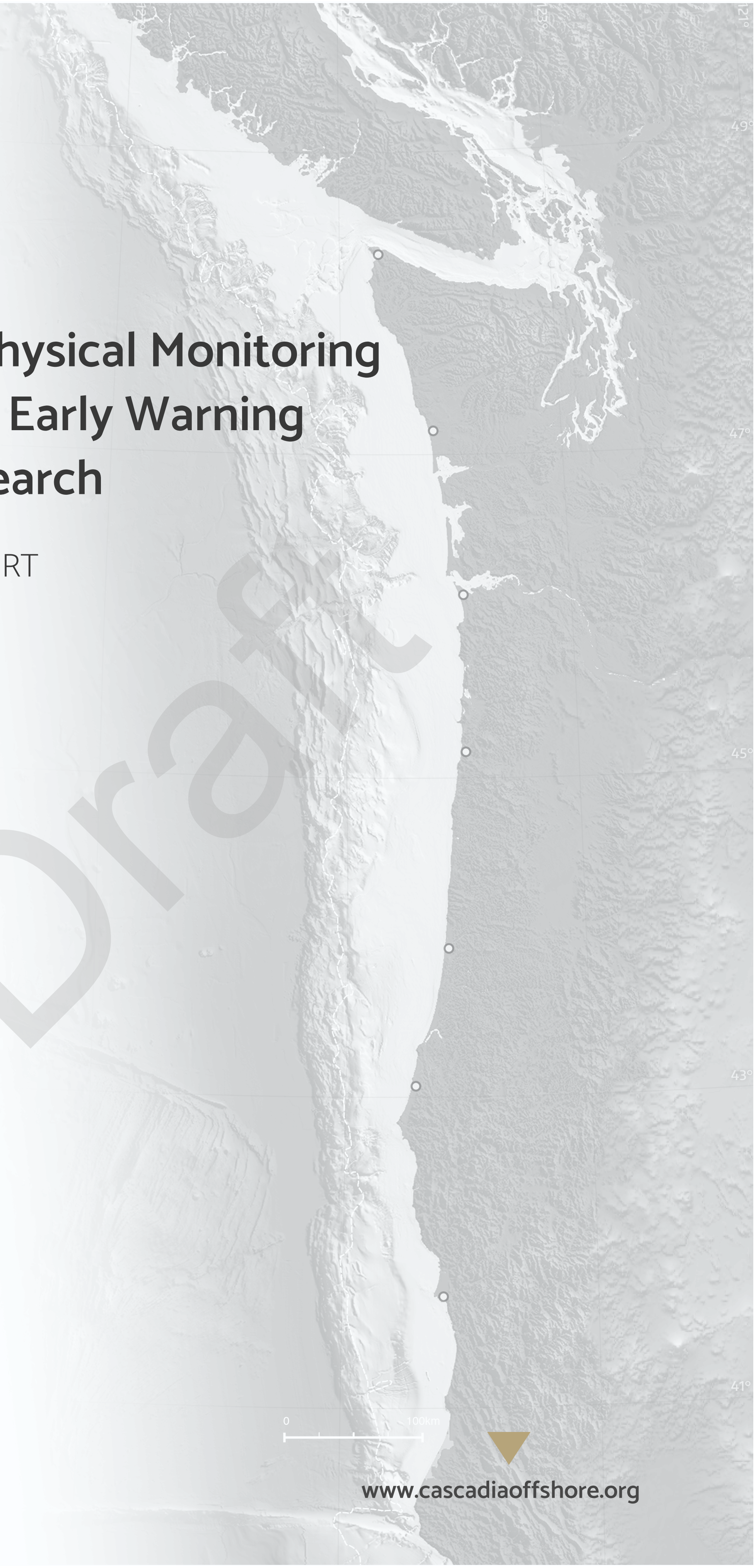
Offshore Geophysical Monitoring of Cascadia for Early Warning & Hazards Research

WORKSHOP REPORT

Seattle, WA

April 3-5, 2017



Funded by:

GORDON AND BETTY MOORE FOUNDATION

www.cascadiaoffshore.org

Draft Workshop Report, November 2017

Offshore Geophysical Monitoring of Cascadia for Early Warning and Hazards Research
Seattle, WA, April 3-5, 2017

Executive Summary

Subduction zones produce the largest earthquakes on our planet and initiate devastating tsunamis that can inundate coastal communities. However, our ability to monitor and study the offshore sources of these events is significantly limited by the logistical and technical challenges of making geophysical observations on the seafloor. Several countries, such as Japan and Canada, are now making investments in offshore infrastructure to better monitor the seafloor in risk-prone areas Real-time data from the seafloor can be used to provide refined earthquake and tsunami early warnings to coastal populations, which will directly help to save lives, reduce injuries, and allow companies and municipalities to enact automated systems to protect infrastructure. In addition, sustained offshore sensor networks can provide observations of subduction zones that will enable new scientific insights into the geological processes and thus help to characterize and mitigate the natural hazards.

This meeting focused on the Cascadia subduction zone, where large earthquakes (up to magnitude 9) and tsunamis occur regularly through geological time and where real time offshore observations are limited in their spatial footprint to multidisciplinary scientific cable observatories off central Oregon and Vancouver Island. It provided a forum for interested scientists and engineers to discuss the scientific and societal motivation for an offshore geophysical sensor network extending the length of the subduction zone, the technical requirements for such a network, and the merits of various engineering approaches. The meeting also considered how the existing seafloor infrastructure in Cascadia could be leveraged to jumpstart this effort.

Through a series of plenary presentations and small group breakouts, workshop participants discussed the merits of such a system and identified a number of scientific, engineering, and policy recommendations. An offshore sensor network can improve the timeliness, reliability, and accuracy of earthquake and tsunami early warnings. While an offshore sensor array would greatly improve our monitoring capability and scientific understanding of the offshore faults, the greatest benefit to society is the early warning capability, particularly for providing an accurate warning and estimate of an incoming tsunamis. Any system design should be focused on a clear set of objectives, such as early warning. Most participants felt that a phased implementation strategy is likely the best way to develop and test the technologies, demonstrate success, and motivate the completion of a margin-wide sensor network; however, others articulated that a push for a full-scale system is the better strategy for success.

Future work is needed to understand whether it is possible to deconvolve the simultaneous movement of the seafloor and sea surface height from seafloor pressure sensors in order to inform real-time assessments of the incoming tsunami or whether additional instrumentation is required to measure sea-surface elevation. Additional modeling studies are needed to optimize the spacing and mix of instrumentation given scientific and/or hazard objectives. There are a number of emerging technologies that might provide the required observations at reduced cost, although further development and testing is needed before such technologies could be deployed on a large scale. Additional offshore geophysical experiments and data sets are needed to inform how best to optimize and design a seafloor system for such questions as where instruments are ideally located in relation to likely earthquake sources and to minimize risks from turbidity currents. A strong leadership team and broad coalition of stakeholders are needed to advance any long-term effort to deploy a seafloor sensor network that extends along the full length of the Cascadia Subduction zone.

Table of Contents

I. Introduction

Subduction zones are inherently difficult to observe given that much of their area is offshore and inaccessible to terrestrial instrumentation and approaches. The challenges of installing, powering, maintaining, and communicating with seafloor instrumentation, make sustained and reliable geophysical observations of the offshore portion difficult. Our understanding and monitoring capability of terrestrial plate boundaries far exceeds that of offshore plate boundaries, largely attributed to the technical difficulties of collecting data on the seafloor. Offshore observations are critical to advancing geophysical science and providing improved understanding of the hazards. These observations will further allow scientists to better monitor changes in seismicity and deformation of the accretionary prism, improving situational awareness in the event of anomalous seismic behavior.

An offshore geophysical observational network would also provide more accurate and timely early warnings of offshore earthquakes, and enable tsunami early warning for incoming waves and forecasts for secondary arrivals. An earthquake early warning (EEW) system that relies solely on land-based instruments can provide a warning from offshore earthquakes. However, that warning could be improved by up to ~15 seconds, the time needed for seismic waves to travel from the source to the first coastal seismic stations. Without an offshore network, this delay eliminates any early warning for coastal communities proximal to the epicenter. It is also currently challenging to quickly discriminate distant offshore earthquakes from the more threatening events on the subduction thrust, which are capable of growing into magnitude 9 events. Therefore, the accuracy and reliability of the EEW is diminished when offshore earthquakes are characterized by only onshore instrumentation. Furthermore, onshore networks are incapable of contributing to an accurate warning of the incoming tsunami wave height, resolving how the tsunami builds as it moves towards the coast, or resolving secondary arrivals.

The Cascadia Subduction Zone is one such system where an offshore sensor network would greatly inform our understanding of the science and enhance our warning capability. The Cascadia Subduction Zone poses a major natural hazard to communities in the Pacific Northwest (including Northern California, Oregon, Washington, and Vancouver Island) in the form of intense and prolonged ground shaking from a megathrust earthquake, and inundation along the coast and inner straits from a triggered tsunami. A sensor system offshore the Pacific Northwest would leverage existing infrastructure. In addition to robust terrestrial seismic and geodetic networks, the Cascadia subduction zone also hosts two multidisciplinary cabled seafloor observatories, the OOI Regional Cabled Array offshore Oregon and ONC's Neptune observatory off Vancouver Island. However, theses networks have limited along-strike extent and were not originally designed with the intent to provide real-time warnings from earthquakes and tsunamis.

An expansion of a seafloor sensor network along the entire margin would require a careful evaluation of requirements and new technologies.

II. Workshop Objectives and Overview

This meeting provided a forum for interested scientists and engineers to discuss the scientific and societal motivation for an offshore geophysical sensor network, the geophysical requirements, and the merits of alternative engineering approaches. Much of the discussion was focused around the Cascadia Subduction Zone, although the issues and methods are applicable to other offshore plate boundaries.

The goals for the workshop included:

- Prioritize the scientific and hazard requirements for an offshore system.
- Seek feedback on possible designs and technologies for offshore observations.
- Provide a forum to explore new ideas and foster discussion.
- Generate constructive interactions amongst scientists, engineers, state & federal agencies, & industry.
- Build a consensus on how to move forward and engage stakeholders.

The workshop consisted of a series of plenary talks to discuss the scientific motivation for making offshore observations, lessons learned from existing seafloor systems, the logistical requirements for early warning capability, the engineering considerations for providing power and telemetry to the seafloor, existing and emerging seafloor technologies, and the tradeoffs of various design options. The plenary talks were organized by topic, and each session was followed by a small group breakout where the issues could be discussed in more depth. This report summarizes the primary concepts, opinions, and suggestions raised in the small-group breakout sessions and plenary discussions. The workshop schedule and list of plenary speakers are provided in Appendix A. The workshop was attended by 109 participants, the majority of whom were from the domestic and international research community, but also included representatives of state and federal agencies, industry, and journalists (See Appendix B). Workshop participants were encouraged to submit abstracts and whitepapers to help document individual accomplishments and visions for the future (see Appendices F & G). And finally, groups were encouraged to submit their own seafloor network designs for Cascadia, and a subset of those products are provided in Appendix D.

III. Breakout Summaries

Each small breakout group was tasked with a central question, listed below. Here we provide a synthesis of the major themes that were discussed.

A. *What are the science and hazards goals and requirements? How should they be prioritized?*

The scientific goals attainable with an offshore geophysical instrumentation network include: (a) the characterization of plate locking over the offshore seismogenic zone and along the trench, (b) the monitoring of aseismic and seismic behavior along the margin to ascertain nominal behavior, and (c) the improved understanding of the structure of the subduction zone so that the earthquake process can be placed in geodynamic and tectonic context. Cascadia represents an end-member "quiet and hot" subduction zone, likely in the late interseismic stage of its seismic cycle, with relatively few earthquakes occurring in the interseismic period to illuminate heterogeneity in geometry or stress, and a seismogenic zone that is estimated to be almost entirely offshore based on thermal models and onshore GPS observations. Determining a more detailed picture of plate boundary locking behavior will require observing the fine-scale spatial and temporal patterns of strain release offshore. Mapping the distribution of plate boundary locking is important, in that it should constrain estimates of maximum earthquake magnitude and the location of strong asperities. Observing and differentiating potential precursory aseismic phenomena possibly accompanying the onset of plate boundary unlocking just before a large magnitude seismic rupture presents a goal that could be pursued with a continuous offshore sensor network, but probably not attainable with onshore monitoring alone. Developing a framework for monitoring precursory behavior at Cascadia, be it deformation, seismic, thermal or hydrological, could be a central priority of an offshore array that serves as an additional long-term 'early-warning' strategy. Attaining this goal will be very difficult without sustained and widespread observations.

The primary hazards-related goals for an offshore geophysical network include: (1) the rapid detection and estimation of an earthquake source, (b) an improved forecast of ground shaking levels along the coast, and (c) a prediction of tsunami height over a set window of time, as well as inundation, given predicted coastal subsidence. A key capability of an offshore system is the ability to provide enhanced warnings from offshore earthquakes and tsunamis. Earthquake Early Warning (EEW) refers to a set of technologies that quickly detects the shaking from an earthquake in-progress and provides useful alerts to nearby communities before the shaking reaches them. There are a range of approaches for providing EEW alerts, but they all involve observing ground motions as close as possible to a radiating rupture, rapid processing to determine the shaking potential of an earthquake (as near to real-time as possible), and rapid telemetry both for data acquisition and alert distribution. Additionally, real-time geodetic observations of ground displacement can contribute to EEW as well as tsunami early warning (TEW) by helping to characterize the source zone of large earthquakes.

Offshore buoys currently maintained by NOAA are primarily designed to inform about far-field tsunamis that originate across the Pacific Ocean. An effective TEW system requires near-field observations of either the changes in water or seafloor height. A tsunami warning system should also be capable of warning against tsunamis initiated by submarine landslides or other non-seismic sources, or from "tsunami earthquakes" that produce a larger tsunami than might be expected from the magnitude of the earthquake alone, as well as from megathrust events. Very rapid forecasting is necessary to be useful for nearby coastal regions, where the first wave arrivals may be less than 20 minutes, but accurate tsunami warning is perhaps even more valuable for locations more distant from the source, e.g. in Puget Sound or at coastal locations farther from the source. At all locations, continuous updates are valuable as new information is collected, especially for decision makers who must deploy resources such as search and rescue personnel during an evolving event.

There were a range of opinions about how best to prioritize the various goals listed above. The general consensus was that it is best to design an offshore network around a more focused set of goals, rather than attempt to design a network to accomplish multiple goals. In particular, the hazards goals, particularly tsunami early warning, might provide the greatest benefit. Additionally, the geophysical observations needed to inform tsunami/earthquake early warning could be used to address many of the scientific goals as a secondary benefit.

B. Which goals require offshore measurements?

Offshore observations are necessary for studying the processes of seismogenesis, locking distribution, seismicity and tremor, structure, and tsunamigenic potential of the offshore portion of the megathrust and splay faults in the accretionary prism. Larger earthquakes can be detected and roughly located from onshore sensors, but with poor depth resolution and rupture characterization. Small earthquakes will go undetected. Similarly, slow slip episodes can only be very crudely estimated from onshore sensors, and only in the cases in which it is quite large. The distribution of plate coupling requires fairly dense and long-term seafloor geodetic monitoring. Imaging and understanding the structure of the subduction zone also would not be adequate without offshore sensors. Current land geodetic arrays are not capable of resolving along-strike heterogeneity in interseismic plate boundary slip behavior, nor would they be able to resolve a slow slip transient of the magnitude that has been observed at other subduction zones offshore. Extending a geodetic monitoring network offshore would be the only way to improve our resolution to test possible locking models, explore for locking segmentation along strike and the occurrence of slow slip transients, and characterize interseismic slip behavior in the updip extent of the plate boundary.

While all of the identified goals require or can greatly benefit from offshore measurements, not all require real-time telemetry. Earthquake early warning is the only goal that requires real-time telemetry. While tsunami early warning can benefit from a near-real-time data feed, latency of seconds-to-minutes may be sufficient for most needs, given that it takes many minutes for the tsunami to evolve. Both terrestrial seismic stations (for shaking) and high-frequency coastal radar (for tsunami wave height) can inform early warning, although at longer delay times and at coarser resolution than having observations over the source. While initial alerts for strong shaking may be advanced by up to 15 seconds, offshore instrumentation would reduce uncertainties of the alerts, and provide much more accurate characterization of the source. For example, high-frequency radiation in large subduction earthquakes appears to be generated by embedded high-stress-drop sub-events, which would be much more rapidly and accurately detected with offshore (i.e., nearby) sites.

Because far more than 99% of the time there will be no earthquakes occurring for which the system would need to provide alerts, it is important that the offshore network be multi-use. Other uses include providing data to increase the scientific understanding of the shaking hazards posed by the CSZ. With a broader perspective, the network should provide a platform for other sensors and experiments to broaden our knowledge of potential hazards posed by a wide variety of subduction zone related processes.

C. What capabilities are needed - observations, coverage, data latency, robustness?

The factors most strongly affecting the performance of an EEW network are the density and proximity of sensors to the earthquake source, the quickness with which the data are available for analysis, the details of the warning algorithm(s) used, and the quickness with which the alerts can be distributed. Earthquake early warning requires real-time telemetry of ground shaking given that early warning algorithms use 2-4 seconds of waveform data to detect the P-waves. The algorithms also require detections from at least 2-4 stations to produce an initial alert about the earthquake source. Geodetic observations provide first-order constraints on net displacement, which help to refine the magnitude estimate of large events ($M>7.5$). The fundamental observations would include seismic shaking above the background noise floor at 10s-of-Hz down to <0.1 Hz and geodetic observations capable of resolving seafloor displacements of several cm-to-10s of meters. Seafloor pressure measurements would help to distinguish between competing models of splay faulting, distributed deformation, and trench-breaking rupture, while also providing primary constraints on the tsunamigenic source. The data needed to enhance EEW performance from offshore instrumentation include seismic and seafloor geodetic observations at interstation spacing of less than 100 km. Ideally, interstation spacing would be less than 50 km, and include at least a few sites seaward of the deformation zone as well (both for azimuthal coverage of CSZ earthquakes and to more assuredly distinguish them from the more commonly occurring intraplate Gorda/Juan de Fuca Plate earthquakes). Seismic instrumentation would minimally include accelerometers capable of remaining on-scale during shaking of up to 4g, presenting requirements to firmly fasten sensors of known orientation to the seafloor. Seismic sensors more important for scientific work would include broad-band sensors capable of accurately detecting motions at the seafloor seismic noise level from hundreds-of-seconds period to frequencies of 10s-of-Hz. Data packet size (i.e. duration) and data delivery latencies should be as small as possible, in any case not more than a few seconds. Individual station data availability and data quality must be such that the entire network is always capable of detecting and alerting on an earthquake that would produce strong shaking (e.g., MMI=V) at an onshore site. The network must be robust such that it is capable of surviving a mega-quake and continuing to be able to alert on the expected numerous large aftershocks or re-ruptures. Another element of robustness is that a foreshock or fore-slip sequence shouldn't damage or unduly degrade the system. In fact observations of any such anticipatory activity are a major potential benefit of an offshore real-time monitoring system, although a bit outside of the mission of EEW as defined here.

For tsunami early warning, Bottom pressure recorders (BPRs) are considered the most important offshore sensors, particularly those specifically designed for near-field measurements (e.g. DART 4G, GPS Buoys). Strong motion sensing is desirable but secondary. As noted, a better understanding of how best to use data from BPRs, given the added complexities of observing in the near-field, is still required. For tsunami applications data latency of 10s-of-seconds to a minute would be required. Much work still needs to be done to determine the necessary station spacing and coverage. This will be dependent to some extent on the particular algorithms developed for inversion and forecasting, and modeling of hypothetical events is required to better answer this question.

For tsunami forecasting, a hierarchy of models would be useful for different time scales. For example, using seismic/GNSS data in the first minute, supplemented by BPR data over 5-10 minutes and perhaps tide gauge or ADCP data at later times may prove the best strategy. The codes must be adequately validated to give confidence in the forecasts. An important question is whether results from different models (ensemble forecasting) should be used in real time. This could be valuable but potentially more confusing for users and decision makers. Because of the need of a hypothetical near-field early warning system to require specific operating procedures, input from federal or state government agencies with operational responsibilities to operate such a system should be considered in the design. Likewise emergency management agencies should be brought to the table to help determine hazard requirements. Different types of forecasts may be needed for nearfield and farfield, and also for harbors, critical coastal infrastructure such as power plants, or ships offshore. The ability to accurately assess small-amplitude tsunamis and cancel warnings quickly when appropriate is also important. Forecasting strong currents in harbors is very important, even when amplitudes are modest or when no inundation is expected; extensive damage to ships and coastal infrastructure can still occur.

Developing seafloor geodetic monitoring infrastructure across the entire Cascadia margin will be the only way to constrain the distribution of locking above the seismogenic zone and any along-strike or down-dip variability in interseismic slip. Both long-baseline, and continuous observations will be necessary to resolve relatively low (<1cm/yr) estimated secular strain rates, and monitor for transient phenomena that may occur. Unlike an array designed to facilitate earthquake early warning or model coseismic slip, characterization of aseismic strain could be accomplished with relatively high-latency instrumentation, as long as it was distributed spatially across the margin with near-uniform density, so as to resolve expected broad-scale heterogeneities in locking behavior. It is likely that, once the first-order slip behavior is constrained, localized smaller-footprint but high-density arrays will also be required to facilitate higher-resolution studies of regions of interest, capable of constraining the details of spatial changes in slip behavior and how those changes are influenced by physical properties or plate boundary structure. Because seafloor geodesy is an emerging technology, it will be critical in the near term to develop a diverse array of instrumentations with some redundancy in observational measurements at the same location. For example, implementing strain, tilt, seafloor pressure and GPS-A at the same location could provide multiple lines of evidence for any observed deformation and serve to validate new measurement tools. Furthermore, if relatively localized regions of interest are identified along the margin, dense arrays at focus areas where aseismic slip phenomena are monitored at fine spatial scales could be augmented by complementary geophysical and geological tools (i.e. high-resolution bathymetric mapping, geophysical imaging, geologic sampling). This multidisciplinary approach would facilitate a comprehensive characterization of the region, targeting key parameters that control slip behavior there, as well as provide insight on optimal array design for a larger, margin-scale high-density geodetic array. For understanding and monitoring earthquake processes aside from early warning, seismometers and geodetic instruments are critical. Less than 50 km spacing is best. Seismometers are essential and fairly cheap; pressure sensors are helpful and cheap; geodesy is necessary but remains a challenge to implement. Auxiliary measurements such as seafloor topography, fluid outflow, formation strain, and ocean current monitoring for correcting pressure measurements also have value. For several monitoring purposes, it is important to cover a larger area than just the downgoing plate. Earthquake characterization and geodesy, for example, require areas of interest be surrounded to set a correct spatial and temporal baseline for activity and cover a wider range of back-azimuths.

D. What are the risks, pros and cons of the different engineering approaches? Is there a clear winner?

There are three broad categories of technologies that could be used to provide offshore early warning: cabled systems, moored buoy systems, and mobile platforms. The breakout group approached their questions by first identifying and discussing the different categories of risks, all of which are common to all offshore systems, and then considering the strengths and weaknesses of different technological approaches in regards to how well it mitigated risks. The group concluded that at this point in the planning, there is no clear winner since each approach has pros and cons and hybrid systems employing multiple approaches are also possible. Before selecting the best engineering design, it will be necessary to develop more detailed system requirements that are based on the community and stakeholders reaching a consensus on the operational goals and priorities of the system.

Any offshore detection and warning system will be subject to known risks during the planning, implementation and maintenance phase of the project. If the risks turn into reality, they can delay or even prevent implementation, increase construction and maintenance costs and reduce the effectiveness of the system because of system downtime or failures. The group identified the following broad categories of risks:

- *Delays in permitting.* Here the successful experiences of the OOI in Oregon are invaluable and demonstrate the political importance of engaging, listening and responding to those impacted, as well as meeting all statutory requirements to apply for permits.
- *Use of unproven technologies.* Where technologically immature approaches are deemed necessary it is important that the system be serviceable to enable fixes later on.
- *Overall lack of system reliability.* For various reasons, the predicted reliability of new systems does not always match subsequent performance and so it is advantageous to use approaches that have been tested and to investigate and exploit historical performance data to enhance reliability.
- *External aggression.* Both fishing activities and landslides that might be induced by earthquakes, or occur in isolation, are a significant risk to seafloor infrastructure.
- *Weather and environment.* Infrastructure at sea surface must be able to withstand severe storms, and shore stations for cabled systems should ideally lie outside tsunami inundation regions.
- *Lack of sustained project funding.* It will be important to identify an adequate and stable source of funding for operation and maintenance because otherwise the system may be hard to sustain given that the catastrophic earthquakes which justify it are infrequent and provide few reminders to the public about the hazards.

In light of the above risks, the group discussed cabled, buoyed and mobile platform systems in turn, analyzing first the general characteristics of each system and then considering in more detail some specific technologies or configurations.

In general, cabled systems have the benefit of providing the lowest possible latency from the instrument to shore, which is of great value for an early warning system. They also tend to have low maintenance costs relative to installation which may be advantageous in terms of sustaining the system. Depending on the configuration, they can also provide support for additional instrumentation, including instruments with high power and/or bandwidth needs to support research goals related to subduction zone hazards or even in other fields.

There are a number of drawbacks to cabled systems.   The upfront construction and installation of thousands of kilometers of seafloor cable over an expansive area in a harsh environment is expensive relative to most other options. A reliable cable system may require many shore stations and cable landings which are expensive and can be difficult to permit. Once the cable is installed it is susceptible being broken due to fishing activities or from the landslides and turbidity currents that follow the earthquakes it is being built to detect. Repairs of cable system are expensive and it can be difficult to schedule repairs at critical times; however, the presence of many telecommunications cables off the coast of the coast of the Pacific Northwest ensures that cable repair ships will always be stationed in the region.

Cabled systems could either employ a basic and fixed sensor suite integrated into the cable repeaters to simplify deployments, increase reliability and lower maintenance costs, or employ the high-power junction box approach of DONET, OOI and ONC with ROV installed secondary cables, low power junction boxes, and sensor infrastructure to allow for flexibility, upgrades and expansion. The latter approach will require careful planning to provide access to junction boxes in regions where cables are normally buried to avoid damage from trawling. A cabled system could also adopt a hybrid approach with inline sensor suites used to cover a large area and junction boxes at sites of particular interest. The choice between cabled approaches would be determined by the detailed system requirements

Moored buoys are an alternative to cabled system that benefit of not being susceptible to cable breaks and thus more likely to remain operational after an earthquake, at which point data delivered by satellite systems could be received at sites away from those impacted by an earthquake. They could be installed at a significantly lower cost (although likely for a much lower density of measurements than a cabled system) and easily moved if the monitoring objectives evolved. One disadvantage of moored systems is that they require more maintenance than cabled systems because they are constantly exposed to the weather at the surface and vandalism – breakages during severe winter storms might be difficult to fix quickly. Acoustically linked moorings would have longer latencies to get the sensor information back to shore and the bandwidth would be limited. The sensor types would be limited to those that could be reasonably powered long-term by batteries. Electric or electro-optical connections between a buoy and the seafloor would increase bandwidth and available power and decrease latency but at significant expense.

Finally, mobile platforms such as Wave Gliders, Sea Gliders or autonomous underwater vehicles (AUV) could be employed to collect data from seafloor sensors. Mobile platforms are reasonably robust to aggression and their reliability is improving. A few mobile platforms could roam over a large area collecting data from a large number of seafloor sensors. However, the data latency would be very large and unusable for early warning systems, making this a more realistic option for efforts to enhance the scientific capabilities of a hybrid system that uses other technologies for the early warning system. Rather than roaming over a large area to collect data from multiple seafloor sites, a system could be configured with a mobile platform stationed permanently above each acoustically connected instrument site. In this case, the capabilities would be similar to a network of acoustically connected buoys and the choice of technology would be based on evaluating cost and reliability.

E. What combination of sensors and spacing are needed? What observations are required before full-scale installation?

The group addressed the first question by initially considering separately the sensor needs and desired spacing for earthquake early warning, tsunami early warning, and science before briefly discussing how these sensors might fit into a single system. They then discussed various observational studies that could help optimize a design and noted the important role that the existing cabled infrastructure of the OOI and ONC could play in such efforts.

On land, earthquake early warning can utilize data from a combination of seismic sensors and real time GPS. In the oceans, real time GPS is not available, and while pressure sensors can provide real time data, they do not provide vertical geodetic data on the short times scales of earthquake early warning because the hydrostatic pressure does not change when the sea surface moves in tandem with the seafloor. Given that earthquake early warning requires timely observations over accuracy, all that is really needed for this objective is a network of strong motion accelerometers, or possibly equivalent observations from fiber optic cables equipped with the new distributed acoustic sensing technology. Strong motion accelerometers could be usefully co-sited with broadband seismometers, hydrophones and pressure sensors to provide redundant information.

If the objective of the offshore observations is to increase warning times (rather than just improving reliability), then at the very minimum, the spacing of seismic sensors must be small enough that they are closer to all locations in the earthquake source regions than the coastline. Participants were reticent to specify a maximum sensor spacing; values varied from 50 km to 15 km to “as close as possible” with some thinking that the spacing should decrease further offshore where the plate interface is shallower. In Japan, the spacing of seismometers on the DONET observatory is 15-20 km and was determined based on modeling and the need to constrain earthquake depths accurately in order to determine if rupture has initiated on the megathrust. It was agreed that similar modeling studies are needed to inform the design in Cascadia.

For the tsunami, it is first worth noting that the shaking induced by a near-field earthquake can be a natural warning for coastal residents, but that “tsunami earthquakes” can occur with only mild shaking that may go unnoticed or may not be recognized as a warning. For the inland waters of the Juan de Fuca Strait and Puget Sound, there is time to base warnings on forecasted waves and avoid the risks of unnecessary evacuations. It is also important to forecast late-arriving destructive waves as well as the end of the period of risk so that residents do not return to lower ground too early. For these reasons, a near-field tsunami early warning system is useful.

Classic forecasting methodology integrates observations and numerical modeling. An important initial estimate of the tsunami waveform can be obtained soon after an earthquake based upon an inversion of seismic data and land GPS data for ocean bottom deformation. Offshore observations of the developing tsunami would then provide data to continually update this model. Seafloor pressure gauges are the basic sensor for monitoring the propagation of tsunami waves but because, as noted above, the static pressure does not change immediately when the seafloor moves up in concert with the seafloor, it is important to independently measure the sea surface height in the source region. This can be accomplished directly by GPS equipped buoys and potentially indirectly (and near-shore) by imaging high-frequency coastal radars.

The ideal spacing of bottom pressure recorders in a tsunami network should be determined by modeling studies. A simple estimate of sensor spacing can be obtained by requiring two samples per wavelength to avoid aliasing of oceanographic signals, and this yields values of ~15-20 km close to shore and ~50 km in deep water. Since this change in spacing moving offshore is contrary to that which might be preferred for an earthquake network, it will be important to optimize the combined performance of earthquake and tsunami early warning networks.

While earthquake and tsunami early warning requires networks with a limited number of sensor types that cover the entire subduction zone uniformly, the variable scientific objectives require sensor networks to be tailored to a particular goal. For example, efforts to constrain the footprint of the locked zone and search for small earthquakes and tremor on the megathrust require subduction-zone-wide deployments of broadband seismometers and seafloor geodetic sites. In contrast, studies to search for shallow slow slip in regions of partial locking near the deformation front would benefit from heavily instrumented boreholes and dense arrays of bottom pressure sensors.

The group identified a long list of observations that would be useful before full scale implementation including:

- More GPS-Acoustic observations to understand first-order patterns of locking near the trench and the level of locking heterogeneity along strike.
- A more complete suite of dense OBS observations along the whole margin to build upon the Cascadia Initiative deployments.
- Multi-channel seismic, wide angle seismic and receiver function studies of the whole margin to understand the structure and properties of the of the margin and plate interface.

- High resolution bathymetry, including the near shore, to characterize geological structure, improve tsunami models, and to provide a baseline for post event comparison.

The group also agreed that it would make sense to use the existing OOI and OCN cabled observatories off central Oregon and Vancouver Island to test sensors and approaches to early warning and to start to address important science experiments. Co-located experiments in these established corridors can be used to learn how best to utilize technology, how complementary instruments can work together to provide redundancy, and how high resolution observations with boreholes and suites of geodetic instruments are best embedded in a broader network.

F. What emerging technologies/platforms are most promising?

Earthquake detection and characterization depends on arrays of seismometers and accelerometers, while tsunami modeling makes heavy use of seafloor-mounted pressure sensors. The breakout group started from the premise that cabled arrays of seismic and pressure sensors should be considered a baseline set of instrumentation for an early warning system, and then they explored technologies that might augment such a baseline system or provide an alternative to some components.

There are a variety of approaches that can replace a cable for communications. Buoys and wavegliders can serve as sea surface platforms to obtain data via acoustic links to seafloor sensors and relay it to land via satellites or possibly radio links. Autonomous underwater vehicles and seagliders can use optical and acoustic data links to gather data when in close proximity to an autonomous instrument and transport data to a location where it can be transmitted to land via cable or satellite or where the data can be retrieved from the mobile platform.

The data latency of buoy or glider based systems was contrasted with the near-zero latency available through a fiber optic cabled network of sensors. A seafloor sensor, linked to the surface by acoustic signals, is first delayed by the acoustic travel time, which may be several seconds. Further delay is encountered in satellite links, which can be several tens-of-seconds. This delay is exacerbated by packet buffering where, for efficiency, data at various stages in the transmission path are collected in a buffer until some amount is acquired, and only then transferred. There was a discussion about the potential use of direct radio links between offshore data buoys and gliders, which would presumably have shorter delays, but the risk of weather-related impairment of such links was felt to make that a less reliable solution. The group's conclusion was essentially that the data link delay in systems with a sea surface relay would likely render them unsuitable for earthquake early warning but acceptable for tsunami warning. Latency may be less important for scientific enhancements and here the alternative communication platforms may provide an attractive alternative to ship-based retrieval and redeployment of autonomous instruments for the purpose of gathering data.

When the cable is removed from design consideration, shore-based power is no longer available; but there are emerging technologies that may provide alternatives to the batteries conventionally used in autonomous instruments. These include advances in ongoing renewable energy harvesting (wind turbines, wave energy converters, tidal current systems) and wireless power transfer developments (i.e. inductive charging, adaptive resonant power transfer).

For geophysical sensing, there was considerable excitement over recently advanced technologies that can convert normal optical-fiber communication cables into seismometer arrays; but it was recognized that possible shortcomings, namely cable-to-ground coupling and maximum strain rate without ambiguity, remained to be investigated. There is also a need to implement new technologies for geodetic observations. Autonomous WaveGliders are now being used in place of a ship to conduct acoustic GPS measurements in Cascadia, and this is an important advance (along with recoverable seafloor transponders) that makes repeat observations significantly more economical. Prototype “A-0-A” pressure sensors were on display during the workshop poster session. This sensor and the Seafloor Calibrated Pressures Recorder developed at Scripps allow for in situ pressure sensor drift correction, should lead to improved long-term geodetic observations of vertical ground motion. Various other sensors such as optical fiber cables for strain and some new tiltmeter designs are also promising for geodesy.

As highlighted earlier, it was noted that near-field seafloor pressure sensors alone are not sufficient to monitor the instantaneous change in sea surface height during coseismic rupture. Approaches to providing additional data to allow observations of the early development of the tsunami include GPS sensors on buoys to monitor sea surface elevation changes and shoreside high frequency radar systems that are capable of detecting current pattern changes associated with tsunamis.

There was consensus that further investigation of emerging technologies is warranted and that it would be advantageous to maintain adaptability and flexibility in the deployed system to incorporate new technologies. As emerging technologies become more mature, the breakout groups determined that the following areas should be considered when determining their use in an early warning and subduction zone monitoring system:

- Functionality (what value to they add to the system?)
- Reliability
- Capital cost
- Operations and Maintenance cost
- Link speed

IV. Questionnaire

On the final morning of the workshop, about 70 participants completed a 2-page questionnaire (Appendix E) during the final plenary on the topic of how to move forward. The purpose of the questionnaire was to get input from all participants, irrespective of whether they were vocal, and to provide participants with an opportunity to record their thoughts as they listened to the discussion. Most participants provided detailed responses. Some participants completed the questionnaire at the start of the plenary but many others added ideas as they participated in or listened to the discussion, so the questionnaires also reflect the ideas expressed verbally. A full compilation of the responses is presented in tabular form in Appendix E and will be an important resource to be mined for good ideas. It is challenging to summarize such extensive input from the discussion and questionnaire but some of the highlights are presented below.

A. What is the path forward to achieve an offshore sensor network for the subduction zone?
There was a consensus that it is important to set priorities, identify potential funders and start the task of engaging stakeholders early on. Most respondents felt that earthquake and tsunami warning should be prioritized above science with several identifying tsunami warning as the highest priority. Several participants favored a phased approach to installing seafloor infrastructure and suggested instrumenting existing nodes on the OOI Cabled Array (and the ONC NEPTUNE observatory) and adding extension cables to show the benefit of the system and evaluate new technologies. There were various suggestions for the design and many responses identified the importance of quantitative simulations to evaluate the risk reduction potential and cost to benefit. Several participants noted the importance of early offshore observations.

B. Is there a sensible phased approach (such as an intermediate experiments or deployments)?
There were mixed views as to whether a phased approach was the best approach but several respondents thought it was the only feasible path. The participants noted the need for planning and the importance of being able to demonstrate success with each milestone. A large number of respondents noted the need for standalone deployments of GPS acoustic systems, bottom pressure recorders and ocean bottom seismometers, the value of temporary deployments to test instrument placements, and the need for seismic imaging and high-resolution seafloor mapping. Many participants also noted the importance of adding sensors to the existing cables, which might also be expanded with extension cables, to test new technologies and conduct pilot early warning efforts. There was also recognition of the importance of numerical simulations and studies of existing datasets, such as the Cascadia Initiative OBS records, to optimize the configuration of a long-term network. A wide range of ideas were advocated for how to phase construction but the most popular approach was to focus on sites that led to the highest risk mitigation.

C. What assessment, development, or studies are required before implementation?
The answers to this question overlapped with those to the first two. The responses identified the importance of engaging early stakeholders such as emergency managers, agencies responsible for warning and funding agencies and developing a plan for public dissemination and engagement. Again, there was a clear preference for prioritizing warning over science and for tsunami warning over earthquake warning on the grounds that it would have a larger impact on public safety. The responses reaffirmed the importance of instrumenting the current cabled observatories, undertaking autonomous deployments, and conducting detailed simulations to optimize the design. It was noted that not all the sensors in the final system need necessarily be cabled. Ideas for funding again centered around the importance of demonstrating that the system will save lives and money.

D. Who are the stakeholders, particularly those groups not represented at this meeting?
A large number of stakeholders were identified including the public and more specifically coastal communities; government at all levels including coastal jurisdictions and tribes; various federal agencies most commonly NOAA and the USGS who are responsible, respectively, for tsunami and earthquake warning/mitigation, the US Navy, the Coast Guard and FEMA; emergency planners, managers and responders; industry including insurance/reinsurance, power companies and other utilities, high tech, maritime, and specific local companies such as Boeing, Microsoft and Amazon; non-governmental policy groups and philanthropic organizations; and various experts and international bodies.

E. How do we build a coalition who can advocate for a plan?
There were many ideas and emphases advanced for how to build the stakeholders into an effective coalition. Participants identified the need for strong leadership built around a common vision developed through collaboration and also the need for one or more persons to interface between academics, government and industry. Many participants identified one or key members of the coalition but the resulting list was as diverse as the list of stakeholders. There was general agreement that it is important to communicate and engage the public, government and other stakeholders by identifying a clear mission and showing what the system could do (how many lives it will save, the financial benefit, effect on everyday life). Ideas for mechanisms to convince people ranged from a sensational movie like San Andreas to developing demonstration systems.

F. Other Thoughts and Suggestions.
This prompt led to eclectic responses with some participants choosing to highlight again a response to an earlier question and others presenting new ideas. The only response repeated more than twice was appreciation for the workshop. There was encouragement to decide on a goal (early warning) and be bold. There was quite a bit of technical advice on how the system might be designed and further suggestions for which stakeholders to engage and how. One

participant felt that the workshop had not fully addressed the lessons learned from existing systems while another felt that the development of conceptual designs would be a more useful exercise if the participants were bounded by budgetary constraints and thus more clearly forced to prioritize. Other advice included the importance for planning for difficult events such as an M7.5 that may or may not generate a tsunami and developing a compelling science plan to use a system designed for warning prior to a big event.

V. Major Findings

The primary findings and recommendations of the workshop are:

1. Offshore monitoring can contribute substantially to the timeliness, reliability and accuracy of earthquake early warning and tsunami early warning/monitoring in Cascadia.
2. Sustained offshore observations are critical to many science goals in Cascadia including understanding plate locking, constraining aseismic and seismic deformation along the margin, characterizing the structure of the subduction zone and identifying signals that might be precursory to large earthquakes.
3. It is important to obtain a set of baseline observations so that changes in offshore behavior can be identified and interpreted.
4. The goals of a subduction-wide offshore network must be prioritized. A system designed for tsunami and then earthquake early warning might provide the greatest societal benefit while also addressing many scientific needs.
5. A network of strong motion and pressure sensors extending the length of the subduction zone with a spacing that would likely be 15-50 km would provide a basic network for earthquake and tsunami early warning.
6. Further investigation is required to understand how pressure observations in the source region can be supplemented by advanced processing or additional observations to measure changes in elevation of the sea surface that results from vertical motion of the seafloor with no change in static bottom pressure.
7. Extensive modeling is required to optimize the position and spacing of sensors for earthquake and tsunami early warning.
8. A latency of 2-4 s is required for earthquake early warning but a significantly longer latency is acceptable for tsunami warning/monitoring.
9. In contrast to early warning, many science goals would benefit from focused deployments of a wide range of sensors in a few regions or along a few profiles of particular interest.
10. There are a variety of technologies that could underpin the design of an offshore system and detailed system specifications need to be developed before selecting the optimal approach which might be a hybrid system.

11. There are many emerging technologies including autonomous vehicles, renewable energy, wireless data and power transfer, distributed acoustic sensing (seismic array observations with an optical fiber) and marine geodesy that should be carefully evaluated for their potential contributions to a system.
12. A observational effort to obtain a variety of data along the whole subduction zone, including GPS-acoustic measurements, bottom pressure records, dense OBS deployments to complement the Cascadia Initiative, modern seismic images and high-resolution bathymetry, would help inform the design of the full scale offshore monitoring system.
13. It is important to consider whether a phased approach is the most practical approach to implementing the full system and consider how the early phases can be optimally configured to show successes that motivate system completion.
14. The existing OOI and ONC cabled observatories off central Oregon and Vancouver Island should be used to test sensors, evaluate technology, develop and test prototype early warning systems and pursue science goals.
15. It will be important to be able to articulate a clear mission and quantify the benefits of a system.
16. Strong leadership will be necessary to build an effective coalition.
17. There are many stakeholders who can contribute to the goals and design of a system, benefit from its operation and potentially provide funds and it is important to engage them early on.
18. Expanding the community to explore the offshore problem might lead to creative new solutions and avoid “group think” about what a system should look like.

VI. Recommendations and Future Steps

This workshop was held as part of a Moore Foundation funded effort to conduct a feasibility study for an offshore monitoring system in Cascadia and the next step will be to complete this feasibility study and present the results in a white paper. Based upon the findings and recommendations of this workshop there are number of steps that should follow the feasibility study:

1. Settle on clear priorities for subduction-zone-wide offshore monitoring
2. Implement a leadership structure that can effectively manage the complex interactions between academia, government and industry necessary for a successful effort
3. Develop a plan to engage and educate the public with a clear message that articulates the benefits of a system.
4. Conduct extensive modeling studies to optimize the design of a tsunami and earthquake early warning systems.

5. Develop and implement a plan to collect offshore data sets that will improve our scientific understanding of the subduction zone and inform the design of a monitoring system.
6. Develop and implement a plan to utilize the OOI and ONC cabled observatories to test sensors and monitoring approaches and develop prototype warning systems.
7. Develop detailed system specifications and a plan for implementation either in phases or single build as the goals and funding dictate.
8. In light of the above goals, work within the scientific community to coordinate efforts with emerging initiatives, namely the NSF Subduction Zone 4D, the USGS Ring of Fire and related international efforts.
9. Hold a follow up workshop to engage a broader community of interested parties including representatives from government at various levels including coastal communities and tribes, emergency managers, federal agencies, industry, educators and interested Canadian parties in order to obtain diverse input and identify how an offshore monitoring system fits into societal needs to improve earthquake and tsunami readiness.

VII. Acknowledgments

Financial support for this workshop was provided by the **Gordon and Betty Moore Foundation** as part of a project at the University of Washington to explore an offshore geophysical network design for earthquake and tsunami early warning in the Pacific Northwest. Workshop graphics were developed by the Center for Environmental Visualization at UW. We thank graduate students Erik Fredrickson, Emma Myers, Carolyn Nuyen, Sarina Patel, Donsub Rim, Marie Salmi, Ian Stone, and Rose Wade for taking meticulous notes and assisting with other logistics during the meeting. We also thank Tracie Hunt and Su Tipple for administrative and planning support.