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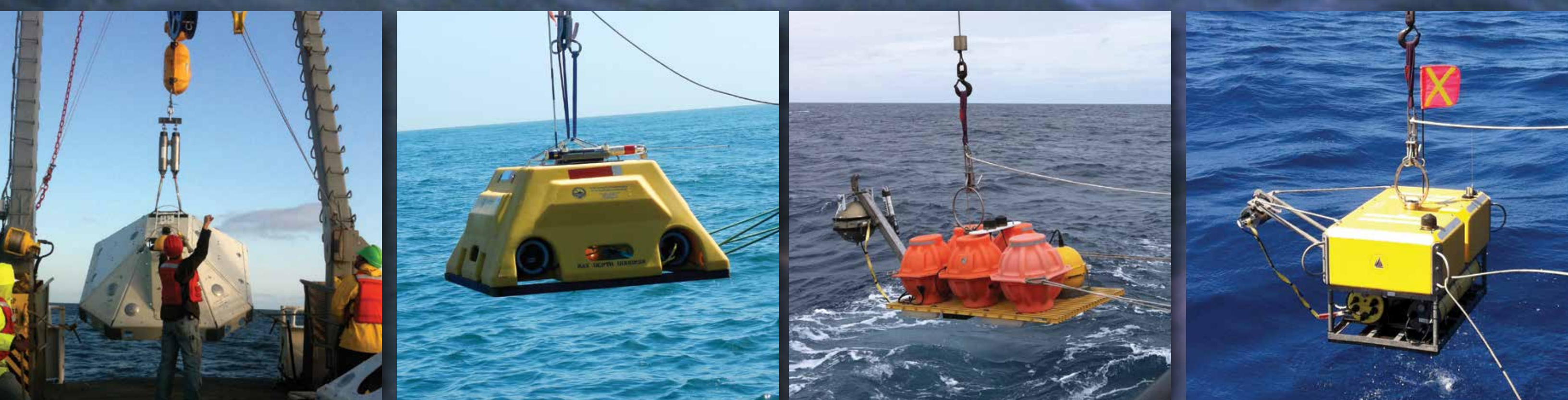
THE CASCADIA INITIATIVE

A Sea Change In Seismological Studies of Subduction Zones



Photos of ocean bottom seismometers (OBSs) used in the Cascadia Initiative. From left to right: Trawl-resistant mount OBS from Lamont-Doherty Earth Observatory, Abalone trawl resistant OBS from Scripps Institution of Oceanography, Woods Hole Oceanographic Institution (WHOI) Keck OBS, and WHOI American Recovery and Reinvestment Act funded OBS. See text for details.

BY DOUGLAS R. TOOMEY, RICHARD M. ALLEN, ANDREW H. BARCLAY, SAMUEL W. BELL, PETER D. BROMIRSKI, RICHARD L. CARLSON, XIAOWEI CHEN, JOHN A. COLLINS, ROBERT P. DZIAK, BRENT EVERS, DONALD W. FORSYTH, PETER GERSTOFT, EMILIE E.E. HOOFT, DEAN LIVELYBROOKS, JESSICA A. LODEWYK, DOUGLAS S. LUTHER, JEFFREY J. McGUIRE, SUSAN Y. SCHWARTZ, MAYA TOLSTOY, ANNE M. TRÉHU, MICHELLE WEIRATHMUELLER, AND WILLIAM S.D. WILCOCK

ABSTRACT. Increasing public awareness that the Cascadia subduction zone in the Pacific Northwest is capable of great earthquakes (magnitude 9 and greater) motivates the Cascadia Initiative, an ambitious onshore/offshore seismic and geodetic experiment that takes advantage of an amphibious array to study questions ranging from megathrust earthquakes, to volcanic arc structure, to the formation, deformation and hydration of the Juan De Fuca and Gorda Plates. Here, we provide an overview of the Cascadia Initiative, including its primary science objectives, its experimental design and implementation, and a preview of how the resulting data are being used by a diverse and growing scientific community. The Cascadia Initiative also exemplifies how new technology and community-based experiments are opening up frontiers for marine science. The new technology—shielded ocean bottom seismometers—is allowing more routine investigation of the source zone of megathrust earthquakes, which almost exclusively lies offshore and in shallow water. The Cascadia Initiative offers opportunities and accompanying challenges to a rapidly expanding community of those who use ocean bottom seismic data.

INTRODUCTION

A major earthquake comparable in magnitude to those that occurred in Sumatra in 2004, Chile in 2010, and Japan in 2011 has, and will again, hit the Pacific Northwest (PNW). The source of this potentially devastating earthquake will be the Cascadia subduction zone, which extends over 1,100 km from Cape Mendocino, California, to northern Vancouver Island, British Columbia. The occurrence of large earthquakes in the past along this boundary was first documented by Atwater (1987), and the date of the most recent event was determined by Satake et al. (1996) to be January 26, 1700, based on historic tsunami records in Japan. Onshore and offshore paleoseismic work over the past two decades has refined the history of earthquakes along this boundary. It indicates an average recurrence interval of 500 years over the past 10,000 years, with individual intervals between earthquakes varying from a few hundred to 1,000 years and recurrence intervals that are less in southern Cascadia relative to northern Cascadia (see Clarke and Carver, 1992; Kelsey et al., 2005; Goldfinger, 2011; Goldfinger et al., 2012; Witter et al., 2012).

Our society is not well prepared for an earthquake of this scale in the PNW. If a magnitude 9 earthquake along the coast occurred today, the US Federal Emergency Management Agency (FEMA) estimates that the direct financial losses would be $60 billion USD, while the Insurance Bureau of Canada expects losses of ~ $75 billion CAD in Canada. Because the locked zone of the Cascadia megathrust lies offshore in shallow water, preventing easy and relatively inexpensive means of studying its structure and monitoring its activity, we do not understand it as well as onshore faults. However, several ongoing initiatives and monitoring efforts—including the US National Science Foundation (NSF)-supported Cascadia and Ocean Observatories Initiatives, the US Geological Survey (USGS)-supported Advanced National Seismic System, and Ocean Networks Canada—are laying a solid foundation for assessing and thus ultimately helping to mitigate the seismic and tsunamigenic hazards of a great earthquake in the PNW. Here, we focus on the Cascadia Initiative (CI), including its diverse scientific objectives, novel instrumentation, community-based organization, and data products and opportunities available to the community.

CASCADIA SUBDUCTION ZONE

The Cascadia subduction zone lies where the North American Plate is overriding the much smaller Juan de Fuca, Explorer, and Gorda Plates (Figure 1). Because the subducting Juan de Fuca Plate is young (5–10 million years old) and thus warm, the locked zone that fails in megathrust earthquakes is relatively shallow and lies mostly offshore (see Flück et al., 1997; Hyndman, 2013). GPS and leveling measurements document northeastward compression above the megathrust, indicating that it is presently locked and accumulating interseismic strain and is in the late (high stress and low strain rate) stage of the subduction cycle (Dragert et al., 1994; Mitchell et al., 1995; Wang, 2003; Burgette et al., 2009; Chapman and Melbourne, 2009; Holtkamp and Brudzinski, 2010; McCaffrey et al., 2012, 2013). Despite the accumulating strain and the history of great earthquakes, the current seismicity is largely confined to intermediate depth, in-slab events in the downgoing Juan de Fuca Plate, largely beneath the Puget Lowland and around the Mendocino Triple Junction, and eerily is almost nonexistent on the plate boundary (Wells et al., 1998; McCrory et al., 2012). Confirmed low angle thrust earthquakes on or near the plate boundary are restricted to the M7.2 Petrolia earthquake of 1992 (Oppenheimer et al., 1992; Velasco et al., 1994; Hagerty and Schwartz, 1996) in northern California and a handful of much smaller events along the southern half of the subduction zone. This includes several clusters of events on the plate boundary offshore Oregon (Tréhu et al., 2008) that may be related to heterogeneity in the upper and lower plate crust (Tréhu et al., 2012).

Assessing the seismic and tsunami hazards of the Cascadia megathrust requires knowledge of the downdip and updip limits of the locked zone that generates earthquakes and how these limits vary along strike (see Hyndman, 2013). Of particular interest for assessing earthquake hazards are the downdip limits of the seismic source zone. A larger downdip extent places the seismic source zone closer to major metropolitan areas, thus exposing critical infrastructure to more intense shaking during an earthquake. Figure 1 shows an early model of the along-strike variation of the Cascadia seismic source zone. The landward extent of the seismic source zone is greatest near Puget Sound due to the shallow dip of the subducting slab in this region, whereas the possible source region is offshore central Oregon. Little is known about the updip limit of the seismic source zone in Cascadia; however, if it extends to the seafloor—as it did in the 2011 Tōhoku earthquake—the tsunami generated by a Cascadia event may be more devastating than the strong shaking produced by the earthquake.

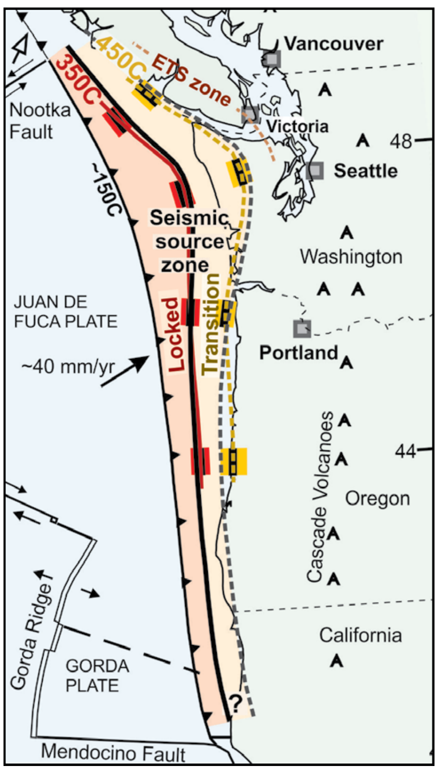


Figure 1. Map of the Pacific Northwest showing plate boundaries, convergence rates across the Cascadia subduction zone, and the approximate extent of fully locked (black line) and transition (dashed line) zones inferred from leveling and tide gauge geodetic data. *From Hyndman (2013), based on Flück et al. (1997)*

THE NSF CASCADIA INITIATIVE

The CI is an onshore/offshore seismic and geodetic experiment that takes advantage of new technology—an amphibious array—to study questions ranging from megathrust earthquakes, to episodic tremor, to volcanic arc structure, to the formation, deformation, and hydration of the Juan de Fuca and Gorda Plates. These wide-ranging science objectives were developed by an NSF-supported, community workshop convened in Portland, Oregon, in October 2010[1]. We briefly summarize these objectives in the online Supplementary Information. The Cascadia Initiative was featured in Vice President Biden's list of "100 Recovery Act Projects that are Changing America"[2] under the heading "Research to Avert Disaster: Understanding Earthquakes in the Pacific Northwest—Oregon, Washington, Northern California."

Two novel aspects of the CI are changing both practices and capabilities within the ocean sciences community. First, the CI is a community-based experiment, meaning that the scientific community vets its scientific objectives, experimental design, and logistical implementation, and that all resulting data are publicly available. Second, the CI is deploying a new generation of ocean bottom seismometers (OBSs) that are designed to withstand direct hits from bottom-trawling fishers and that are equipped with sensors shielded from ocean bottom currents, thereby opening up the shallow marine environment (< 1,000 m) for more routine geophysical investigations. Below, we discuss how these sea changes in practices and capabilities are benefiting science, attracting a new generation of seismologists, and delivering results that will benefit society.

Experiment Design and Implementation

Addressing the diversity of the CI science objectives requires an ambitious, plate-scale seismic experiment, one that encompasses both onshore and offshore components of the Cascadia subduction zone as well as the underthrusting Juan de Fuca Plate. The 2010 CI Workshop concluded that the OBS component of the CI should comprise both a plate-scale deployment of OBSs that replicated the 70 km spacing and 18-month duration of the EarthScope Transportable Array (http://www.usarray.org/researchers/obs/transportable) and a tighter array along the subduction zone, including several focused experiments at key sites (Figure 2). To achieve this coverage, the CI leverages seismic instrumentation from a number of international facilities, regional monitoring networks, and experiments proposed

[1] http://www.oceanleadership.org/wp-content/uploads/2010/05/CI_Workshop-Report_Final.pdf
[2] http://www.whitehouse.gov/sites/default/files/100-Recovery-Act-Projects-Changing-America-Report.pdf

by principal investigators (PIs). The available onshore and offshore instrumentation is described below.

Amphibious Array Facility

The onshore seismic component of the Amphibious Array Facility (AAF) consists of 27 EarthScope USArray Transportable Array (TA) seismic station sites that have been deployed to complement the existing distribution of broadband stations in Cascadia. All 27 sites incorporate a broadband velocity sensor (Nanometrics Trillium 240 recording at 40 sps) and a strong-motion accelerometer (100 sps).

The offshore seismic component of the AAF consists of 60 OBSs operated by the Ocean Bottom Seismograph Instrument Pool (OBSIP). All 60 OBSs are equipped with Nanometrics Trillium Compact seismometers. In addition to the seismometers, the Scripps Institution of Oceanography (SIO) and Woods Hole Oceanographic Institution (WHOI) OBSs are equipped with differential pressure gauges (DPGs) while the Lamont-Doherty Earth Observatory (LDEO) OBSs carry absolute pressure gauges (APGs). The CI also utilizes 10 additional Keck OBSs owned by WHOI; these instruments are equipped with a Guralp CMG-3T broadband seismometer, a Kinemetrics Episensor strong-motion accelerometer, and a DPG.

Thirty-five of the AAF OBSs were designed to meet new challenges of shallow-water (< 1,000 m deep) recording along the continental shelf and slope of the Cascadia margin. Instrumenting this region, directly above the locked zone of the fault, was critical to the experiment but required novel approaches and instrument designs to address the problems of bottom trawling, seafloor currents, and increased ocean wave noise. The photos on the first page of this article show the SIO Abalone and LDEO Trawl Resistant Mount (TRM) OBSs. Both instruments house the electronics and the seismometer within a shield whose profile is designed to deflect bottom-trawling nets and that reduces environmental noise resulting from bottom currents. The SIO Abalone free-falls to the seafloor, and upon command, releases an anchor that allows it to float to the surface for recovery; this instrument can be deployed at all water depths shallower then 6,000 m. The LDEO OBS houses the electronics and the sensor beneath a large (1,500 lb or 680 kg) steel frame. It is deployed using a heave-compensated winch and recovered by either a pop-up buoy (for depths < ~ 200 m) or a remotely operated vehicle (~ 200–1,000 m depth). The LDEO TRM can be deployed at depths < 1,000 m.

Regional Broadband Seismology Networks

In addition to the USArray TA sites reoccupied with American Recovery and Reinvestment Act of 2009 (AARA) funding, there is a large network of onshore broadband seismometers in the Cascadia region led by the Pacific Northwest Seismic Network, the Northern California Seismic Network, and the Geological Survey of Canada. Ocean Networks Canada also operates four broadband seismometers offshore as part of its NEPTUNE cabled seafloor observatory (see Heesemann et al., 2014, in this issue). There are plans for the NSF Ocean Observatories Initiative

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to install four more cabled broadband seismometers on the seafloor offshore of Cascadia. The combination of these instruments provides a stable, long-term, onshore-offshore regional network consisting of over 120 broadband instruments in which the CI's program of annual OBS experiments are embedded.

Offshore Temporary Seismic Arrays

A number of temporary deployments of OBSs that are independent of the CI have occurred in recent years or simultaneous with the CI. These operations provided additional data for a variety of studies that can be integrated with CI data. In some cases, passive OBS deployments were coordinated with the CI to maximize the overall combined data set. Additionally and contemporaneous with the CI, in 2012, two active-source seismic experiments collected high-resolution images of the crust and uppermost mantle that complement the CI data and science objectives. We describe these various experiments and the available data sets in the online Supplementary Information.

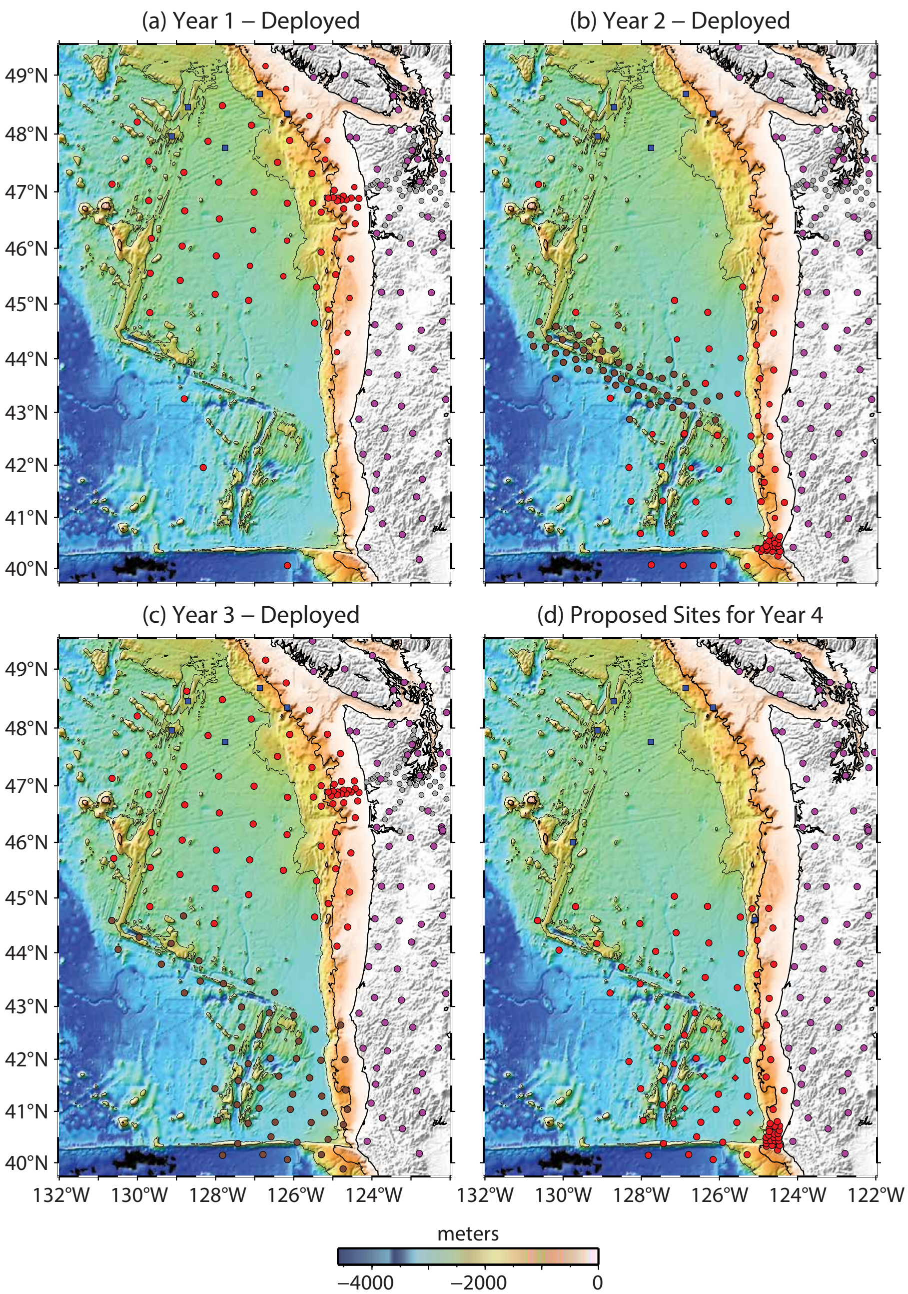

Figure 2. Maps showing the deployment positions of Cascadia Initiative (CI) ocean bottom seismometers (OBSs) for Years 1 to 3 (a–c) and the planned deployment positions for Year 4. Red circles indicate CI OBSs. Brown circles indicate deployment locations of principal-investigator-driven experiments that complement the CI design.

Implementing the CI OBS Experiment

The Cascadia Initiative Expedition Team (CIET) is a group of scientists who lead seagoing expeditions to deploy and recover CI OBSs and who develop related education and outreach modules. The PI team, which is knowledgeable about CI science and operational objectives and represents both the continental and the marine seismology communities, includes individuals with marine chief scientist experience as well as individuals who have not yet been to sea.

The OBS component of the CI is well underway. Figure 2 shows the location of OBSs deployed during the first three years. The CI OBS deployment plan divides the region into Cascadia North deployments in Years 1 and 3 and Cascadia South deployments in Years 2 and 4, resulting in a total of ~ 280 OBSs deployed and recovered at ~ 160 different sites. Each 10-month deployment is composed of three elements: a plate-scale reference array of broadband instruments, a TA-scale deployment of wide-band OBSs (70 km spacing), and a more dense, focused deployment on the continental shelf and slope above the thrust interface. By switching between North and South, the initiative can take advantage of the infrastructure and experiments described above, including the following key design objectives: to provide coverage of the seismically active forearc region between Vancouver Island and Ocean Networks Canada's NEPTUNE nodes; to provide dense coverage in the high-priority GeoPRISMS corridor off Grays Harbor, WA; to occupy sites along active source transects between the Endeavour Segment of the Juan de Fuca Ridge and Grays Harbor, WA, and between Axial Seamount and Hydrate Ridge off Oregon; to align rows of stations subparallel to the relative spreading direction; and to overlap the Cascadia Regional Arrays by ~ 200 km, thereby allowing four continuous years of monitoring of what is thought to be a segment boundary along the Oregon forearc.

Cascadia Reference Array

The Cascadia Reference Array is composed of broadband OBSs (WHOI Keck OBSs) and cabled OBSs that are part of Ocean Networks Canada. The Cascadia Reference Array sites were occupied during each of the first three years of the CI to provide continuous plate-scale monitoring of larger magnitude seismicity. The Cascadia Reference Array also provides a stable backbone for structural studies, thus facilitating integration of data from the Cascadia North and South deployments.

Cascadia Regional Array

The Cascadia Regional Array provides interstation separation of ~ 70 km (comparable to the TA) covering the Juan de Fuca and Gorda Plates and their boundaries. This allows seismic imaging of the subduction zone, including the mantle wedge, the subducting plate, the asthenosphere beneath the subducting plate, and the structure near the edges of the Juan de Fuca/Gorda plate system, including key features that contribute to edge dynamics. Over the forearc, the Cascadia Regional Array has a smaller interstation separation of ~ 35 km, with the goal of capturing seismic activity or tremor that may exist along the updip extension of the subduction zone. This also provides coverage of the forearc prism to document regional changes in the style of deformation, the extent of the updip locked zone, and the structural heterogeneity of the forearc.

Cascadia Focused Arrays

Each year of the CI includes a focused array with inter-station spacing of 5–10 km. The focused array sites for Years 1 and 3 are off Grays Harbor, WA, and for Years 2 and 4 near the Mendocino Triple Junction. The Grays Harbor array provides dense instrumentation directly above the locked zone during an expected episodic tremor and slip (ETS) event, allowing any microseismicity, tremor, or low-frequency earthquakes to be recorded and for these events to be interpreted within the structural constraints from the Cascadia Open-Access Seismic Transects (COAST) active source experiment. This array also forms the offshore extension of the 2006–2008 Cascadia Arrays For Earthscope (CAFÉ) onshore seismic profile (Abers et al., 2009), forming an offshore extension to receiver function studies that provided evidence of high fluid pressures in the ETS zone.

The region around the Mendocino Tripe Junction (MTJ) has one of the highest seismicity rates in North America. The MTJ focused array will (1) locate small interplate earthquakes to define the updip edge of the seismogenic zone, (2) locate slow slip phenomena that might occur at the updip edge of the seismogenic zone, and (3) locate intraplate seismicity and image the crust and upper mantle in the tectonically complex and actively deforming MTJ. Year 4 initial plans included a focused array at a possible segment boundary in central Oregon. Due to uncertainty in the location of this boundary and the low seismicity levels in this region, the Year 4 focused array will be deployed in the summer of 2014 in the MTJ region. The Year 4 MTJ focused array also includes somewhat broader coverage to the north to provide a record of seismicity along the southern, and most seismically active, portion of the Gorda Plate deformation front.

Benefits and Challenges of a Community Experiment

The CI is the first community experiment to use an amphibious array, and it exemplifies the benefits and challenges of this mode of data collection and sharing. The community experiment concept was developed at the "Experiments With Portable Ocean Bottom Seismographs Workshop" held at Snowbird, Utah, in September 2010. The key characteristics of a community experiment are that the community—through openly announced, NSF-supported workshops—acts as the proponent of the experiment and that all data are immediately made available to the public.

The benefits of a community experiment are several. The primary benefit is that the community can do experiments that would be otherwise unaffordable, given the expense of working in the ocean. Large-scale experiments can only move forward by establishing community buy-in, including defining the science objectives, instrumental capabilities, availability of data and metadata, and an overall plan for an integrated analysis and synthesis of results. Second, a policy of open data access increases the breadth of inquiry and types of methodologies applied to the resulting data, thereby increasing the data's value. Lastly, open data access and opportunities to participate in seagoing expeditions attract a growing number of graduate students and postdocs, ensuring the future health and vigor of the seismology community.

Community experiments are not without their challenges, however, and several have come to the fore during the CI, including oversight of the AAF; coordinating multiple facilities and related personnel; delivering data and metadata to scientists and educators, many of whom have not previously used marine seismic data; and managing the differing expectations of the continental and marine seismology communities and the facilities that support them. Due to the unique and accelerated manner in which the AAF was funded and the CI was developed, meeting each of these challenges has been a work in progress.

CI Data Products

The primary seismic and geodetic data from the CI are available for public download at the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC for seismic data; http://www.iris.edu/dms/nodes/dmc/data) and UNAVCO (for geodetic data; http://www.unavco.org/data/data.html) websites, respectively. Here, we focus on the seismic data, including their availability and usability, along with suggestions for improving both.

The IRIS DMC archives and distributes waveform (time-series) data from all CI seismometers, from many of the regional seismic networks, and from all NSF-supported PI experiments. Typical metadata include instrument response and station information, such as location, channel types, operational dates, and, for land-based stations, the orientation of the horizontal channels.

Compared to typical observatory seismic data recorded on land, OBS data are considerably more prone to daily and seasonal variations in environmental noise—including ocean loading, bottom currents, and marine organisms—as well as instrumental problems (e.g., dead channels, tilted seismometers, and data dropouts; see Buskirk et al., 1981; Tréhu, 1985; Duennebier and Sutton, 1995; Webb, 1998; Olofsson, 2010; Bécel et al., 2013). The reasons for this are clear: OBSs are deployed remotely, often by free-fall, in a harsh and noisy ocean, on a rugged seafloor or one covered with abyssal ooze and organisms, and only upon retrieval can the instrument health be evaluated. OBS data downloaded from the IRIS DMC clearly should not be treated in the same manner as those recorded by onshore sites.

The OBS community has developed a do-it-yourself tradition for assessing data quality and deriving metadata. This tradition gave rise to a division of labor where any metadata that require data analysis—including orientation of horizontals or evaluation of data quality—are solely the responsibility of the PI. In this model, the OBSIP Institutional Instrument Contributors deliver only time-corrected waveform data to the IRIS DMC, along with some limited metadata. The do-it-yourself model works acceptably well for PI-driven science, where only a few investigators are processing data, but it is not well suited to community experiments.

The seismological community is only beginning to grapple with the ramifications of the contrasting reliability of continental versus ocean bottom instruments, and the resulting implications for data quality and usability. At the user level, scientists must tackle the difficult problem of simultaneously analyzing land and ocean bottom seismic data that have markedly different characteristics of background noise, at the same time as ocean bottom data characteristics are still being actively researched. At the facilities level, the IRIS DMC—which was initially developed to archive observatory data based on the SEED (Standard for Exchange of Earthquake Data) standard—is not accustomed to handling a data stream (including metadata) that undergoes revisions as problems are found and solutions patched together. For example, the SEED standard used by the IRIS DMC does not provide version control of archived data, and as a result, users do not know if the data they are analyzing are the best available.

The ongoing analysis of CI amphibious array data is likely to catalyze a community-wide discussion of the reliability of ocean bottom instrumentation, the best design of shielded and trawl-resistant seismometers, and the overall usability of amphibious data, particularly by "armchair" seismologists. In view of the ongoing and exploratory nature of both the science and the engineering of ocean bottom seismology, there is not yet a quick and easy solution to evaluating and disseminating metadata that describe data quality and usability. Toward this end, it is likely that the community will need to develop methods to "crowd source" reports on OBS metadata, and that these reports will need to be either part of the data package downloaded from the IRIS DMC or keyed to the data in such a way that users can use algorithms to process both data and metadata.

CI Education and Outreach

The CIET engages and informs the research community in a variety of forums. The goals are to ensure that the community knows how the experiment is progressing, researchers know where CI data and metadata can be found, and early career scientists get involved with both the seagoing operations and the data analysis. To achieve these goals, CIET maintains an extensive website (http://cascadia.uoregon.edu), has contributed to community newsletters, organized special sessions at meetings of the American Geophysical Union, and held community workshops.

The CIET Education and Outreach (E&O) program has also provided pathways for junior people to enter the field. In total, 71 students, postdocs, and early career scientists have participated in CIET efforts. CIET has developed three specific E&O programs: two involve seagoing participation, and the third promotes teacher-student involvement in measuring and interpreting site response at public schools.

The Community College at Sea (CC@Sea) program supports the participation of two community college (CC) students each year in CIET cruises (Livelybrooks, 2013). To promote nontraditional participation in Science, Technology, Engineering and Math (STEM) fields, this program requires follow-up outreach activities at CCs, high schools, and in the community during the academic year following the at-sea experience. This program also developed experiential- and research-focused videos and posters, along with supporting extensive "telepresence" efforts aboard R/V *Atlantis* (sponsored by the Ocean Exploration Trust) that reached aquarium and science museum audiences in Connecticut, Texas, and California.

During the 2013 and 2014 spring and summer field seasons, the Apply to Sail program included additional seagoing participation by undergraduates, graduate students, and faculty from four-year colleges and universities. The goal of this program is to build the OBS user group and increase users' understanding of how OBS seismic data are collected and differ from land seismic data.

COMMUNITY USE OF CASCADIA INITIATIVE DATA

A growing segment of both the seismological and the nonseismological communities are downloading and using CI data for a variety of scientific studies. Figure 3 shows the steady growth in the amount of data downloaded from the IRIS DMC. At the time this plot was made (February 2014), over 13.6 TB of CI OBS data had been downloaded. Even more impressive—from the viewpoint of growing a vibrant community of scientists that are using OBS data—is that there were over 350 unique users of CI OBS data (Figure 3b). A typical PI-driven experiment, by comparison, will have fewer than 10 data users within the first couple of years of data collection, and once the two-year moratorium is lifted, it is clear from the literature that the number of unique users is a small fraction of those using CI data. The large number of users and immediate data access has resulted in quick analysis of experiment data quality and immediate investigations into diverse research topics. Although only half of the CI data

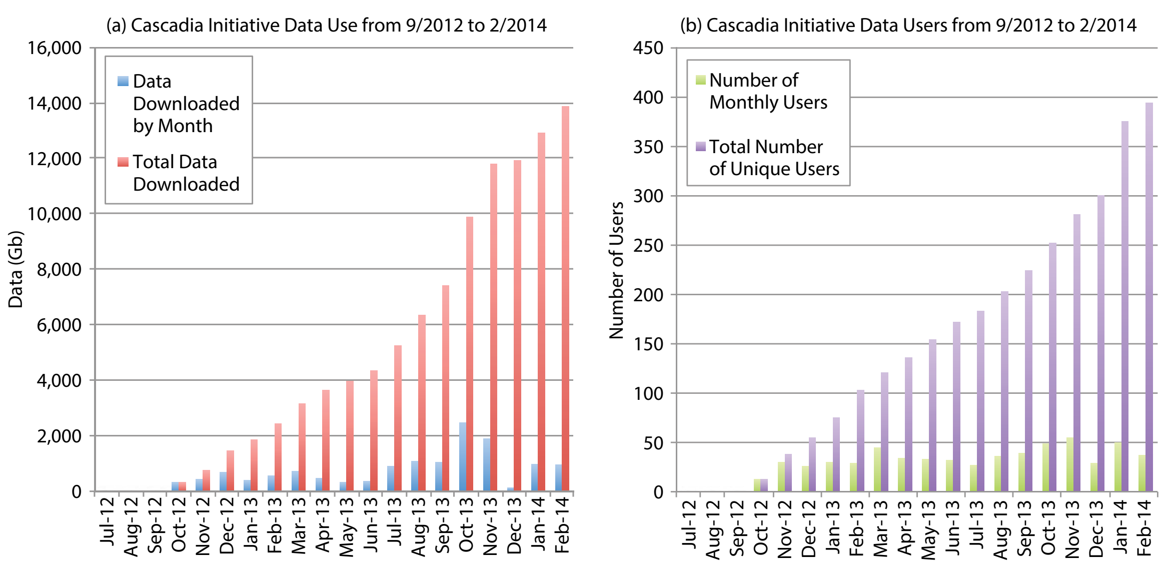

Figure 3. Bar charts showing the usage of CI data by the community. (a) The amount of data downloaded by the community has grown exponentially with time. (b) The number of unique users of CI OBS data is approaching 400 after just two years.

has been collected, researchers have already begun to present results. Below, we summarize the types of studies being conducted, with an emphasis on novel uses of OBS data.

Solid Earth

The solid Earth community is using CI data for a variety of structural, earthquake, and noise-related studies. Preliminary results derived from the first year of CI data were presented at a special session of the 2013 fall meeting of the American Geophysical Union entitled "Understanding the Cascadia Subduction Zone: Contributions from the Cascadia Initiative and Multidisciplinary Studies."

The Year 2 Focused Array recorded considerable seismicity in the magnitude 1 to 4 range within the general area of the MTJ (Figure 4). Much of this activity was not locatable using only onshore networks, and the added precision from the OBS data reveals multiple active fault zones. For small earthquakes (M < ~ 3.5) where the waveforms did not clip, the quality of the OBS data is sufficiently high for detailed earthquake source studies. Figure 4 shows an example of the earthquake source spectrum averaged over 17 stations (both land and OBS) using an empirical Green's function method. The flat spectrum at low frequencies and the clear resolution of the corner frequency and spectral fall-off indicate that the CI data will be useful for earthquake source studies.

Investigations of instrument noise levels and how they vary with instrument design, sensor type, and water depth are demonstrating the importance of shielding seismometers from bottom currents and of using absolute pressure gauges in shallow water (Webb et al., 2013). To illustrate horizontal bottom current noise, author Bell and colleagues recently selected a day with very few earthquakes and calculated displacement spectra for the horizontal components. For each station, they show the average value of the amplitude at 0.02 Hz (Figure 5). Although bottom current noise grows considerably stronger in

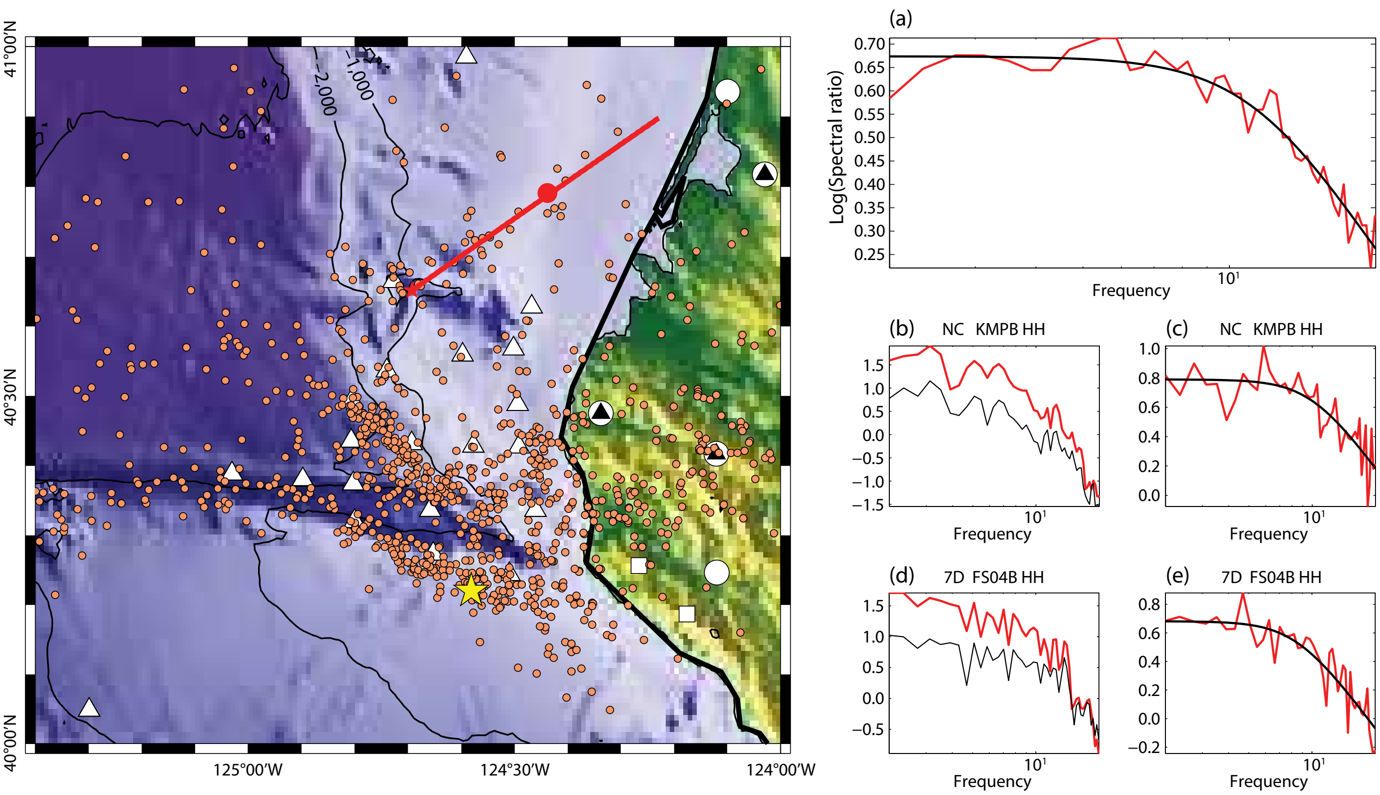

Figure 4. Map of CI Year 2 earthquake locations and spectral ratio examples for an event pair: an M~2 target event and an M~1.4 event along the transform fault (yellow star). Preliminary epicenters (orange circles), CI OBSs (white triangles), onshore Northern California Seismic Network (NCSN) stations (white circles, squares, and black triangles), and the fault plane of a 2010 M_W 6.5 earthquake (red line and circle) are shown. The right-hand panels show an example of earthquake source spectrum recovery using the combined OBS and land seismic network. (a) Average spectral ratio from 17 stations. (b) and (d) Observed (red) and calculated (black) displacement spectra for target event at permanent NCSN station "KMPB" and LDEO OBS "FS04B." (c) and (e) Spectral ratios at the two stations. In (a), (c), and (e), red curves show measured spectral ratio, and black lines show the best-fitting models. The y-axis in each figure is the log value of the spectrum. The corner frequency for target event is 12.3 Hz.

shallow water, controlling for water depth reveals a clear hierarchy of bottom current noise among the three station designs analyzed. With the sensor package deployed independently inside a shield of syntactic foam, the SIO Abalone instruments are the most effective at minimizing bottom current noise. In both WHOI designs, the sensor packages are deployed separately from the recording and flotation package but with no shielding, so it is not surprising that they yield more bottom current noise. The more recent of the WHOI designs, for the WHOI ARRA instrument, uses a small cylindrical sensor package, while the WHOI-Keck instruments use a larger spherical one. The smaller profile of the new instrument reduces noise in two ways: laminar currents increase in velocity with increasing distance above the bottom, and the smaller profile, even with the same current velocity, should produce fewer eddies. With this advance in shielding, Love and SH waves at low frequencies will be much easier to detect with deepwater OBS stations.

Microseisms

The CI OBS array samples the ocean-bottom pressure and seismic spectra from deep to shallow water. In addition to earthquakes, ocean gravity-wave-generated seismic signals are also recorded. These include primary microseisms (PM) at the frequency of ocean waves, and double-frequency (DF) microseisms at twice the ocean wave frequency. PM and DF microseisms (the continuous background vibrations of Earth) are observed globally. Most microseism energy occurs in the 0.005–0.5 Hz band and propagates as seismic surface Rayleigh waves (Rg). Because of their ubiquitous nature, PM and DF microseisms can be used to resolve Earth's structure (Sabra et al., 2005; Shapiro et al., 2005).

Typical microseism spectra (Figure 6a) indicate that the shallow water PM is 50 dB higher than both deepwater and land spectral levels, with the latter two about the same magnitude. The similar PM levels suggest that these are fundamental crustal Rg that attenuate slowly. The larger DF component in deep water might not be due only to global Rg, but likely has a significant "local" component from overhead wave activity.

The peak amplitudes of the DF microseism spectra (0.13–0.2 Hz) in Figure 6b show their variation as a function of distance from the coast. The land DF are 20 dB lower than those from deep water, which are 10 dB lower than those from shallow water, similar to previous observations along the Oregon coast by Bromirski and Duennebier (2002). The large differences between deep-ocean and land DF levels indicate that much of this energy does not propagate from the deep ocean to land, suggesting either that signals other than crustal Rg contribute or that the crustal Rg does not propagate well across the continental shelf boundary.

Despite being studied for more than 100 years (Haubrich and McCamy, 1969), various aspects of microseisms are not well understood (see Bromirski et al., 2013). It is anticipated that the CI seafloor and land array data will help resolve unanswered questions, such as locations of dominant source areas, significance of shallow water overhead wave contributions, and propagation characteristics of DF microseisms from the deep ocean to land.

Physical Oceanography

The absolute pressure gauges (APGs) on the LDEO OBSs create an exciting opportunity for oceanographers to address longstanding questions about the currents and waves offshore of Cascadia. The extraordinary value of the CI APGs to physical oceanography is in the large number of sensors, as multi-element arrays for physical oceanography are relatively rare due to their cost.

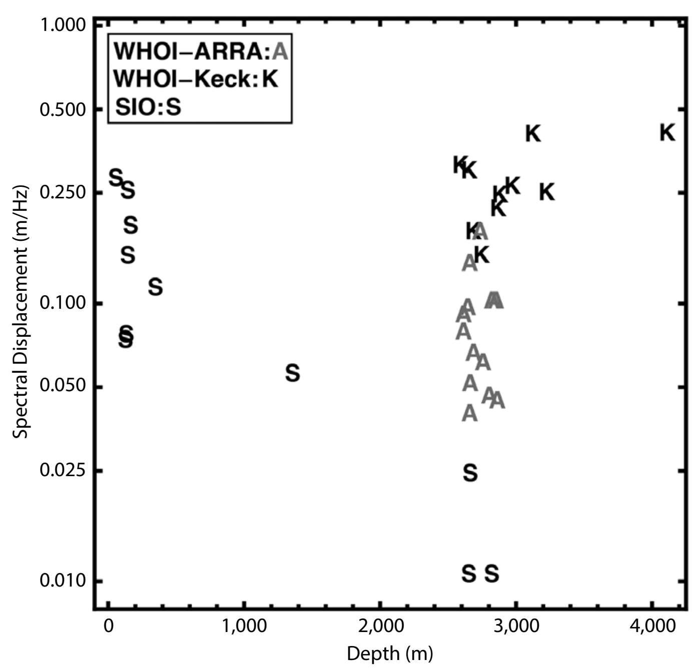

Figure 5. Amplitude of the horizontal noise at 0.02 Hz versus water depth for shielded and unshielded OBSs. Letters indicate different instrument types. SIO Abalone (S) is shielded. WHOI ARRA (A) and Keck (K) instruments are unshielded. The amplitude of the horizontal noise decreases with water depth, and at a given water depth, shielded instruments are less noisy.

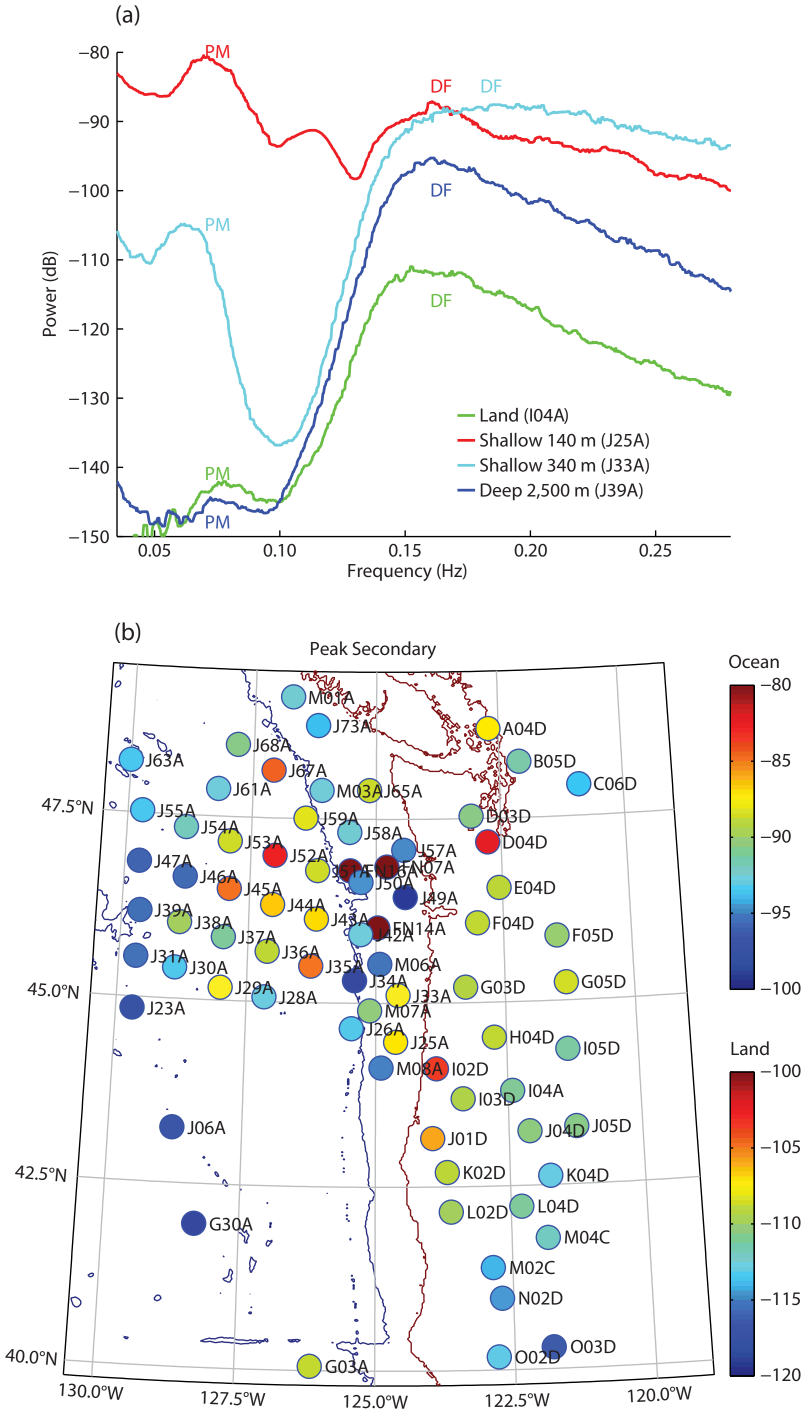

Figure 6. (a) Typical five-month averages of Cascadia vertical velocity power (dB re: $(m/s)^2$/Hz) spectra. Land data (green) show weak primary microseism (PM) and weak secondary microseism (DF). Shallow-water data show very strong PM and strong DF. Deep-sea data show weak PM and intermediate DF. The weak 0.06 Hz PM signals at the deep ocean and land stations likely have a nonlocal contribution. (b) Peak vertical velocity power (dB re: $(m/s)^2$/Hz) over five months of Cascadia microseisms spanning the 0.13–0.20 Hz band, determined from December 2011 to April 2012, with earthquakes removed. Note that land station levels are substantially lower, reflected in the different amplitude scales.

At frequencies less than that of infragravity waves, the CI APGs will be used to define the pattern of surface tide energy flux, permitting determination of areas of high local dissipation (see Egbert and Ray, 2001) that may signal the existence of strong vertical water property fluxes forced by tidal mixing. At even lower, subtidal frequencies (< 0.00001 Hz), APGs along the continental slope will reveal the temporal and spatial nature of near-bottom current variability, including the northward California Undercurrent. These currents play critical and time-varying roles in the strength of annual hypoxia events along the Oregon and Washington continental shelves by advecting low-oxygen water onto the slope and shelf from offshore, as well as advecting nutrient-rich water from the south that enhances phytoplankton production (Connolly et al., 2010). Out on the Juan de Fuca Plate, bottom pressure will provide information about direct atmospheric forcing of subdiurnal, mesoscale variability in the presence of an eastern boundary current and a mid-ocean ridge (Cummins and Freeland, 1993; Matano, 1995). Such variability is a dominant factor in the energetics of the abyssal ocean.

Marine Mammals

Ocean bottom seismometers often detect signals that are not related to earthquakes or geophysical surveys. The songs of both blue and fin whales, for example, are at least partially within the sensitivity range of typical OBSs. Previous studies have demonstrated the use of OBSs for studying these whales, including tracking (McDonald et al., 1995; Soule and Wilcock, 2013), density estimation (Harris et al., 2013), and investigating response to airgun sounds (McDonald et al., 1995; Dunn and Hernandez, 2009).

An initial analysis of five stations along the western edge of the network shows that hundreds of thousands of fin whale calls were detected during the first two deployment seasons, dominating the frequency band between 15 Hz and 25 Hz. Male fin whales are believed to produce these calls as a breeding display (Croll et al., 2002), and individuals will often vocalize in repetitive sequences for many hours. Fin whales range throughout the world ocean, but their distributions and migratory patterns remain poorly understood. The CI instruments provide an opportunity for passive acoustic monitoring of these endangered mammals on a spatial scale that covers a significant portion of their potential migratory range in the Northeast Pacific Ocean. Variations in the number of calls can help determine spatial distributions and indicate whether there are links to environmental conditions or a seasonal migration. Quantifying subtle shifts in the pitch and rhythm of these calls may reveal finer details in distributions over time.

A FOUNDATION FOR THE FUTURE

The new technology comprising the Amphibious Array Facility combined with the ambitious scale of the Cascadia Initiative—which is possible largely because it is a community experiment—constitutes a sea change in studies of subduction zones and continental margins in general. Efforts to respond to the Cascadia opportunity are awakening many to the growing science opportunities for OBS studies and to a broader user base for marine seismic data. The success of, and enthusiasm for, collaborative efforts between the terrestrial and marine seismology communities bodes well for future interdisciplinary and interdivisional cooperation at NSF. That said, the emergence of the CI has also pointed out that the marine and continental seismological communities are not yet fully integrated.

In view of the ambitious science objectives of the CI—and future deployments of the amphibious array—and considering the expense of marine experiments, it is readily apparent that future success depends heavily on mutual shared interests. To achieve a level of cooperation that will carry weight with funding agencies and satisfy the end users of data will require significant improvements in community organization, community leadership, and management of both expeditions to collect data and subsequent development and reporting of high-quality metadata.

Ultimately, the success of the Cascadia Initiative will be measured by the scientific discoveries and engineering advances that it facilitates.

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