Amphibious Array Facilities Workshop Report

Following the Amphibious Array Facilities Workshop that took place on October 22-24, 2014 in Snowbird, Utah

Last Update February 19, 2015

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Executive summary

The Amphibious Array Facilities (AAF) represent a major new capability, providing novel geophysical observations that span the coastline. The AAF were built with a $10M ARRA award to NSF, evenly split between the Divisions of Ocean and Earth Sciences, to build a seismic and geodetic array consisting of 27 broadband onshore seismographs, 60 new broadband ocean-bottom seismographs (OBSs), and upgrades to 232 GPS EarthScope sites. The array's initial deployment took place across the Cascadia margin of Washington, Oregon, and northern California, and is referred to as the Cascadia Initiative (CI). These instruments were built and operated by existing facilities operators, deployed in full for four years starting in 2011.

The full deployment design arose from an open community workshop plan to blanket the entire Juan de Fuca plate and to emphasize critical transects across the Cascadia megathrust. In anticipation of the 2015 completion of the Cascadia deployment, a second workshop was held in October 2014 to assess the array's performance in Cascadia, and address scientific rationale and strategies for subsequent deployments. Participants focused on critical scientific targets and also considered multiple scenarios, identified resources and strategies, and broader impacts. Efforts have been made to complement the EarthScope and GeoPRISMS science goals through 2018. This report describes the workshop outcome.

Several complex, critical and societally relevant solid-earth systems span the coastline, making amphibious approaches necessary for scientific progress. These systems also generate major hazards such as great earthquakes, tsunami, volcanic eruptions and landslides, sometimes in populated coastal environments and are the site of many sediment-hosted resources. The workshop identified three major systems, building on recent EarthScope and GeoPRISMS Science Plans:

1. *Subduction Factory and Magma-Volatiles.* Crustal rocks, magmas, and other materials cycle through subduction zones. These cycles control the long-term budget of volatiles such as H_2O and CO_2 and evolution of earth's crust, and regulate some of the planet's most explosive volcanoes.

2. *Passive Margins and Transform Faults.* Significant questions remain such as how rifting initiates, how critical magmatism is to rifting, and what controls segmentation of rifts and mid-ocean ridges. Transform margins offer some of the best opportunities to directly sample major faults that reach the surface and occur in places like California both offshore and onshore.

3. *Seismogenic Processes at Subduction Margins.* Recent great earthquakes in Chile and Japan have highlighted our ignorance of megathrust rupture processes and tsunami-genesis, that include the controls on updip and along-strike variability in rupture. The few sea-floor measurements off Tohoku have clearly shown enormous slip magnitudes, illustrating the power of amphibious arrays in addressing seismogenic zone problems.

The Cascadia Initiative deployment of the Amphibious Array has already been very successful, even though the first large part of the data set was only available a few months prior to the Workshop. Early analyses have seismically imaged the full Juan de Fuca Plate showing strong along-strike variations and have imaged a sharp boundary at the subducting plate interface. Other studies have resolved directionality of microseismic noise and its oceanographic sources and have begun documenting source characteristics of microearthquakes. Many of these preliminary analyses benefitted from new, shielded designs for OBSs as well as high-quality onshore installations that greatly reduced noise. It is expected that, once the final year of data are collected and archived, these data will give one of the most comprehensive views of an entire plate and subduction margin anywhere.

The Cascadia Initiative has been extremely successful in building a large community of scientists in the experimental design, implementation, and in use of the data. Community planning and vetting of science plans has led to a well-designed, and broadly applicable array. It has brought many scientists into marine geophysics who had never worked in that realm previously, including many early-career scientists. All data and metadata have been made available as rapidly as technically feasible to anybody without cost, which is a critical step in scientific success and community building. As of October 2014 over 20 TB of data have been downloaded to over 500 unique users in 25 countries, many times more than typical PI-driven experiments. Overall, the workshop participants were strongly supportive of continued open community approaches to this type of large-scale projects and were able to enumerate many scientific, logistical and financial advantages.

The community identified major scientific targets addressing each of the three major systems discussed above. In the subduction systems, a majority of participants prioritized placing the array in the Alaska-Aleutian subduction system both to study the magma/volatile/arc growth system and to study the seismogenic zone. Alaska has a long history of subduction and arc growth, clear magmatic systematics related to deep processes, and along-strike trends in many inputs. It also has a well-documented history of great earthquakes and abundant megathrust seismicity. There was also some support for keeping some instruments in Cascadia to better fill out the seismicity record.

The Subduction Factory group highlighted two corridors, one off the Alaska Peninsula and one in the Central Aleutians, offering contrast between a continental and oceanic arc. The latter is an ideal site for looking at oceanic arc growth and along-strike changes at segment boundaries. The Alaska Peninsula site can take advantage of the EarthScope Transportable Array deployed on land there through 2018 and was prioritized for earlier deployment. The Megathrust group highlighted a "Megaswath" off the Alaska Peninsula that spans regions with very different recorded great earthquake history, background seismicity and geodetic locking. The Megaswath substantially overlaps with the eastern Subduction Factory site.

The third group identified a critical corridor along the eastern North America margin, from Maine to Nova Scotia, spanning an abrupt geophysical transition from what appears to be magmatic to amagmatic rifting. This transition should figure critically into understanding the role of magmatism in continental breakup and offers access to major rift basins and major sutures within North America that straddle the shoreline. Onshore-offshore segments of the California transform fault system were also identified as potential targets.

All of these scenarios feature one or more 15-18 month OBS deployments, spanning two summers and complementing onshore deployments. The array seems most effective if it deployed at full strength so that the potential for major transformative discovery is greatly aided by fully spanning critical boundaries and operating at a scale that is not accessible to single-PI science. All planned scenarios rely upon simultaneous deployments onshore and offshore, since most imaging and all earthquake location schemes rely upon an array spanning both sides of the shoreline. Any of the subduction scenarios would have great value as a test-bed for potential activities of a subsequent Subduction Zone Observatory (SZO) initiative. Past 2018, coordination with a developing SZO may provide a framework for future studies.

Several approaches that complement the seismic array were seen as having high value. Particularly for the Megathrust efforts, parallel geodetic operations both onshore and particularly offshore are necessary to obtain clear observations of aseismic deformation and strain accumulation. Electromagnetic methods provide a powerful complement to seismic imaging of volatile and melt cycles and fluid flow. Scientific drilling provides in situ samples of major faults at the updip end, while a host of geological observations provide critical chronological constraints and information about exhumed systems being imaged. In all scenarios, geodynamic modeling is critical for integration and synthesis.

Overall, additional deployments of the Amphibious Array Facilities were seen as having tremendous potential for significant discovery and should be enabled. The workshop participants reached the following consensus recommendations:

1. There is great value to Amphibious Array Facilities deployments. These should continue.

2. The Community Experiment approach has been a success and seems required to continue an effort of this magnitude.

3. The amphibious array has most potential to contribute if kept relatively intact with all 60 OBSs and 27 onshore seismometers. At full strength it provides a powerful tool to do things that single PIs cannot. The most compelling deployment strategies involved leveraging additional resources such as the presence of the EarthScope TA to increase the scale of observation.

4. Continued evaluation is required to come up with strategies to reduce data acquisition costs and optimize future experiments is required.

5. Community-organized experiments work best with both adequate support for science and support for facilities that is independent of core science budgets. NSF should prioritize additional funding to support science that utilizes data from cross-divisional facilities because it is high impact and cost effective.

6. Where a dense onshore GPS network does not already exist, new GPS sites need to be considered as part of the array. The deployment of sites would depend on the specific scientific problem and are particularly critical for seismogenic zone studies.

7. In the 2016-2018 timeframe, several targets complement the EarthScope TA footprint. There is some rationale for keeping resources in Cascadia at relatively low cost. In Alaska at least two scenarios are favored: an Aleutians array that targets deeper subduction-factory-volatile-cycles problems and one closer to the Alaska Peninsula that targets the thrust zone. The latter is at high priority to be deployed while the Transportable Array is operating within Alaska (2016-2018). Off the Eastern North America passive margin, deployments were envisioned that complemented onshore resources such as the Central-Eastern U.S. Network that are planned to replace the TA as it moves to Alaska, still within the EarthScope footprint.

8. Past 2018, lessons learned can be applied more broadly although even in margins like Alaska-Aleutians there is more to be done. Longer-term efforts could be coordinated with a Subduction Zone Observatory should its development mature.

9. Communities that conduct parallel observations should be continually engaged and their efforts coordinated with Amphibious Array deployments as much as possible. It is recognized that funding for such efforts would have to be found separately, but that the value of multidisciplinary science for amphibious problems is clear.

0. Introduction

On October 22-24, 2014, nearly ninety scientists met at Snowbird, Utah to evaluate the ongoing deployment of the Amphibious Array Facilities (AAF; a coordinated operation of multiple existing facilities) and to chart potential future directions for the array. Starting with Recovery Act funds, the AAF were built to constitute three coordinated shore-crossing elements that were initially deployed in Cascadia: upgrade of 232 onshore PBO geodetic sites to real-time data transfer, reoccupation or occupation of 27 broadband sites at EarthScope-Transportable Array spacing near the Cascadia coast, and 60 new broadband ocean-bottom seismometers (OBSs) deployed across the Juan de Fuca plate with emphasis on Cascadia. The latter include 20 “trawl-resistant” instruments, the first broadband seismometers specifically engineered for deployment in shallow water. While extensive projects on land and offshore have been done before, this is perhaps the first time that a community-driven science project of this scale has been carried out that crosses the shoreline. It also provides open data access and archival and provides opportunities for a very large user base. This array is described in other documents, most notably the report from a 2010 Portland workshop that finalized the scientific goals and deployment strategy:

http://www.oceanleadership.org/wp-content/uploads/2010/05/CI_Workshop-Report_Final.pdf

and a highlight in the White House list of “100 Recovery Act Projects that are Changing America”:

http://www.whitehouse.gov/sites/default/files/100-Recovery-Act-Projects-Changing-America-Report.pdf

The combined deployment is scheduled to end in mid-late 2015. By late 2014, it was felt that sufficient data and managerial experience had been acquired to assess the overall capabilities of such an array and that it was the right time to consider possible valuable targets for its future use. The workshop participants were charged with answering several questions, including “*What science absolutely requires a coordinated Amphibious Experiment? Given the Cascadia experience, what is this tool good/bad for?”* and *“Given these science motivations, how could it be implemented by amphibious arrays or projects, at candidate margins?*” In all of the discussions, participants were encouraged to describe why coordinated or simultaneous land and sea observations were necessary; to identify resources, instrumentation, and deployment strategies and durations needed; to consider multiple scenarios at multiple scales; and to articulate societal and community impacts. Through 2018 at least, activities that complemented the EarthScope and GeoPRISMS science plans were emphasized but participants were also encouraged to think about a longer time horizon.

1. Why do amphibious science?

While the coastline marks a logistical barrier to data collection, most processes in the earth's interior are not influenced by this boundary. For several critical problems, the relevant system components straddle the coastline making amphibious research a necessity. The Amphibious Array Futures Workshop identified three major systems for which fundamental questions can only be addressed by amphibious geophysics, where synchronized marine and terrestrial observation are required to resolve critical issues. A number of workshops have highlighted the scientific goals over the last several years, notably those hosted by GeoPRISMS and EarthScope. Related workshop reports provide extensive background to the material here. Coastal environments are places where human populations are both concentrated and highly exposed to natural hazards and where resources are concentrated, giving significant broader impact to these studies.

1.1. Subduction Factory and Magma Volatiles

The circulation of chemical elements and volatiles through subduction zones and arc/backarc volcanoes is one of the most important geological processes on earth (**Figure 1.1**). It is responsible for generating arc volcanism and forming continental crust. Volatiles such as H_2O and CO_2 are incorporated in the oceanic lithosphere through hydrothermal circulation at spreading centers and sedimentation on the seafloor. As oceanic lithosphere is subducted, bending in the fore-arc bulge causes fracturing and active transport of fluids into the crust and underlying mantle. As this hydrated and carbonated package of heterogeneous rock enters the subduction zone a series of progressive metamorphic dehydration reactions release fluids and change the physical and chemical structure of the slab. An important series of dehydration reactions start when the slab reaches the hot part of the mantle wedge, where fluids are released and trigger melting by the melt-point lowering of peridotite. The generated magmas differentiate and interact with the arc crust as they ascend to the volcanic front. The high volatile content and intermediate to felsic composition of the final magmas greatly contribute to the explosive and dangerous nature of arc volcanoes.

In order to understand the full cycle and the causes and consequences of volatile release and transport the GeoPRISMS community (*http://geoprisms.org/research/science-plan/*) formulated a number of main questions that need to be addressed. They are documented in the GeoPRISMS science plan (page 2-5) as:

1. *How do volatile release and transfer affect the rheology and dynamics of the plate interface, from the incoming plate and trench through to the arc and backarc?*

2. *How are volatiles, fluids, and melts stored, transferred and released through the subduction system?*

3. *What are the geochemical products of subduction zones from mantle geochemical reservoirs to the surface and how do these influence the formation of new continental crust?*

Geophysical imaging of the entire system, from trench to back-arc is a critical component to address all of these questions. Imaging can provide constraints on the volatile budget of the incoming plate by determining the depth extent of faulting and the degree of serpentinization. The thickness and composition of arc crust, as constrained by active source seismic surveys, is required to understand the outputs of island arc volcanism through time and to investigate its possible role in continental crust formation. The pathway of water from the subducting slab to the mantle wedge, the formation of aqueous melts in the hot part of the wedge, and the transport process of aqueous melts to the near-surface region in island arc settings are also highly uncertain. Geophysical imaging using amphibious arrays can provide strong constraints on these processes by elucidating the geometry and physical properties of volatile and melt pathways along the entire subduction factory, from ridge to trench to depth and back to the surface in volcanic arcs.

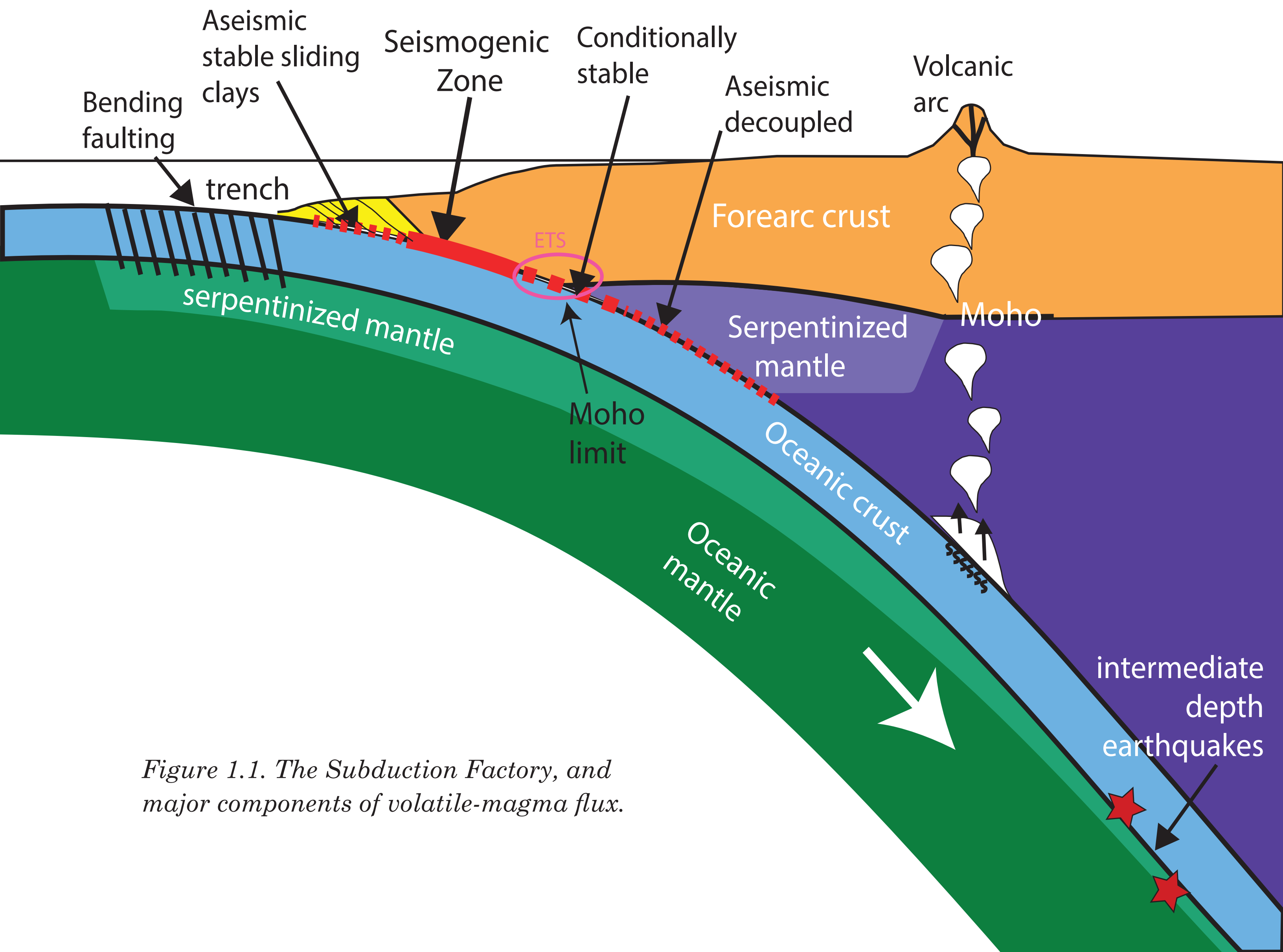


Figure 1.1. The Subduction Factory, and major components of volatile-magma flux.

1.2. Passive Margins & Transform Faults

The breakup of continents remains one of the least understood aspects of plate tectonics. The forces that drive rifting, the rheological processes that accommodate it, and the structures that it leaves behind all provide crucial clues to the key factors that control extensional deformation and the surface evolution of the planet (**Figure 1.2**). As the geological remnant of ancient rifts, passive continental margins represent an ideal system for constraining the full evolution of rifting. The GeoPRISMS science and implementation plans lay out the critical questions associated with rift initiation and evolution and identify the Eastern North American Margin as a type locale for passive-margin investigations. Significant research questions as elucidated in the GeoPRISMS Rift Initiation and Evolution Implementation plan focus on:

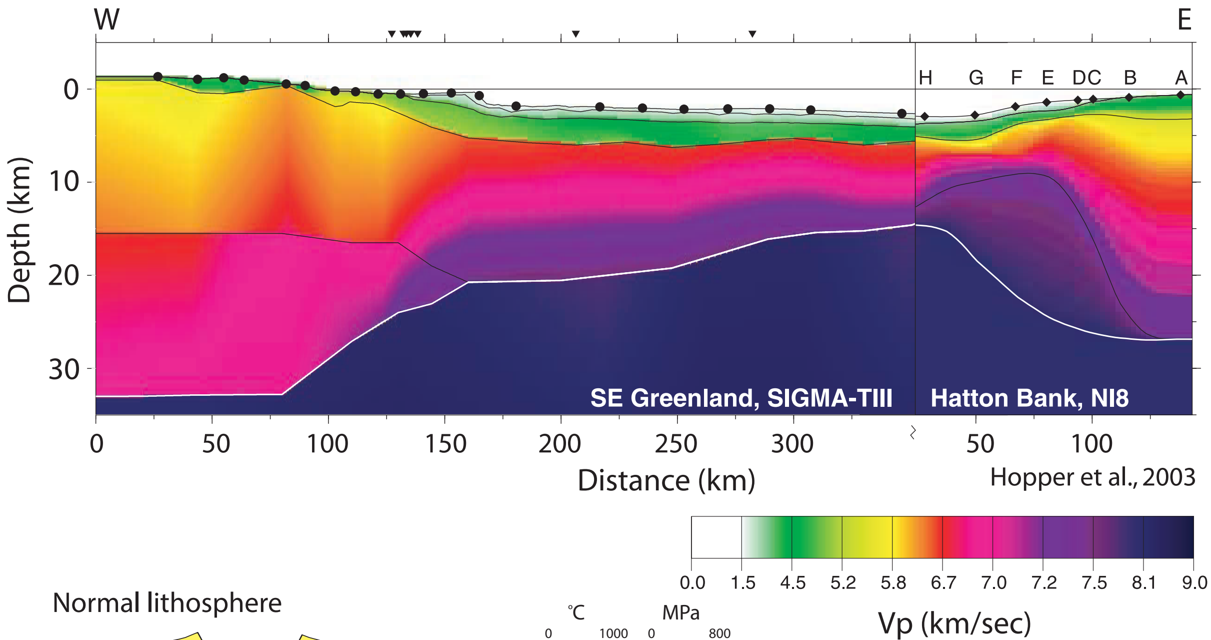
1. *How and why rifting initiated, including the potential role of magmatism, pre-existing structural and compositional variations?*

2. *What controls the large scale form (segmentation) of the rifted margin, and does this form influence the eventual geometry of sea-floor spreading?*

3. *What are the critical geodynamical and surface processes that control the post-rift evolution of the margins and associated geohazards?*

This is clearly an amphibious problem – the shelf break that topographically defines the edge of the continent typically lies 100 km offshore. Major geological structures (e.g. ancient sutures and failed rift basins) and geophysical indicators (e.g. the East Coast Magnetic Anomaly) that illuminate rifting processes extend several hundred km in each direction from the coastline. Comprehensive geophysical imaging that spans this full system is required to accurately quantify the spatial extent and volume of magmatism that accompanied the rifting process, the relationship of rifting to ancient lithospheric sutures, and the transition between continental-rift structures and early-stage segmentation of oceanic lithosphere. An amphibious array would also enable unprecedented opportunity for monitoring of active deformation on a passive margin, including submarine landslides and passive-margin earthquakes.

Many of the transform faults worldwide that present great earthquake hazards to large population centers straddle the coastline and thus are not well characterized. They have complex geometries, motions, and exhibit transpressive and transtensional behavior. Notable examples of major transform faults around North America include the Queen Charlotte Fault System, the Caribbean-North America Plate boundary, and the San Andreas system along the California margin. Although the onshore component of the latter is relatively well studied and instrumented, the offshore portion is poorly characterized and hardly instrumented, which is surprising given the seismicity and high hazard and exposure to tens of millions of Californians. Major questions associated with transform systems concern their long-term stability, how they grow or shorten,



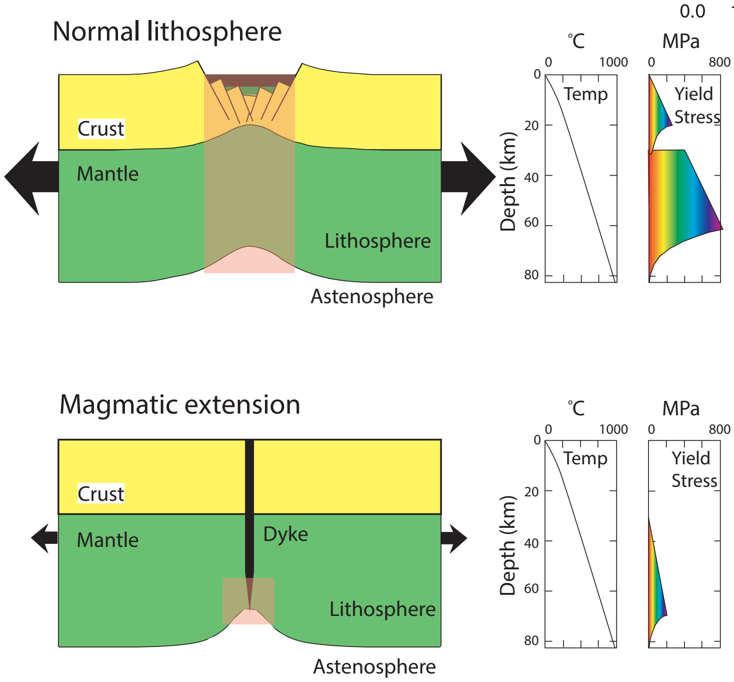


Figure 1.2. Rifts Processes: (top) asymmetrical structure imaged across conjugate North Atlantic margins (Hopper et al., 2003); (bottom) Strength of extending lithosphere, for normal continental lithosphere or after diking (Buck, 2006)

what controls lateral steps, fault branching and block rotation, and how transforms are manifest at depth in the crust and mantle lithosphere in terms of both active deformation and cumulative lithospheric structure. Earthquake rupture scenarios along these faults are based on geologic and geodetic measures and inferences of the strain field, which requires simultaneous seismic and geodetic observations onshore and offshore. Although deep tremor is observed within the San Andreas Fault, it is unknown if this is common to other transforms, nor are the implications known for the deep processes in transforms. Finally, transform boundaries straddling the coast also present a unique environment in which to examine the extent and localization of deformation at depth in the lithosphere. The juxtaposition of oceanic and continental lithosphere with very different properties across the transforms near the coast line makes them attractive targets for lithospheric seismic and MT imaging.

1.3. Seismogenic Processes at Subduction Margins

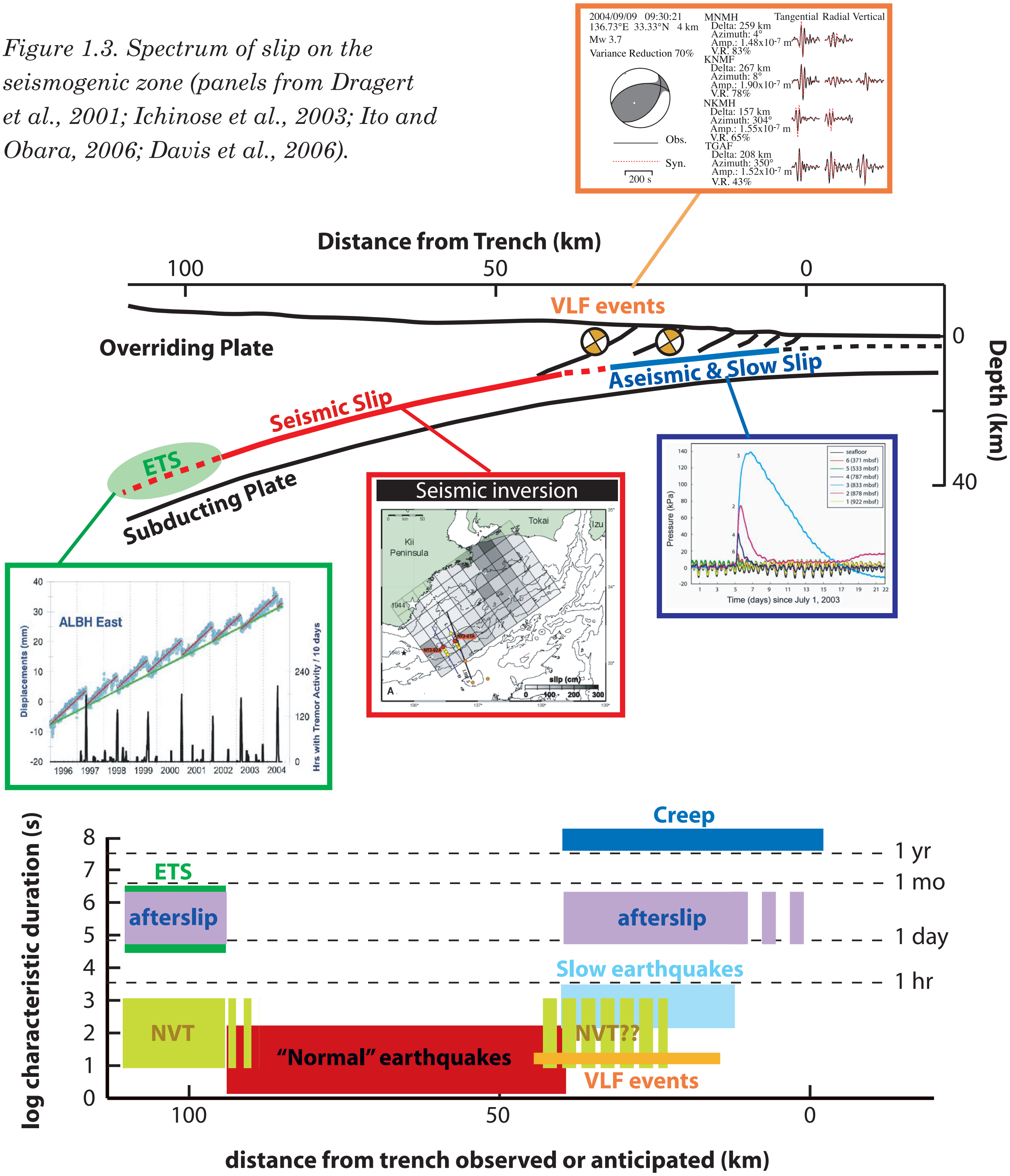
Subduction zone thrusts generate the planet's largest earthquakes and tsunamis, as well as a suite of slow to aseismic deformation phenomena that are just beginning to be understood (**Figure 1.3**). Characterizing processes that influence seismogenesis is a fundamentally amphibious problem, in that both structural elements and the megathrust slip zone both span the coastline. A typical subduction zone features a main seismic slip zone that has its downdip end close to the shoreline and a region that exhibits slip and transient slip behavior below that. As a consequence, both onshore and offshore measurements are required for imaging and estimation of slip processes. Substantial improvements in the extent and precision of land based geophysical datasets during the last several decades have given us a clearer view of how strain is accommodated both during large earthquakes and in the interseismic period, and what processes control this. These observations have been complemented by deep-sea drilling and seismic imaging that highlight the complex thermal, volatile and deformational environment of these fault systems. Although our understanding of the spectrum of slip phenomena is rapidly improving, continued advances in characterizing seismogenesis at subduction margins will require comprehensive observations by continuous, integrated arrays that span the coast. The Cascadia Initiative is generating data relevant to addressing these problems. However, due to the low level of seismicity at the Cascadia margin further AAF studies targeting subduction thrusts are still required.

The offshore portions of most subduction zones worldwide tend to be significantly less well instrumented than onshore. The offshore seismic and geodetic behavior is much more poorly known. It is therefore important to focus on the potential insights that could be gained from a future AAF effort. A simultaneous land array will also be critical to augment offshore recordings over the down-dip extent of the megathrust. A possibly more important aspect is that it will guide Amphibious Array OBS data analyses using land-derived data that is often easier to acquire, less expensive, exposed to lower noise levels, and has fewer engineering challenges. Currently we are in the early stages of Cascadia Initiative data analyses. Events detected easily by land-based arrays are providing template catalogs to guide earthquake detections on offshore stations. In the case of geodetic observations, data are broadly available only on land, although absolute pressure gauges can be integrated into an OBS instrument package. Until a clear and practical strategy for widespread seafloor geodesy emerges, onshore GPS still provide the best insight into interseismic plate locking behavior as well as the time and spatial distribution of transient aseismic slip events.

Recent great earthquakes in Chile and Japan were recorded with unprecedented land and (for Japan) offshore data. This have illuminated properties of fault slip behavior leading up to and during significant megathrust rupture events that suggest early observable processes occur prior to large earthquakes at some margins.

Seafloor geodetic observations for the 2011 Tohoku earthquake were of particular importance, as they demonstrated an enormous magnitude of slip (≥50 m) on the shallow portion of the megathrust. Our ability to build upon these recent observations to improve our understanding of seismogenesis and to anticipate future large events will hinge on our ability to make detailed observations of seismic and geodetic behavior beyond the coast in addition to land based observations.

Figure 1.3. Spectrum of slip on the seismogenic zone (panels from Dragert et al., 2001; Ichinose et al., 2003; Ito and Obara, 2006; Davis et al., 2006).



2. The Cascadia deployment of the Amphibious Array

The Cascadia Initiative offers the opportunity to begin to assess the quality of science enabled by having seismic observations from both sides of a subduction zone. Installation of the land stations began in late 2009 and was complete in 2010, but the first of four yearlong OBS deployments did not take place until the summer of 2011, in which many new equipment designs were tested for the first time. **Figure 2.1** shows the geophysical instrumentation deployed. The first data for Year 1 became publically available in late 2012. The first fully-corrected suite of data from full deployments (Years 1 and 2) were released in mid-2014. Year 3 data with full metadata were available just after the Workshop in late 2014 and it is anticipated that the full dataset will be released in the fall of 2015. Although we do not yet have a complete picture of the science impact of this project, the science accomplishments highlighted below demonstrate that an amphibious array is absolutely required to make significant advances in our understanding of several critical processes. Besides the direct scientific benefit, the Cascadia Initiative Expedition Team has a good deal of experience in the benefits and challenges of running this mode of community experiment, as discussed below in Section 5.

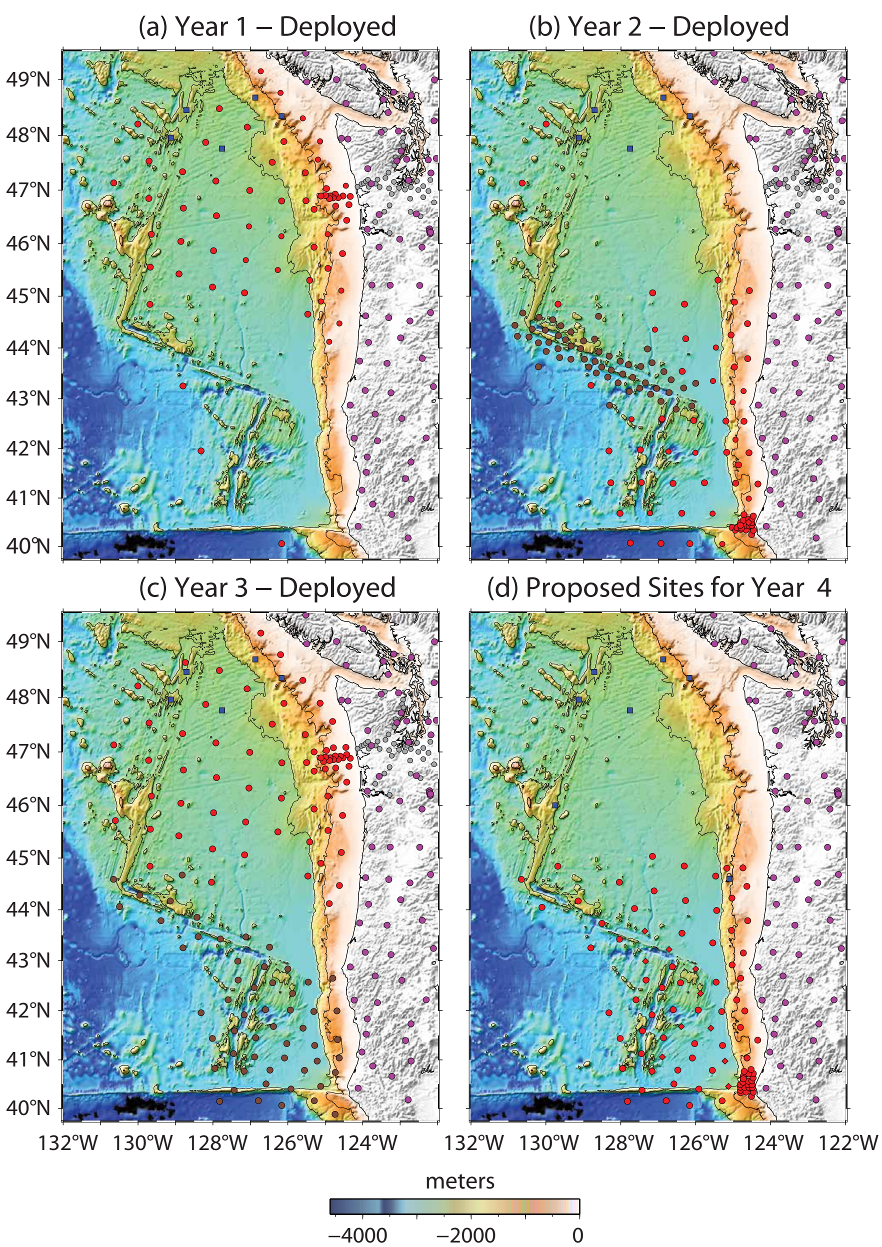


Figure 2.1 The four-year deployment of the Cascadia Amphibious Seismic Array. Red circles: CI OBSs (~65 per year); gray circles: synchronous Gorda experiment OBS; purple circles: onshore CI and other broadband seismometers.

2.1. Scientific advances

As a target subduction zone, Cascadia offers several advantages. First, the deformation zone is close to the mid-ocean ridge. Together with the low speed of subduction the thermal regime is at the hot end of subduction zones globally. The relatively small size makes it tractable to study an entire plate from formation at a ridge to destruction after subduction. Second, the subduction zone has a well-characterized history of both aseismic slip events and pre-historic great earthquakes. Third, the onshore structure has been well characterized by both the EarthScope Transportable Array and a series of dense array studies in the US and Canada. Fourth, as the Ocean Observatories Initiative (OOI) comes on line it will be possible to relate long-term monitoring at seafloor nodes to the synoptic views obtained from the already extensive AAF. The main disadvantage has been the very low rate of interplate seismicity, except for the Mendocino Triple Junction region that was the target of an OBS focus array in Years 2 and 4. These properties and obvious societal relevance made Cascadia a clear first target for the AAF.

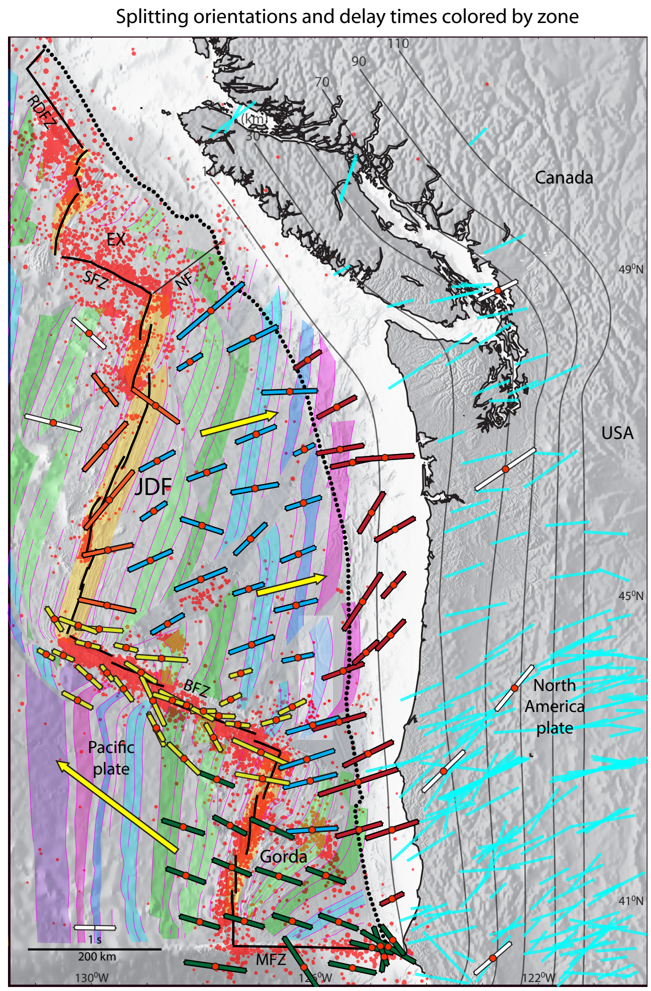


Figure 2.2. An example of science emerging from the Amphibious Array: shear-wave splitting that spans the shoreline, showing systematic deviations from ridge-normal or trench-normal fabric (Bodmer et al., 2014).

Some of the first analyses of the offshore data were highlighted by the talks at the workshop. A review article in Oceanography also highlights some initial results (Toomey et al., 2014). The amphibious array provides a more comprehensive and puzzling view of the anisotropy present in the Cascadia subduction zone by providing measurements on both sides of the trench (**Figure 2.2**; Bodmer et al., 2014). Full-wave seismic tomography by Gao and Shen (2014) demonstrates the multimode along-strike variations of the seismic structures from offshore to the backarc, which has strong implications for seismic hazards in

Cascadia and general understanding of subduction zone segmentation. By analyzing the directionality of ambient noise on the Juan de Fuca plate, Tian and Ritzwoller (2014) located the sources for primary and secondary microseisms. Receiver-function studies show that the low-velocity plate interface observed on land extends offshore well into the locked zone and may indicate that a weak plate interface is not confined to the downdip region of episodic tremor and slip (Janiszewski et al., 2014). Near Cape Mendocino, where earthquakes are abundant, spectra show simple and consistent shapes, indicating robust signal recovery from offshore earthquakes.

Complementary to the seismic component, geodetic measurements greatly help our understanding of how strain builds up and is released near the updip end of the seismogenic zone, both from existing PBO equipment and their CI upgrades. The scope of the CI upgrades triggered a broad effort (in many cases supported by other agencies and sources) to compute and distribute real-time GPS data products for a wide range of science, hazard monitoring and engineering applications. Real-time access to high-rate GPS data is rapidly becoming the expected mode of operation for onshore networks.

These scientific studies have been complemented with new analyses of noise characteristics in shallow and deep water, which demonstrate that shielding such as done for shallow-water instruments yields a high reduction in horizontal-component noise (S. Webb; S. Bell presentations). This noise reduction has facilitated many of the scientific discoveries. Without the shore-crossing deployment of the CI amphibious array, these newly discovered patterns prior to and after subduction in the Cascadia subduction zone would not have been observable.

A special focus section of Seismological Research Letters has been organized for Fall 2015 to highlight some of these and other early science results for the Cascadia Initiative.

2.2. Technical lessons

The Cascadia Initiative was a highly successful experiment. It made possible the acquisition of OBS with new capabilities including current shielding, trawl protection, atomic clocks, and absolute pressure gauges. It is producing prodigious amounts of high quality data from both land and offshore instruments that are being used to accomplish significant and exciting science. Much was learned from the CI that will help guide future AAF deployments. A list of useful technical information gleaned from the CI is provided below. An important conclusion from this project is that OBSIP, IRIS and UNAVCO can support another CI type experiment in many environments. Preferred options for a future experiment include: an OBS deployment of 15 to 18 months encompassing two summer seasons; at least a 9 month period to repair and test equipment before redeployment if required; and a start date of 2016 or later.

Fifteen month deployment periods would also have the significant added advantage of giving OBSIP engineers and seismologists the opportunity for first order evaluation of the data quality and time for modifications to instrumentation or deployment strategies if needed. Other physical environments different than found in Cascadia are likely to lead to other technical and data quality issues. The higher seismicity rates found elsewhere makes continued data evaluation necessary. We list the main lessons learned from the CI below. Most of these apply to the OBS deployment, since this involved relatively novel technology, and to the integration of the offshore and onshore deployments.

1. Use of a heave-compensating winch is essential for the deployment and recovery of all trawl-resistant OBSs. Pop-up recovery systems are limited to water depths shallower than 170 m and a line-spool elevator is required for the ROV assisted recoveries at greater depths. Development of shallow water ROV capability to recover the trawl resistant OBS is highly desirable.

2. Long period horizontal component noise is dominated by current noise, but heavy large shields can greatly reduce horizontal component noise levels in shallow water.

3. The “Abalone” shields are useful but more work on deep water shielding is needed.

4. In deep water, vertical sensors exhibit long period tilt noise that can be removed using horizontal component data.

5. Ocean waves cause huge currents and infragravity waves leading to large vertical seafloor deformations in water depths less than 300 m. Pressure gauge data can be used to predict and remove this noise providing useful data. Either DPGs or APGs can be used to remove wave-loading noise but DPG sensors clip in shallow water.

6. Wave noise in depths <80 m becomes very large and shallower depths should be minimized.

7. Trillium compacts are excellent sensors, but will clip on large local events so strong motion sensors on some OBSs would be useful.

8. Offshore deployments should be staged such that sufficient time exists between them to fully evaluate data quality and make operational adjustments before redeploying OBSs, for example during the winter between consecutive 15-18 month deployments

9. As offshore arrays are redeployed, it is valuable to redeploy matching onshore arrays and not just sparse fixed grids.

10. In general, it is valuable to coordinate closely the much simpler onshore deployments with those offshore, to ensure that station spacing, sample rate, and other experimental-design factors are kept as uniform a possible.

11. An integrated seismicity catalog should be a priority in future deployments, particularly in more seismically active regions.

3. High-priority questions and targets for amphibious science

Given the broad science questions outlined in Section 1, it is important that any future deployments of an AAF be focused to address high-priority, tractable questions. For most of these, it is clear that an amphibious approach is necessary – all the operative geodynamic systems lie near the coastline and tend to span it. Seismic analyses that depend on locating sources or use differential signals absolutely require simultaneous recording and close coordination is needed. In each of the following sections we outline the top priorities and their amphibious nature. We describe the implementation of an array to address these questions, which includes the duration, scale of arrays, organization, and value of complementary data.

3.1. Subduction Factory and Magma Volatiles

The main science questions related to the Subduction Factory (cited in Section 1.1) can only be answered with a coherent and coordinated amphibious approach. The storage of volatiles and their initial release in subduction zones occurs offshore while the progressive release of fluids and triggering of arc volcanism happens most commonly below the continents. In some cases arc volcanism also occurs below sea level, such as witnessed by recent eruptions in the Tonga arc. Attributes of an ideal subduction zone to investigate are along-strike variations in magma composition, structure of the arc crust, and inputs to the system including sediments and oceanic lithosphere and a simple tectonic history.

The workshop participants considered possible locations and concluded that the Alaska/Aleutian subduction zone presents the best location to study subduction factory and volatile cycling objectives, as it has all the required variations in inputs and outputs noted above. In addition, it is a current focus area for the EarthScope Transportable Array (TA) and GeoPRISMS subduction zone studies, so there are many opportunities to leverage other efforts. To demonstrate the range of science that could be done on this topic and the scope of resources needed, the workshop participants devised a plan based on two deployments, which ideally would be carried out in sequence, as they image very different parts of the arc where diverse questions can be addressed (**Figure 3.1**).

3.1.1 Deployment 1: Continental arc transect at the longitude of Kodiak Island and the nearby Alaska Peninsula.

The Alaska Peninsula deployment will study subduction factory cycling in a highly sedimented environment. It has the advantage of allowing land instrumentation across a wide swath of the mantle wedge, extending from Kodiak Island in the forearc across the arc and into the backarc along the Bering Sea coast. A deployment concurrent with the TA deployment in Alaska leverage those stations to increase coverage and reduce overall cost.

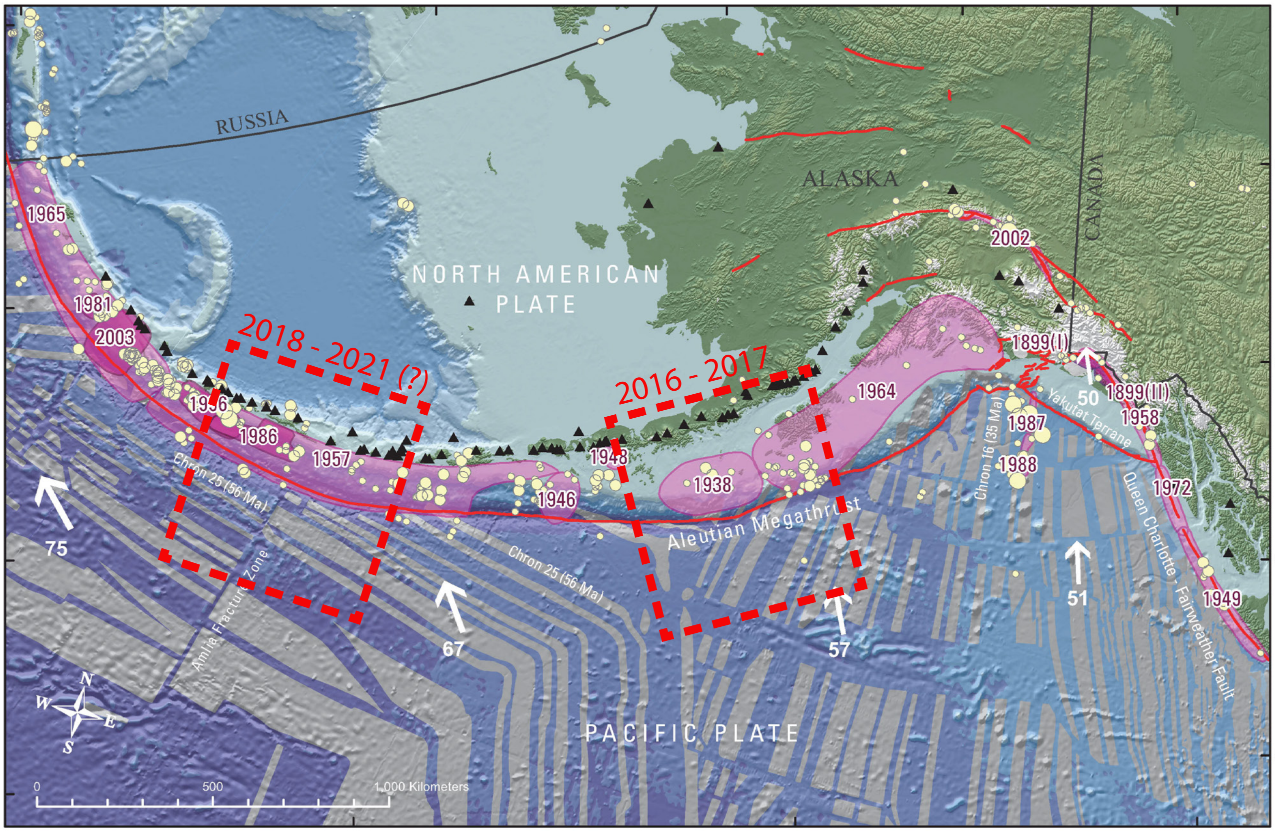


Figure 3.1. National deployment strategies in Alaska to address the Subduction Factory and Magma-Volatiles questions. The box labeled "2016-2017" would take advantage of coincident TA deployments on land. Rupture patches from Davies et al. (1981).

We envision one 15-18 month deployment of the entire amphibious array, consisting of 60 OBSs and 27 land seismic stations. Because of the high seismicity rate, a single deployment will provide sufficient data for the various types of imaging necessary for subduction factory studies. OBSs are now capable of operating for 15-18 months and a deployment at the beginning of summer and a recovery in early autumn of the following year will maximize the data recovery by including two summer seasons. Seismic noise levels are typically lower in summer than winter (see contributed whitepaper by Wilcock).

A sparse network of OBSs will be deployed on the incoming plate beginning about 250 km seaward of the trench to capture incoming plate seismicity and faulting and image hydration of the incoming oceanic plate by water circulating along the faults. A dense deployment of land seismographs and shallow water OBSs in the region of the arc and adjacent forearc will ensure high resolution imaging of the subarc magmatic system. The oceanic part of the backarc in this area is too shallow for optimal OBS deployment (< 100 m water depth), but Earthscope TA land seismic stations will provide good coverage of most of the backarc. As the western part of this region is also selected for study by the seismogenic processes breakout group (see Section 3.3) it is conceivable that a deployment in this region could fulfill the science requirements for both topics.

3.1.2 Deployment 2: Island arc transect across the Aleutian Islands near the Amlia Fracture Zone.

Many subduction factory goals are best met along an oceanic island arc, where crustal growth and geochemical cycling can be studied without the complication of pre-existing continental crust. The Central Aleutians are ideal in this respect, as subduction has built an arc since 50 Ma without major collision or rifting events, so that seismic imaging of the arc captures the process of arc growth in as simple a way as possible. The Amlia island region is particularly interesting because rapid along-strike changes in subducting material and other variables is reflected by changes in the spacing and geochemical output of the arc. Slab dip changes suddenly in this region and terrigenous sediment input to the trench stops at the Amlia Fracture Zone due to a bathymetric barrier to westward sediment flow. Seismic imaging of this segment is needed to clarify the changes in structure and the magmatic system that correspond to these changes in arc input and output.

The deployment strategy for the Amlia Island segment will be similar to that of the Alaska Peninsula segment, except that land area is limited and more of the imaging relies on OBSs. Again we plan for a 15-18 month deployment of 60 OBSs and 27 land seismographs, beginning in the summer with recovery in the early autumn of the following year. A sparse network of OBSs will be deployed on the incoming plate extending 250 km beyond the trench to image incoming plate hydration and faulting. A sparse OBS network will also be deployed up to 250 km into the Bering Sea backarc to image the backarc part of the mantle wedge and to ensure good recording of slab seismicity in all directions. A dense array of OBSs will be deployed in the forearc and in oceanic regions adjacent to the arc. The 27 land seismographs will be deployed by helicopter or boat and distributed along the Andreanof and Four Islands segments of the Aleutian Islands. The former includes accessible places both along the volcanic arc and forearc.

3.1.3 Overall strategy and timing.

We recommend that the continental arc transect is deployed first starting in the summer of 2016 with recovery in the early autumn of 2017. This ensures that the continental arc transect, which requires coordination with the Earthscope TA stations in Alaska, will be completed prior to the phase down of Earthscope which begins in 2018. The amphibious array equipment can then be checked and refurbished over the winter months and redeployed in the summer of 2018 along the Andreanof Island segment of the arc, with recovery in the autumn of 2019. Both deployments are required to comprehensively cover subduction factory objectives. Each deployment has significant objectives that will be achieved independent of the other array.

3.2. Passive Margins & Transform Faults

To address the key science questions associated with continental rifting and passive margins, summarized in Section 1.2 and articulated in the GeoPRISMS Science Plan, a comprehensive amphibious approach is necessary. At the workshop discussion quickly centered on the northeastern stretch of the North American-Atlantic margin as a potential area for an AAF deployment. Specifically, the stretch of continental margin from eastern Maine to the southwestern tip of Newfoundland, Canada (spanning New Brunswick and Nova Scotia) offers an ideal location for evaluating critical rifting questions in a passive-margin setting. Most importantly, it captures the abrupt termination of the East Coast Magnetic Anomaly, which is typically interpreted as an indicator of voluminous magmatic processes operating at the time of breakup. North of this termination extensional deformation is broad and appears to have occurred nearly amagmatically. South of this transition deformation is more localized near the shelf break (**Figure 3.2**).

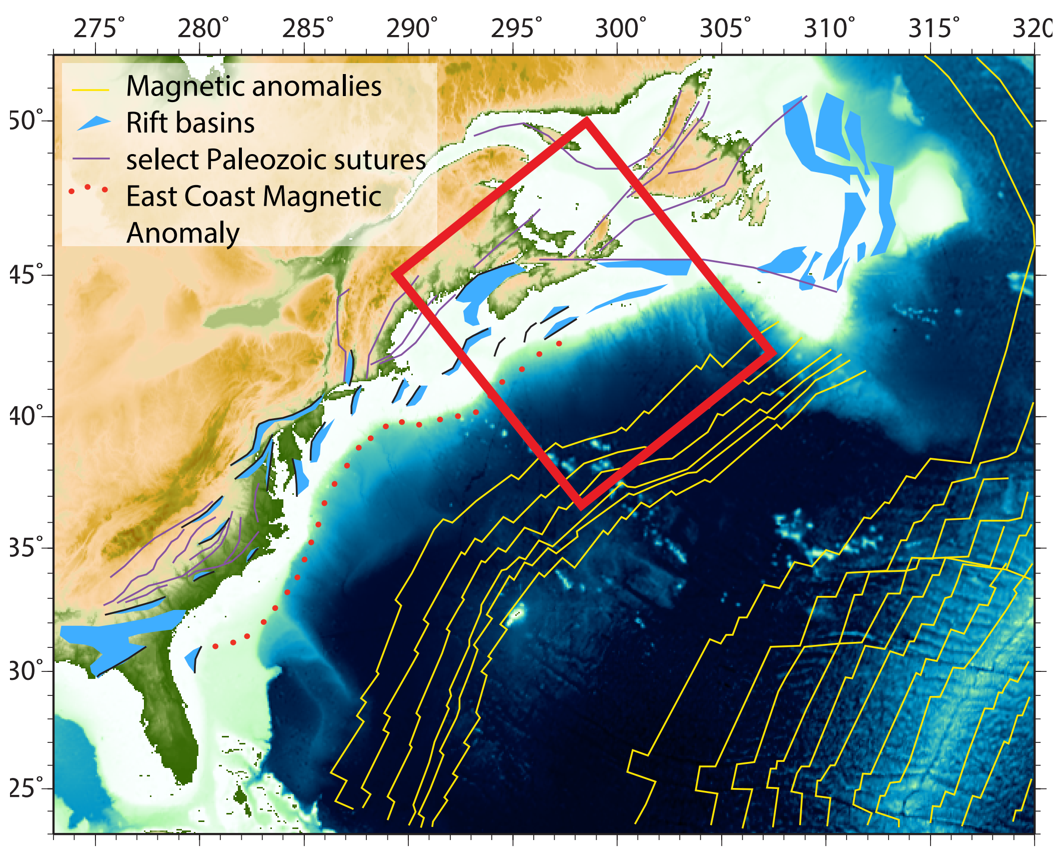


Figure 3.2. Hypothetical location of an amphibious-array experiment to address major questions of continental rifting and passive-margin evolution. Array is centered on the inferred major transition in magmatic behavior marked by the termination of the East Coast Magnetic Anomaly, while capturing major tectonic sutures, extensional rift basins, and the complete transition to seafloor spreading and associated segmentation.

Imaging the composition and deformation patterns at depth through the lithosphere will provide unambiguous and critical data on the role of magmatism in accommodating breakup. In addition, this stretch includes several prominent rift basins, including the Bay of Fundy, which is one of the largest rift basins along the ENAM system. Any imaging beneath these basins and comparison to the successfully rifted margin offshore will provide new perspectives on the mechanisms that promote the localization of deformation. Finally, this stretch includes several near-margin sutures within the North American continent, which provide an opportunity for studying the role of pre-existing structures on rift evolution. Offshore the seafloor in this region shows evidence of strong segmentation. Contrasting images of oceanic and continental lithosphere across these segment boundaries will provide a test of the notion that rift segmentation provides a causal link to segmentation of seafloor spreading.

Specific deployment scenarios were not discussed, but a full deployment of the existing AAF instrumentation could provide an experiment that is spatially comparable to the Cascadia initiative. The total span of the region is approximately 800 x 800 km. Onshore instruments could be deployed across New Brunswick, Nova Scotia, Prince Edward Island, and the southwestern corner of Newfoundland. Shallow, trawler-protected OBS instruments would be distributed on the shelf, both seaward of the coastline, as well as in the Gulf of St. Lawrence between New Brunswick and Newfoundland (north of Nova Scotia and PEI). Deep OBSs would populate the continental slope and the oceanic lithosphere. Densification of subarrays could focus on critical points of along-strike segmentation or basin formation. For optimal imaging a two-year deployment is recommended.

For the Transform Margin deployments, three scenarios were briefly discussed. Two offer opportunities to evaluate the behavior of transforms directly along the continental margin, where oceanic and continental lithosphere are juxtaposed: the northern San Andreas fault from San Francisco to Cape Mendocino, CA and the Queen Charlotte Fault from Vancouver Island to southeastern Alaska. The third scenario focused on the strike-slip Caribbean – North America plate boundary, which stretches from north of Puerto Rico, across northern Haiti and the Dominican Republic, and along southern Cuba. Both the northern San Andreas and Caribbean boundaries are particularly compelling from a seismic-hazard and great-earthquake perspective. The northern San Andreas entirely ruptured in the 1906 event and the Caribbean boundary spans a region of elevated seismic risk, as evidenced by the 2010 Haiti earthquake and the long history of damaging historical earthquakes across the region. Deployment specifics were not discussed, but all the regions involve onshore, shallow water, and deep-water deployment sites, over spatial scales comparable to or smaller than the Cascadia Initiative deployments.

3.3. Seismogenic Processes at Subduction Margins

The recent discovery of huge slip near the trench in the 2011 Tohoku earthquake and the recognition that material properties of the accretionary prism are critical for tsunami generation highlight how much we still have to learn about earthquakes in this environment. The Tohoku earthquake also highlighted the importance of this information for keeping global populations near sea level safe from tsunami hazards. The scientific challenge will be to characterize the spectrum of slip that occurs on the plate interface and to relate it to structural properties of the subduction zone, so that we can improve our knowledge of earthquake physics and hazards. In order to do this, we need accurate locations of events that are seismic (earthquakes) and aseismic (slow slip, tremor, LFE, VLFE) as well as imaging of the three-dimensional velocity structure. This requires instrument coverage on the ocean floor and on land, with ideally seismic and geodetic instrumentation for both. Optimal attributes of a plate boundary to target for study include abundant seismic activity, variable slip behaviors in space and time, and an existing geophysical framework to best take advantage of data from an AAF experiment. The Alaska-Aleutian margin meets all of these conditions with all ten of the largest US earthquakes in the last century, over 80% of the US earthquake energy, an average of one M≥7 earthquake every other year. An AAF study of the Alaska-Aleutian region would allow deployment strategies that can address key questions about seismogenic processes.

Specific questions related to seismogenesis that an amphibious study of this regions is well poised to answer include:

1. *What is the nature of seismicity and the potential for large slip in the toe of the prism? Is its behavior better described as locked, freely slipping, or something else?*
2. *What is the relationship between shallow seismicity, aseismic slip and the structure of the accretionary prism?*
3. *What is the along-strike variation in the nature of seismicity in regions with different slip behavior, and how do seismic slip patches interact with regions of aseismic slip? How do these variations correspond with variations in material or interface properties?*
4. *What material or structural features control transitions in slip behavior of the megathrust in the down-dip direction?*

At this workshop an ~1200 km along strike section of the Alaska-Aleutian margin, termed the "Megathrust Megaswath" was identified as the highest priority location for a future AAF deployment that focuses on megathrust earthquake behavior. This segment is shown in **Figure 3.3** and includes historical rupture areas of large earthquakes that are in different parts of the earthquake cycle and exhibit different tsunami behaviors. It also spans regions that display a range in locking behavior from completely locked

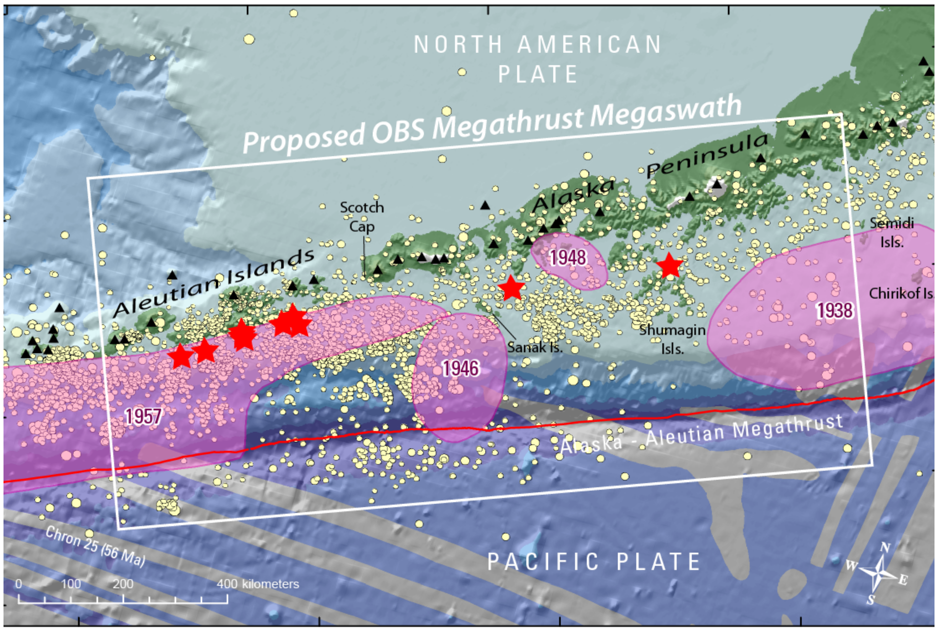


Figure 3.3. Megathrust Megaswath proposed deployment, spanning several rupture segments and Shumagin creeping segment.

to almost freely slipping. The Megaswath also contains some tremor hot spots and straddles the transition from continental to oceanic parts of the arc. This segment was identified as the highest interest transect to study at the 2011 GeoPRISMS/EarthScope Alaska meeting and it partly overlaps with the first priority of the Subduction Factory and Magma Volatiles group (Section 3.1).

Various deployment strategies were discussed with an important aspect being the ability to instrument a region large enough to cover multiple megathrust ruptures and changes in slip behavior. This could be done for the entire Megaswath region with the current configuration of the Cascadia Amphibious Array deployment. This would permit good coverage of the forearc and megathrust plate boundary but would require additional coverage to the north to also investigate arc processes. If done during the EarthScope TA deployment then a backbone for flexible array deployments could be leveraged. Smaller deployment strategies were also discussed and it was felt that much could be learned about megathrust slip behavior by focusing on a 300-400 km along strike region that overlapped a change in slip behavior. If this effort targeted the eastern section of the Megaswath, it would overlap the western part of the Alaska Peninsula segment of the Subduction Factory and Magma Volatiles focus area and many objectives of both subgroups could be accomplished. In this scenario, one or more strike-parallel lines would be accompanied by two or three downdip profiles across the regions exhibiting different slip behaviors. Seismometer spacing of up to 40 km would be acceptable for earthquake location and seismic imaging while detailed studies of tectonic tremor would require smaller station spacing of 20 km or less. Instrument coverage should extend from just seaward of the trench to where the plate interface is about 40 km below land to focus on plate boundary behavior and extended to greater slab depth in order to study arc processes.

Over much of this region, existing GPS sites are sparse and a denser onshore network is needed. In parts of the area, islands in the forearc region offer the opportunity to site onshore instruments. Absolute pressure gauges could be integrated with the OBS instrument package. Due to instrumental drift these cannot measure secular trends associated with interseismic deformation, but they can potentially record the displacements due to significant events. GPS/Acoustic horizontal positioning could provide critical information about the extent of slipping and locked patches offshore, even with a small number of well-placed sites.

This type of deployment would leverage from the transportable array coming to Alaska and significantly improve the onshore network. While opinions varied, in some scenarios a 15-18 month deployment may turn out to be sufficient due to the high level of seismic activity, provided it spanned two summers. Other deployment scenarios that were discussed included a "webfoot" reconnaissance study of a large portion of Alaska (i.e., a grid at the 85 km TA spacing), three different 15-18 month deployments with one focused on slip behavior, one on magma/arc and the other webfoot-like.

There were several meeting participants that advocated keeping 20-30 of the AAF OBSs in the Cascadia region for another year. They felt that some of the compelling science questions that originally motivated the amphibious array to be deployed in Cascadia will not be answered with the four years of data being collected. They argued that due to instrument failure or poor data quality, OBS data coverage of the subduction zone region off northern Washington State contains a significant hole between Grays Harbor and the Straits of Juan de Fuca. Improved coverage here would be valuable both for seismicity location efforts and for receiver function studies to characterize the depth, thickness, and properties of the plate interface.

3.4. Longer-term objectives

While the emphasis of the workshop was on deployments over the next five years, which would substantially overlap the lifespan of the EarthScope and GeoPRISMS science plans, it is clear that the Amphibious Array Facilities have significant potential to contribute globally. A few presentations in other settings showed the potential for other deployments in other subduction zones and rifted margins, particularly if done in concert with international partners. Discussions about a potential SZO (*http://www.iris.edu/hq/initiatives/subduction-zone-observatory*) indicated that a facility with much broader scope has tremendous potential for scientific impact. Such a facility might include many other observations (see Section 5), involve international partners, and cover a substantial fraction of the planet's subduction system. The AAF was seen as a critical test-bed, currently deployable, that could perhaps serve as a nucleus for a more ambitious SZO program. Many of the deployment scenarios discussed above could be natural first steps toward a larger SZO.

4. Benefits of a Community Experiment model

As the scale of a scientific project grows, it becomes increasingly important to ensure that scientific targets and implementation strategies are chosen to have the highest impact. One approach has been to involve a larger, open community in major decision making, rather than relying upon closed PI groups, and to establish free and open data access. While this approach has been successful for very large projects such as EarthScope or IODP, the Amphibious Array Facilities present a unique opportunity to try this approach on mid-size projects still larger than PI groups can reach and on a project that naturally spans the divisional structure at NSF. In the process of managing the AAF through the Cascadia Initiative, it has become clear that there are numerous benefits to this approach. Workshop participants were overwhelmingly supportive of future uses of the AAF being handled in a community manner. Some of the important lessons we learned include:

1. Community-planned and managed experiments can be cost-effective ways to achieve high overall scientific impact. A very large PI community has been engaged and is starting to extract a wide spectrum of science that a single PI team cannot achieve.

2. Open and rapid access to data is critical. A great many more scientists have been using the data than were ever envisioned in original planning. Also, close scrutiny by a number of independent groups has led to rapid communication and correction of data problems, leading to robust high-quality data.

3. The community workshops to design the project and evaluate its progress have been successful at bringing together diverse groups to study earth processes, not just primary users of the data but a variety of people doing critical complementary work.

4. The open community approach has been an excellent way to reinvigorate communities and bring early-career scientists to levels of engagement critical for their longevity. New PIs join in without having to secure funding by themselves for major initiatives. This has been particularly apparent in the offshore component, which has led to tremendous growth in the OBS user base.

5. By coordinating efforts of several technical support and engineering groups on a single project advances have been more rapid, it has been possible to support more technical innovation and feedback between users and builders has been much more efficient.

6. Overall, there is tremendous scientific value to being part of a larger effort. Even if individual PIs are supported separately, their contributions hang together as part of a larger synoptic effort, enabling many synergies and more sophisticated approaches to the problems being addressed.

There are of course some difficulties with this model, the primary being the overall commitment by both NSF and the group leading the deployments (see Box), so scientific goals must be sufficiently large and significant to justify it. Of course, such a commitment in data acquisition only succeeds with a commitment to fund scientific research projects that use it. There also seems to be an economy of scale at work for large amphibious projects; putting all resources on a single project like the CI was felt to be a much better way to ensure success than diffusing the effort in many directions and makes it possible to garner resources to achieve otherwise unreachable scientific objectives. On the other hand, some meeting participants were concerned that focusing resources on community science projects reduce critical support for individual-PI projects. Community initiatives stand the best chance of success if new funds are made available both to support the science and to appropriately support the facilities necessary for the initiative's success.

Cascadia Initiative (CI): The advantages of an ambitious Community Experiment

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 (Toomey et al., 2014). These wide-ranging science objectives were developed by an NSF-supported, community workshop convened in Portland, Oregon in October 2010. The CI exemplifies the benefits and challenges of this mode of data collection and sharing. Two aspects of the CI are novel and 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 publically available. Secondly, the CI is deploying a new generation of ocean bottom seismometers that are designed to withstand a direct hit by bottom trawling fisheries and that are equipped with sensors shielded from ocean bottom currents, thereby opening up the shallow marine environment (<1000 m) for more routine geophysical investigations. These sea changes in practices and capabilities are benefitting science, attracting a new generation of seismologists, and delivering results that will benefit society.

The CI is having a profound influence on the community that uses ocean-bottom seismometer data, particularly early career scientists. The Cascadia Initiative Expedition Team's Apply-to-Sail program has taken over 100 early career scientists to sea, including undergraduates, graduate students and post-docs. To date, over 20 TB of CI OBS data have been downloaded from the IRIS DMC, by over 500 unique users, at over 300 unique institutions, in 25 different countries (**Figure C1**). That so many users are downloading CI OBS data ensures that there is wider use of the data, thereby enhancing the scientific return and making the overall experiment cost effective.

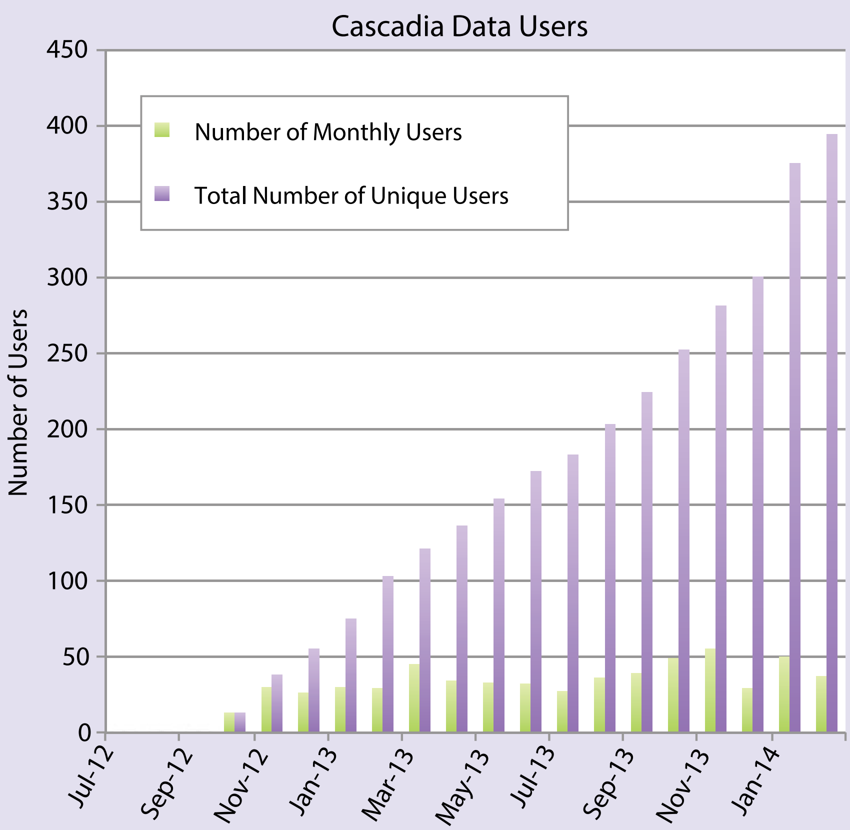


Figure C1. Rapid growth of the community using Cascadia Initiative data (Toomey et al., 2014).

5. Opportunities for related complementary observations

The science questions discussed in Section 1 are nearly always broader than can simply be examined with seismological or geodetic data alone. Both the EarthScope and GeoPRISMS Science plans demonstrate quite clearly that there are important needs and opportunities for complementary observations. These include additional geophysical data (such as electromagnetic and heat flow), scientific drilling, geologic (largely extending the time scale and interpretive framework), and environmental studies (using the observation networks as broad environmental sensing platforms). In addition, geodynamic models should be employed hand in hand with the data integration for heuristic exploration of physically based interpretations.

Seafloor geodesy involves mainly three distinct measurements: pressure gauges that measure vertical displacement of the seafloor, direct ranging (over short distances) to measure horizontal relative motions, and GPS/Acoustic (GPS/A) positioning to measure displacements and velocities over long distances. Pressure gauges can be integrated with OBS instrument packages, or deployed separately. Due to instrumental drift, they can measure displacements due to events, but not most secular deformation signals. GPS/A measurements require a surface platform (ship or buoy) to either remain in the center of a transponder array so that path delay errors in the water cancel, or move through the array in a controlled pattern so that the acoustic velocity structure can be estimated. Although this technique has been applied extensively in Japan with great success, much less has been done in the US. Future developments that could make GPS/A measurements much more affordable might include using autonomous vehicles like a wave glider, such as currently-operational prototypes (Chadwell, 2013), or buoys that could be tethered or towed behind a small vessel.

Electromagnetic (EM) methods that can be used in an amphibious setting include magnetotellurics (MT) and marine controlled-source electromagnetic (CSEM) sounding. MT has been a successful component of Earthscope with TA coverage as well as flex-array studies. MT methods are able to constrain the incoming plate, identify water losses from the downgoing slab through the whole dewatering cycle and trace the generation and transport of melt from the slab to the volcanic arc (e.g. McGary et al., 2014). There are very little MT data across the continental-oceanic transition in passive margin settings, yet MT has the potential to constrain changes in lithospheric thickness, as well as key properties of the underlying asthenosphere, such as water content. CSEM has higher resolution at shallower depths and can be used to look at the porosity evolution of the incoming oceanic crust, the shallow dewatering and fluid flow along the decollement and fluid flow through the over-riding plate or sediment wedge (Key et al., 2012; Naif et al., in prep). One advantage of the MT method is that coverage can be built up over time with no need for land and marine sites to be deployed at the same time.

Scientific drilling is the tool that enables in situ observations of phenomena as well as retrieval of materials directly associated with the processes under investigation. Despite its expense and extremely narrow aperture, drilling of active fault zones has recently demonstrated its great value. For example, the San Andreas Fault Observatory at Depth (Zoback, et al., 2007) has laid to rest decades of debate about the strength of the San Andreas fault by demonstrating that its "slipperiness" was due to the presence of low friction minerals such as clays in nano-coatings along the failure surfaces of the fault zone. The bold JFAST experiment also demonstrated low coseismic friction along the Tohoku-Oki fault surface activated in the 2011 M9 Tohoku earthquake (Fulton et al., 2013).

Field geological observations, geochronological constraints, and interpretations are important integrative elements of a broader amphibious science plan. The geological field observations document rock types, geochemical properties, geometric relationships, and plausible histories of events which may be critical analogues for or constraints on processes. In addition, modern geochronological methods can provide numerical age control for events ranging from $>10^7$ to 10^2 years; that is, from the geological evolution of the plate boundary to the decadal stages of the earthquake cycle (e.g., *http://www.earthscope.org/events/earthscope-institute-geochronology-and-the-earth-sciences*).

Significant effort for geophysical observations in amphibious settings goes into the underlying physical, computation, and communications infrastructure of the networks themselves. Therefore, existing and future deployments represent valuable environmental sensing platforms. For example, the COCONET geodetic array of the Caribbean measures positions of benchmarks continuously using GPS, but also senses precipitable water vapor in the atmosphere. The broadband seismometers of the USArray Transportable Array are collocated with and share power and data infrastructure with atmospheric sensors including barometers and infrasound microphones (e.g., *http://www.usarray.org/researchers/obs/transportable/atmospheric*).

Geodynamic models should be employed hand in hand with the data integration for heuristic exploration of physically based interpretations. For example, the Computational Infrastructure for Geodynamics (CIG; *http://geodynamics.org/*) is a community-driven organization that advances Earth science by developing and disseminating software for geophysics and related fields. This community has advanced the simulation of long and short term tectonic processes. These physically-based models naturally require idealization but also are inspired and constrained by the observations described here for amphibous systems (e.g., Cooper et al., 2015).

6. Societal relevance, hazards, and other broader impacts

Amphibious array deployments target the land-ocean boundary, zones of major societal risk. Major subduction zones can generate large earthquakes and tsunamis and these can pose significant societal hazard to both local and distant population centers, by ground shaking and tsunamis. Volcanic hazards can also be present as part of the structure of these regions, which further compounds the risks. Passive margins also host dense populations that are subject to progressively higher levels of risk from severe weather and flooding. Proper assessment of future sea level depends critically on understanding their deep structure and geologic history.

To understand the risks and implement monitoring and risk reduction strategies requires a clear picture of the geophysical processes and structure of these regions – and these are natural results of amphibious science and AAF observations. Progress in understanding the underlying physics requires an integrative and multi-disciplinary approach. This generates the best form of feedback to policymakers and others, who require an integrated big-picture understanding of what otherwise would be complex and disparate results.

As described in Sections 4 and 5, there are several broader impacts within the geosciences. Community experiments have been shown to be tremendously enabling of early-career scientists. They bring together technical experts on a single project, leading to advances in the infrastructure for science. They serve as natural focal points for outreach activities at all educational levels. Finally, they can catalyze a multidisciplinary community to take advantage of significant new observations and help focus research agendas.

7. Summary and recommendations

Significant and societally-relevant scientific questions in the solid earth are ones best addressed at continent-ocean boundaries. Amphibious sensing arrays are a critical component to advancing our understanding of these systems, but they are logistically complex and expensive. The Cascadia Initiative has shown the power of the Community Experiment approach, where the entire Amphibious Array Facilities are brought to bear on a single problem in a single area. Advantages of this approach include the ability to address large-scale problems, engaging a wide community and a large population of scientists continually, efficiencies and technological benefits of focused deployments, and using open rapid data access effectively. While this report concentrates on a seismic array, which has the highest potential to be moved to new sites in the future, redeployment of the AAF has the potential to catalyze a wide variety of parallel complementary scientific efforts. Looking farther forward, such an array seems a likely test bed for a critical component of a Subduction Zone Observatory or other similar large and multinational infrastructure efforts.

The broad consensus from the Snowbird meeting included the following recommendations:

1. There is great value to Amphibious Array Facilities deployments. These should continue.

2. The Community Experiment approach has been a success and seems required to continue an effort of this magnitude.

3. The amphibious array has most potential to contribute if kept relatively intact with all 60 OBSs and 27 onshore seismometers. At full strength it provides a powerful tool to do things that single PIs cannot. The most compelling deployment strategies involved leveraging additional resources such as the presence of the EarthScope TA to increase the scale of observation.

4. Continued evaluation of how to reduce data acquisition costs and optimize future experiments is required.

5. Community-organized experiments work best with both adequate support for science and support for facilities that is independent of core science budget. NSF should prioritize additional funding to support science that utilizes data from cross-divisional facilities because it is high impact and cost effective.

6. Where a dense onshore GPS network does not already exist, new GPS sites need to be considered as part of the array. The deployment of sites would depend on the specific scientific problem and are particularly critical for seismogenic zone studies.

7. In the 2016-2018 timeframe, several targets complementing the EarthScope TA footprint were considered. There is some rationale for an East Coast array and some for keeping resources in Cascadia at relatively low cost. In Alaska at least two scenarios were discussed: an Aleutians array that targets deeper subduction-factory-volatile-cycles problems and one closer to the Alaska Peninsula that targets the thrust zone. The latter is at high priority to be deployed while the Transportable Array is operating within Alaska (2016-2018). Similarly, off the Eastern North America passive margin, deployments were envisioned that complemented onshore resources such as the Central-Eastern U.S. Network that are planned to replace the TA as it moves to Alaska, still within the EarthScope footprint.

8. Past 2018, lessons learned can be applied more broadly although even in margins like Alaska-Aleutians there is more to be done. Longer-term efforts could be coordinated with a Subduction Zone Observatory should its development mature.

9. Communities that conduct parallel observations should be continually engaged and their efforts coordinated with Amphibious Array deployments as much as possible. It is recognized that funding for such efforts would have to be found separately, but that the value of multidisciplinary science for amphibious problems is clear.

References cited

Bilek, S. (2014), Detection of Repeating Earthquakes Using Cascadia Initiative Data, *IRIS Future of the Amphibious Array Meeting*, Snowbird Utah.

Bodmer, M., D. R. Toomey, E. E. Hooft, J. Nabelek, and J. Braunmiller (2014). Shear wave splitting observations across the Juan de Fuca plate system: Ridge-to-trench constraints on mantle flow from 2 years of Cascadia Initiative OBS data, Abstr. DI33A-4300, *Amer. Geophys. Un. 2014 Fall Meeting*, San Francisco CA., 15-19 Dec.

Buck, W. R. (2006), The role of magma in the development of the Afro-Arabian rift system, Yirgu, G., Ebinger, C.J. and Maguire, P.K.H. (eds), The Afar Volcanic Province within the East African Rift System, Geological Society, London, Special Publications, 259, 43-54.

Chadwell, C.D. (2013), GPS-Acoustic seafloor geodesy using a wave glider, Abstr. G14A-01, *Amer. Geophys. Un. 2013 Fall Meeting*, San Francisco CA., 9-13 Dec.

Cooper, C.M., E. Mittelstaedt, C. Currie, J. van Wijk, L. Kellogg, L. Hwang, and J R. Arrowsmith, Moving Lithospheric Modeling Forward: Attributes of a community computer code, Groundwork article, GSA Today, in press, 2015.

Davies, J. N., and L. House (1979), Aleutian subduction zone seismicity, volcano-trench separation, and their relation to great thrust-type earthquakes, *J. Geophys. Res., 84*, 4583-4591.

Davis, E. E., K. Becker, K. Wang, K. Obara, Y. Ito, and M. Kinoshita (2006), A discrete episode of seismic and aseismic deformation of the Nankai trough subduction zone accretionary prism and incoming Philippine Sea plate, *Earth Planet. Sci. Lett., 242*(1–2), 73-84, doi:http://dx.doi.org/10.1016/j.epsl.2005.11.054.

Dragert, H., K. Wang, and T. S. James (2001), A silent slip event on the deeper Cascadia subduction interface, *Science, 292*, 1525-1528.

Fulton, P. M., E. E. Brodsky, Y. Kano, J. Mori, F. Chester, T. Ishikawa, R. N. Harris, W. Lin, N. Eguchi, S. Toczko, T. Expedition 343, and K.-. Scientists (2013), Low Coseismic Friction on the Tohoku-Oki Fault Determined from Temperature Measurements, *Science, 342*(6163), 1214-1217, doi:10.1126/science.1243641.

Hopper, J. R., T. Dahl-Jensen, W. S. Holbrook, H. C. Larsen, D. Lizarralde, J. Korenaga, G. M. Kent, and P. B. Kelemen (2003), Structure of the SE Greenland margin from seismic reflection and refraction data: Implications for nascent spreading center subsidence and asymmetric crustal accretion during North Atlantic opening, *J. Geophys. Res., 108*(B5), art. no. 2269.

Ichinose, G., P. Somerville, H. K. Thio, R. Graves, and D. O'Connell (2007), Rupture process of the 1964 Prince William Sound, Alaska earthquake from the combined inversion of seismic, tsunami and geodetic data, *J. Geophys. Res., 112*, B07306, doi:07310.01029/02006JB004728.

Ito, Y., and K. Obara (2006), Dynamic deformation of the accretionary prism excites very low frequency earthquakes, *Geophys.Res. Lett., 33*(2), L02311.

Ito, Y. R. Hino, M. Kido, H. Fujimoto, Y. Osada, D. Inazu, Y. Ohta, T. Iinuma, M. Ohzono, S. Miura, M. Mishina, K. Suzuki, T. Tsuji, J. Ashi (2013), Episodic slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake, *Tectonophysics, 600*, 14–26, doi:10.1016/j.tecto.2012.08.022.

Janiszewski, H., G. Abers, J. Gaherty and H. Carton (2014). Imaging the locked zone of the Cascadia Subduction Zone using receiver functions from the Cascadia Initiative, Abst. T41E-07, *Amer. Geophys. Un. 2014 Fall Meeting*, San Francisco CA., 15-19 Dec.

Kato, A., K. Obara, T. Igarashi, H. Tsuruoka, S. Nakagawa, and N. Hirata (2012), Propagation of Slow Slip Leading Up to the 2011 Mw 9.0 Tohoku-Oki Earthquake, *Science*, *335*(6069), 705–708, doi:10.1126/science.1215141.

Key, K., S. Constable, T. Matsuno, R. L. Evans, and D. Myer, (2010), Electromagnetic evidence for plate hydration due to bending faults at the Middle America Trench, *Earth and Planet. Sci. Letts.*, 351-352, 45-53.

McGary, R. S., R. L. Evans, P.E. Wannamaker, J. Elsenbeck, and S. Rondenay, (2014), From slab to surface: Imaging the complete pathway for melt and fluids beneath Mount Rainier in the Cascadia subduction system, *Nature*, doi:10.1038/nature13493, 511, 338-341.

Naif, S., K. Key, S. C. Constable, R. L. Evans, Water-rich faults at the Middle America Trench, in prep.

Oleskevich, D., R. Hyndman, and K. Wang (1999), The updip and downdip limits to great subduction earthquakes: Thermal and structural models of Cascadia, south Alaska, SW Japan, and Chile, *J. Geophys. Res., 104*, 14965-14991.

Schurr, B., G. Asch, S. Hainzl, J. Bedofrd, A. Hoechner, M. Palo, R. Wang, M. Moreno, M. Bartsch, Y. Zhang, O. Oncken, F. Tilmann, T. Dahm, P. Victor, S. Barrientos, and J-P. Vilotte (2014), Gradual unlocking of plate boundary controlled initiation of the 2014 Iquique earthquake, *Nature*, doi:10.1038/nature13681, 512, 299-302.

Tian, Y. and M. Ritzwoller, Directionality of ambient noise on the Juan de Fuca Plate: Implications for source locations of the primary and secondary microseism, Abstr. S41A-4419, *Amer. Geophys. Un. 2014 Fall Meeting*, San Francisco CA., 15-19 Dec.

Toomey, D. R., R. M. Allen, A. H. Barclay, S. W. Bell, P. D. Bromirski, R. L. Carlson, X. Chen, J. A. Collins, R. P. Dziak, B. Evers, D. W. Forsyth, P. Gertsoft, E. E. E. Hooft, D. DLivelybrooks, J. A. Lodewyk, D. S. Luther, J. J. McGuire, S. Y. Schwartz, M. Tolstoy, A. M. Tréhu, M. Weirathmueller, and W. S. D. Wilcock (2014), The Cascadia initiative: A sea change in seismological studies of subduction zones, *Oceanography, 27*(2), 138-150.

Zoback, M., S. Hickman, W. Ellsworth and the SAFOD Science Team (2011), Scientific drilling into the San Andreas Fault Zone – an overview of SAFOD's first five years, *Sci. Drilling*, 11, 14-28.

Appendix 1: Contributors to this report

** indicates member of Workshop Organizing Committee*

Geoff Abers, Cornell University (Editor) *

Susan Schwartz, University of California Santa Cruz (Editor) *

Ramon Arrowsmith, Arizona State University
(Chair, EarthScope Science Steering Committee)

Rob Evans, Woods Hole Oceanographic Institution *

Jeff Freymueller, University of Alaska Fairbanks *

Jim Gaherty, Lamont-Doherty Earth Observatory of Columbia University *

Haying Gao, University of Massachusetts *

Dan Lizarralde, Woods Hole Oceanographic Institution

Emily Roland, University of Washington

Doug Toomey, University of Oregon

Peter van Keken, University of Michigan
(Chair, GeoPRISMS Steering and Organizing Committee)

Doug Wiens, Washington University of Saint Louis *

Bob Woodward, Incorporated Research Institutions for Seismology *

Appendix 2: Workshop program

Workshop website:
http://www.iris.edu/hq/workshops/2014/10/amphibious_array_facility_workshop

Wednesday - October 22, 2014

5:00 PM - 8:00 PM	Pre-workshop program for students and post-docs
	Introductions – Rob Evans, Susan Schwartz (15 mins)
	NSF remarks – Jennifer Wade (10)
	Overview of AAF technical issues – Susan Schwartz (15)
	Pop-up talks – Students and Post-docs (50)
	Buffet dinner, discussion, and overview of Cascadia science – Anne Trehu (30)

Thursday - October 23, 2014

7:00 AM - 8:00 AM	Group breakfast
8:00 AM - 9:00 AM	*Session 1: Introductions, overview, NSF perspectives and goals, desired outcomes, Chairs: Rob Evans and Doug Wiens*
	Purpose of workshop – Geoff Abers (15 mins)
	Guidance from NSF – Donna Blackman, Greg Anderson, Jennifer Wade (20)
	Perspective from the AASC Chair – Susan Schwartz (15)
9:00 AM - 10:00 AM	*Session 2: Cascadia - scientific and technical results, Chairs: Susan Schwartz and Jim Gaherty*
	"The Cascadia Initiative: A Sea Change in Seismology" – Doug Toomey (40)
	"Detection of Repeating Earthquakes Using Cascadia Initiative Data" – Sue Bilek (12)
10:00 AM - 10:30 AM	Break
10:30 AM - 12:30 PM	Session 2 (continued)
	"Imaging the Downgoing Juan de Fuca Crust Using Receiver Functions from the Cascadia Initiative" – Helen Janiszewski (12 mins)
	"Offshore Structure of the Cascadia Subduction Zone from Full-Wave Ambient Noise Tomography" – Haiying Gao (12)
	"Ambient Noise as an Imaging Tool for the Juan de Fuca Plate" – Weisen Shen (12)
	OBSIP-IC perspective on Cascadia (Title TBA) – John Collins (25)

	Data handling, station performance, noise characteristics (Title TBA) – Jessica Lodewyck (25)
12:30 PM - 1:30 PM	Group lunch
1:30 PM - 3:15 PM	*Session 3: Ideas for future sites, deployments, and strategies, Chairs: Jeff Freymueller and Doug Wiens*
	Southern Alaska – Peter Haeussler (20 mins)
	Eastern U.S./Canada – Vadim Levin (20)
	"Why Determining the Location and Shape of the North America Slab beneath the Northeastern Caribbean Is Important for Earthquakes and Tsunami Risk Assessment for the Caribbean Region" – Liz Vanacore (5)
	"Why Are SSE's Invading the Seismogenic Zone in the Guerrero Seismic Gap and How Can the Amphibious Array Answer That Question?" – Allen Husker (5)
	"The Arctic Beaufort Sea Alaska, Yukon, Northwest Territories Margin and the Amphibious Array" – Roy Hyndman (5)
	Aleutian Arc Structure – Geoff Abers (5)
	"The Need to Extend the Cascadia Initiative Two More Years: Enabling Definitive Results for a Critical Region" – Emily Roland (5)
	Lessons from Cascadia: Noise – Spahr Webb (15)
3:15 PM - 4:00 PM	General discussion, plan for breakouts and guidance
4:00 PM - 4:30 PM	Break
4:30 PM - 6:00 PM	Breakout group sessions: science motivators that require future the AAF
	Group 1
	Group 2
	Group 3
6:00 PM - 7:30 PM	Poster session (with Hors d'oeuvres and cash bar)
7:30 PM	Dinner on your own

Friday - October 24, 2014

7:00 AM - 8:00 AM	Group breakfast
8:00 AM - 8:30 AM	Breakout group reports
8:30 AM - 10:00 AM	*Session 4: Other perspectives, techniques, data, science questions, and other country's plans, Chairs: Haying Gao and Geoff Abers*
	"Imaging Subduction Seismogenic Zone: Marine Seismic Studies Around Japan" – Shuichi Kodaira (20 mins)

	"Pacific Array" – Hitoshi Kawakatsu (20)
	"Mapping Fluids Along Plate Margins with Amphibious Electromagnetic Exploration" – Kerry Key (12)
	"Seafloor Geodesy: Techniques and Recent Advances" – Scott Nooner (12)
10:00 AM - 10:30 AM	Break
10:30 AM - 11:00 AM	*Session 4 (continued), Chairs: Jim Gaherty and Rob Evans*
	"The Amphibious Array Facility: Good and Cheap" – William Wilcock (12)
	"SeaJade Earthquake Observations in Cascadia Subduction Zone off Vancouver Island" – Koichiro Obana (5)
	Observing Tremor on OBS – Aaron Wech (5)
	Subduction Zone Observatories – Doug Wiens (5)
11:00 AM - 11:45 AM	General discussion, plan for breakouts and guidance
11:45 AM - 12:45 PM	Group lunch
12:45 PM - 2:15 PM	Breakout group sessions: Setting- or site-specific scientific opportunities
2:15 PM - 3:30 PM	Poster session
3:30 PM - 5:00 PM	*Session 5: Group discussion, identify consensus on a path forward, Chairs: Geoff Abers and Susan Schwartz*
5:00 PM	Adjourn

Appendix 3: List of whitepapers submitted prior to the workshop

Available at:
http://www.iris.edu/hq/workshops/2014/10/amphibious_array_facility_workshop

Cascadia Amphibious Array ocean bottom seismograph instrument performance, J. Lodewyk, D. Sumy, B. Evers, R. Woodward

The Amphibious Array Facility: good and cheap, W. Wilcock

Monitoring baleen whales with the offshore component of the Amphibious Array Facility, W.S.D. Wilcock, M. Weirathmueller

Why can the breakup of the continental lithosphere take different paths? Understanding the transition from magmatic to amagmatic rifting, V. Levin, M. Nedimovic, M. Withjack, S. Carbotte, K. Louden, C. Beaumont

The Arctic Beaufort Sea Alaska, Yukon, NWT margin and the Amphibious Array, F. Vernon, R. Hyndman, M. Riedel, J. Orcutt, M. West

The Gulf of Alaska shear zone: a potential future Amphibious Array scientific target, J. Walter, G. Christeson, S. Gulick, R. Reece

A proposed 'Megathrust Megaswath' OBS deployment in southern Alaska, P. Haeussler, G. Abers, N. Bangs, A. Becel, R. Briggs, S. Engelhart, J. Freymueller, S. Gulick, R. Koehler, M. Nedimovic, A. Nelson, T. Parsons, E. Roland, D. Shillington, R. Witter, L. Worthington

Exploring seismic and aseismic slip interactions in the eastern Aleutians, A. Wech, E. Roland, J. Freymueller, C. Thurber, K. Creager, J. Gomberg, A. Ghosh, S. Prejean.

The need to extend the Cascadia Initiative two more years: Enabling definitive results from a critical region, E. Roland, E., P. Bodin, J. Gomberg, H. Houston, J. Vidale, W. Wilcock.

Appendix 4: Workshop participants

Name	Student or Post-Doc?	Country	Institution
Aaron Wech	Post-Doc	us	US Geological Survey
Allen Husker	No	mx	Universidad Nacional Autonoma de Mexico
Andrew Barclay	No	us	Lamont-Doherty Earth Observatory of Columbia University
Andy Frassetto	No	us	IRIS
Anne Trehu	No	us	Oregon State University
Aubreya Adams	Post-Doc	us	Washington University in St. Louis
Bob Busby	No	us	IRIS
Bob Detrick	No	us	IRIS
Bob Woodward	No	us	IRIS
Brent Evers	No	us	IRIS - OBSIP
Daniel Bowden	Student	us	Caltech
Dayanthie Weeraratne	No	us	California State University, Northridge
Don Forsyth	No	us	Brown University
Donna Blackman	No	us	NSF / Scripps Institution of Oceanography
Donna Shillington	No	us	Lamont-Doherty Earth Observatory of Columbia University
Doug Toomey	No	us	University of Oregon
Doug Wiens	No	us	Washington University in St Louis
Emily Morton	Student	us	New Mexico Tech
Emily Roland	No	us	University of Washington, School of Oceanography
Erin K. Todd	Student	us	UC Santa Cruz
Fan-Chi Lin	No	us	University of Utah
Frank Vernon	No	us	Scripps Institution of Oceanography, UCSD
Gabi Laske	No	us	IGPP, Scripps Institution of Oceanography, UCSD

Name	Student or Post-Doc?	Country	Institution
Gail Christeson	No	us	Institute for Geophysics, University of Texas at Austin
Geoff Abers	No	us	Cornell University
Gillean Arnoux	Student	us	University of Oregon
Greg Anderson	No	us	National Science Foundation
Haiying Gao	No	us	University of Massachusetts Amherst
Harmony Colella	Post-Doc	us	Arizona State University
Heidi Houston	No	us	University of Washington
Helen Janiszewski	Student	us	Lamont-Doherty Earth Observatory of Columbia University
Hitoshi Kawakatsu	No	jp	ERI, University of Tokyo
Hongzhu Cai	Student	us	University of Utah
Jake Walter	No	us	Institute for Geophysics, University of Texas at Austin
Jeff Babcock	No	us	Scripps Institution of Oceanography, UCSD
Jeff Freymueller	No	us	University of Alaska Fairbanks
Jennifer Wade	No	us	National Science Foundation
Jesse Hutchinson	Student	ca	University of Victoria
Jessica Lodewyk	No	us	IRIS
Jim Gaherty	No	us	Lamont-Doherty Earth Observatory of Columbia University
Joan Gomberg	No	us	US Geological Survey
John Collins	No	us	Woods Hole Oceanographic Institution
John Nabelek	No	us	Oregon State University
Jose Mieres-madrid	No	cl	Universidad de Chile
Joseph Byrnes	Student	us	University of Oregon
Juli Morgan	No	us	Rice University
Kasey Aderhold	Student	us	Boston University
Kent Anderson	No	us	IRIS
Kerry Key	No	us	Scripps Institution of Oceanography, UCSD
Koichiro Obana	No	jp	JAMSTEC
Liz Vanacore	No	us	PRSN @ UPR-Mayaguez
Maya Tolstoy	No	us	Lamont-Doherty Earth Observatory of Columbia University
Miles Bodmer	Student	us	University of Oregon

Name	Student or Post-Doc?	Country	Institution
Mostafa Mousavi	Student	us	University of Memphis
Nathan Bangs	No	us	Institute for Geophysics, University of Texas at Austin
Paul A Bodin	No	us	University of Washington
Peter Haeussler	No	us	U.S. Geological Survey
Peter Van Keken	No	us	University of Michigan
Ramesh Singh	No	us	Chapman University
Ramon Arrowsmith	No	us	Arizona State University
Richard Allen	No	us	UC Berkeley
Rob Evans	No	us	Woods Hole Oceanographic Institution
Roy Hyndman	No	ca	Pacific Geoscience Centre, Geol. Survey Canada
S. Shawn Wei	Student	us	Washington University in St. Louis
Sam Bell	Student	us	Brown University
Samer Naif	Student	us	Scripps Institution of Oceanography
Sampath Rathnayaka	Student	us	California State University, Northridge
Scott Nooner	No	us	University of North Carolina, Wilmington
Sean Gulick	No	us	Institute for Geophysics, University of Texas at Austin
Shuichi Kodaira	No	jp	JAMSTEC
Spahr Webb	No	us	Lamont-Doherty Earth Observatory of Columbia University
Susan Bilek	No	us	New Mexico Tech
Susan Schwartz	No	us	UC Santa Cruz
Takashi Tonegawa	No	jp	JAMSTEC
Vadim Levin	No	us	Rutgers University
Weisen Shen	Post-Doc	us	University of Colorado Boulder
William Wilcock	No	us	University of Washington
Xiaowei Chen	Post-Doc	us	Woods Hole Oceanographic Institution
Yang Zha	Student	us	Lamont-Doherty Earth Observatory of Columbia University
Yen-joe Tan	Student	us	Lamont-Doherty Earth Observatory of Columbia University
Yuanyuan Liu	Student	us	Stony Brook University
Zhao Chen	Student	us	Scripps Institution of Oceanography, UCSD