.

Effective characterization of the eruptive plume requires maneuverability and, ideally, hovering within the plume. Multi-thruster AUV designs, like WHOI's Sentry and the Saab Sabertooth, can deliver up to six degree of freedom maneuverability. While multiple thruster systems are generally more maneuverable, there are often power consumption tradeoffs when compared to a single thruster, torpedo-shaped AUV. Conveniently, operating within the range of a submerged docking station with ample power available for battery recharge makes this a reasonable trade in return for the precise vehicle control that is realized in return.

C. *Docking Station (wireless power and high-speed data transfer)*

The key system that enables expansion from the cabled array to a wireless network of fixed and mobile nodes is the AUV docking station/communications gateway. The docking station will transfer power to the AUV system, and serves as the gateway to the cable's high-bandwidth data network. The most efficient way to transfer power and data is through physical wired connections, but autonomously mating a connector to the AUV requires a precision mechanical coupling that is difficult to mate and can wear over time with repeated mate/demate cycles, thereby reducing the integrity of the connection. Multiple wireless power and data transfer technologies offering high power transfer efficiency and respectable bandwidths, respectively, have recently been developed and demonstrated in ocean environments.

The McLane deep profiling system, modified by the University of Washington and installed on the OOI cabled array, uses inductive battery charging to transfer energy from the cable, and wifi communications to download data [13]. While inductive charging requires very close range, adaptive resonant wireless power transfer techniques are now being used to achieve 70% power transfer efficiency with less sensitivity to range and alignment of transmit and receive coils [14]. These systems are well-suited to subsea operations as they are fully functional in salt water, and the coils can be molded into non-corrosive polymers.

The acoustic network used for positioning and simple commands is not practical for the large volumes of data that will be collected by the AUV system. Multibeam and video files can easily reach several gigabytes, so efficient data transfer is imperative. Therefore, it will be necessary to equip the AUV docking station with a complementary high-bandwidth data transfer system. optical modems, developed at Woods Hole Oceanographic Institute [15] and commercialized by Sonardyne, are capable of data rates of up to 500 Mbps [16], making them an attractive solution for wireless data transfer. With ranges up to 50m, optical modems can also enable "wireless tether" AUV operations, during which a remote operator (on land) takes full control of AUV operations with real-time video feedback.

III. TECHNICAL CHALLENGES

Autonomous Underwater Vehicle (AUV) system residency represents a significant step for AUV systems, which are typically deployed from surface ships and recovered for data download and battery recharge after tens of hours of operations. Deployments that may last months to years present the specific challenges of maintaining system reliability and conducting long-term autonomous operations.

A Resident AUV must operate reliably for months to years between maintenance cycles. Because most of the AUVs in use today have much shorter mission times, it is often acceptable to replace or service worn or failed components frequently. As documented by Podder, et al, of MBARI in 2004, there are multiple failure modes for AUV systems [17]; however, the system's mean time between failure improves over time as faulty or premature subsystem failures are corrected. To achieve long-term residency, a thorough review of component and material selection should be conducted as well as extensive testing. By incorporating more rigorous industrial practices, such as accelerated life testing, we can develop confidence in the vehicle's ability to endure long deployments, just as we expect our appliances and automobiles to operate when we need them.

Docking stations for AUVs were demonstrated by MBARI in 2008 [18], with a number of custom docking stations being developed by commercial vendors like Kongsberg-Hydroid, Battelle-Bluefin, and Saab Underwater Ltd. since then. To make long term Resident AUV operations feasible, autonomous docking operations must become routine, which requires both precise vehicle control and sophisticated guidance systems. Most docking stations use acoustic homing signals to guide AUVs into docked positions, but it is also possible to augment the acoustic system with optical signals and computer vision [19].

Wireless charging systems have been demonstrated both on land and in water, but these systems must be integrated with sophisticated AUV docking stations and hardened for long-term operations in the extreme environments of the deep ocean.

Because of increasing demand for Resident AUV systems, not only for academic research, but also in industry, new advanced AUV systems, like the Saab Sabertooth [20], are being developed to meet offshore vehicle residency needs. As AUV developers look to fill this demand, it may open up unique partnering opportunities between academic, industrial and military AUV users.

IV. DISCUSSION

We have argued that unique scientific and technological opportunities arise from the recent successful implementation of the OOI Submarine Sensor-Robotic Fiber-optic Network off the WA-OR Coast. These opportunities build on the considerable real-time instrumental coverage of a portion of the Juan de Fuca Ridge, as well as continuous access to unprecedented electrical power and communications bandwidth at Axial Seamount, a highly active Mid-Ocean Ridge Volcano. There has never been comprehensive scientific documentation of any submarine volcanic eruption before, during, and after the eruptive event to analyze the impacts that such a common phenomenon must have on the overlying oceanic ecosystems.

We will be able to measure high-energy fluxes of heat, chemicals, organisms and particulates that issue from below the seafloor and mix rapidly with the dynamic overlying ocean. Technologically, we are now in a position to support a highly capable, fully controlled, extensively instrumented Resident AUV docked on a link connecting through the existing cabled infrastructure (shown in Figs. 1, 2, and 3). By pursuing this combination of opportunity and challenge, ocean scientists could, for the first time ever, demonstrate the ability to remotely detect, define, respond to, and thoroughly characterize a dynamic and complex oceanic system as it occurs in real-time, taking samples, making measurements of temperature, chemical, particulate and microbial gradients within an unpredictable transient event.

In an era of changing climatic patterns, ocean acidification, fossil fuel depletion, remote ecosystem assessment, management and policy development, we have an opportunity to vastly enhance our ability to interactively document and understand the natural interplay of the complex processes that comprise our global ocean ecosystem. At present, we know relatively little of the processes taking place within the oceans of our home planet. Energetic eruption events on the MOR system offer an opportunity to develop novel, generalizable, interactive approaches to understanding spatial-temporal variations in the oceans, with humans "in the loop", without having to be physically present. Utilizing these opportunities to develop flexible and highly capable remote systems as extensions of human inquiry and discovery in the undocumented domains of the ocean will become increasingly valuable in the coming decades.

A Resident AUV system elegantly addresses these scientific objectives while offering a multitude of synergies as an augmentation to the existing cabled infrastructure. Despite the challenges of the harsh seafloor environment for long-term autonomous operations, the building blocks of the system: an acoustic navigation, ranging and data network; capable and reliable AUV platforms; and cabled AUV docking system components, including wireless power and optical data transfer, exist and have been demonstrated both theoretically and in practice.

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