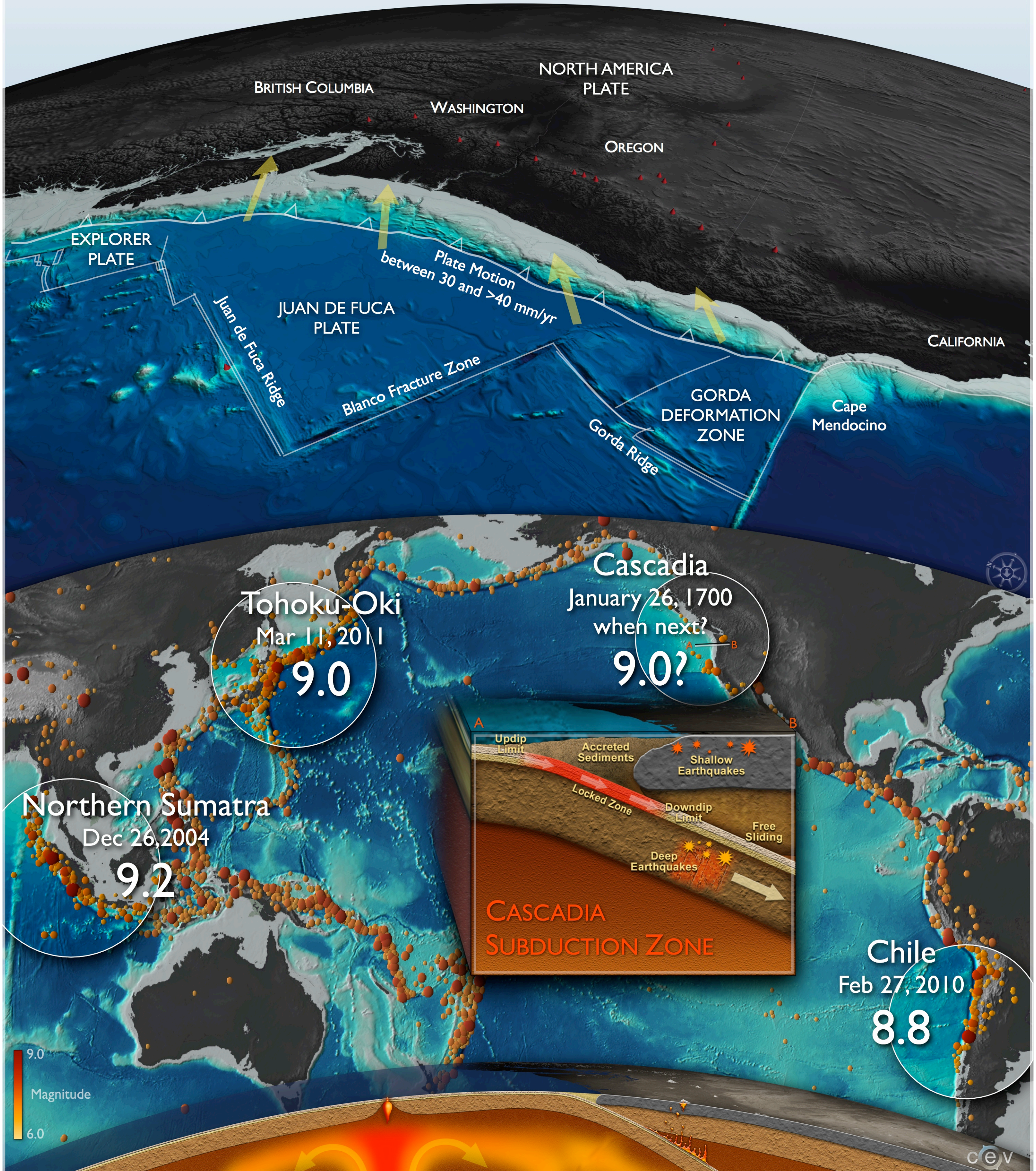
Seafloor Geodesy in Cascadia

Report of June 11-12, 2012 workshop
University of Washington



Conveners: William Wilcock, Paul Bodin, John Delaney & John Vidale

Front Cover. **(Upper)** Perspective view of the Juan de Fuca plate showing plate boundaries and the convergence between the Juan de Fuca and North American plates across the Cascadia subduction zone. **(Lower)** Map of the Pacific Ocean showing epicenters of teleseismic earthquakes with the sites of the 2004 Northern Sumatra, 2010 Chile and 2011 Tohoku-Oki megathrust earthquakes and the Cascadia subduction zone labeled. **(Inset)** Schematic cross section of the Cascadia subduction zone illustrating the location of the locked zone responsible for megathrust earthquakes and distribution of deep and shallow earthquakes. **(Base)** Schematic cross-section of a portion of the Earth illustrating mantle flow and melting associated with an oceanic spreading center and a subduction zone (figure created by the Center for Environmental Visualization, University of Washington).

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Meeting Summary

Recent devastating megathrust earthquakes off Sumatra, Chile and Japan have raised awareness of the hazard posed by subduction zones and the inevitability of a comparable earthquake along the coast of the Pacific Northwest. In contrast to seismic observations, relatively little attention has been given to the rationale for offshore geodetic observations, despite their potential importance for understanding the basic science and hazard of the Cascadia subduction zone. Seafloor geodetic measurements on the incoming plate, trench, and accretionary prism would contribute in many ways to understanding the subduction zone because they have the potential to resolve a variety of deformation sources that cannot be observed by other means. Initial objectives of seafloor geodesy should be to address scientific questions related to measuring and understanding: (1) The motion and deformation of the Juan de Fuca plate, (2) the spatial extent of the locked zone of the megathrust and whether some segments of the subduction zone are creeping, and (3) the characteristics of offshore transient deformation events. The long-term objective should be real-time monitoring along the entire length of the subduction zone. This would serve the dual purposes of providing long-term scientific seismic and geodetic observations and supporting earthquake and tsunami warning systems. Discussions at this workshop have led to general recommendations for an initial phase of observations which are summarized in this report. A community workshop supported by multiple agencies would be the most productive mechanism to refine rationale and develop specific plans for a multi-component geodetic observatory network.

Goals of the Workshop

Recent devastating megathrust earthquakes off Sumatra, Chile and Japan have further raised awareness of the hazard posed by subduction zones and the inevitability of a comparable earthquake along the coast of the Pacific Northwest. This meeting arose from several conversations at the University of Washington that explored the potential synergies between land-based seismic and geodetic monitoring in the Pacific Northwest and ongoing efforts to establish cabled observatories off the coast of the Pacific Northwest. Both the NEPTUNE Canada and Regional Scale Nodes cabled observatories are supporting networks of seafloor seismometers. Their installation is a result of extensive discussions and documentation within the scientific community of their scientific worth. In contrast, relatively little attention has been given to the rationale for offshore geodetic observations, despite their potential importance for understanding the basic science and hazard of the Cascadia subduction zone.

For this reason John Delaney, the Director of Regional Scale Nodes Program, and John Vidale, the Director of the Pacific Northwest Seismic Network, provided internal University of Washington funds to host a small meeting of twenty participants to explore the potential of seafloor geodesy in our region. As a result of community interest, the size of the meeting grew significantly and on June 11-12, 2012, about fifty scientists and engineers (Appendix A), including twenty from out of town, met for a day and a half on the University of Washington campus. The meeting agenda (Appendix B) was designed to address three goals:

1. Developing the scientific rationale for making seafloor geodetic observations of Cascadia subduction zone.
2. Discussing what is best to measure, where to measure it and how.
3. Exploring short-term and long-term plans for how to build seafloor geodesy upon current efforts.

This report provides a short summary of the meeting.

Cascadia Subduction Zone

The Cascadia subduction zone extends 1100 km from Cape Mendocino, California to northern Vancouver Island and marks the boundary along which the small Juan de Fuca oceanic plate subducts beneath North America (Figure 1). Convergence occurs in a northeast direction at modest rates ranging from 30 mm/yr off northern California to over 40 mm/yr off Vancouver Island. Because the subducting Juan de Fuca plate is young (5-10 Ma) and thus warm, the locked zone that fails in megathrust earthquakes is relatively shallow and lies almost exclusively offshore. The Juan de Fuca plate is blanketed by up to 4-5 km of glacial sediments that bury the trench and reduce seafloor depths. Most of the sediments on the incoming plate are scraped off to form an active accretionary prism that extends shoreward from a sharp deformation front and lies outboard of older, accreted terranes that form the rock framework of the margin. An active volcanic arc extends the full length of the subduction zone.

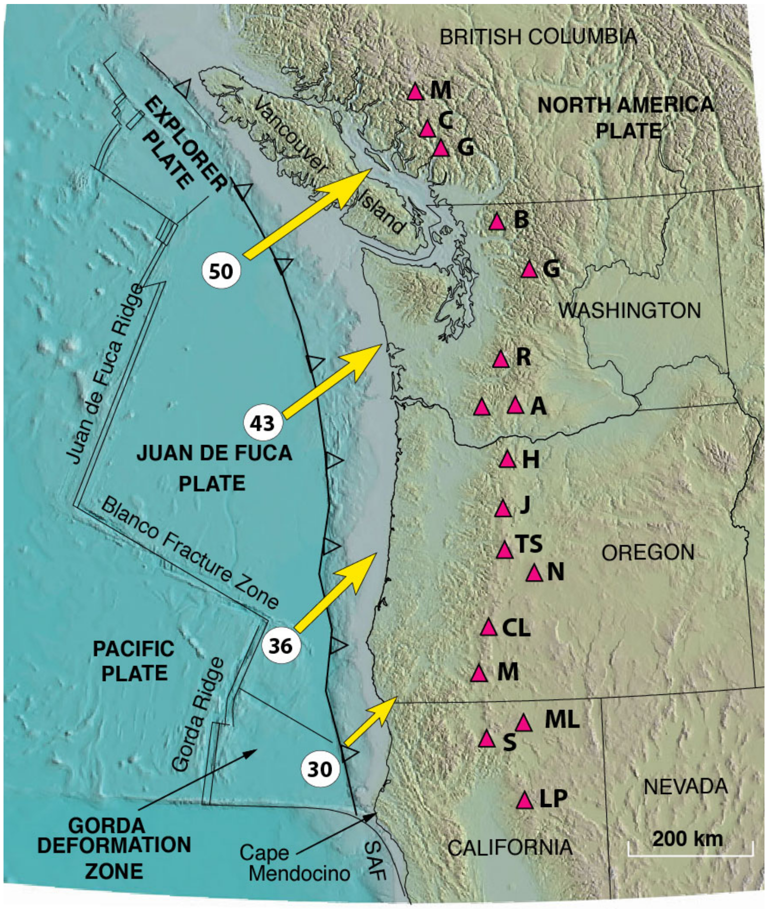

Figure 1. Map of the Pacific Northwest showing plate boundaries, convergence rates across the Cascadia subduction zone and arc volcanoes (modified from Haugerud, 2000).

Current seismicity in the subduction zone is largely confined to < 90 km depth, in-slab events in the down going Juan de Fuca plate, largely beneath the Puget Lowland and around the Mendocino Triple Junction and eerily is almost non-existent on the plate boundary. However, the geologic record of episodic coastal subsidence and offshore turbidites confirm that this interface has produced numerous great megathrust earthquakes and tsunamis in Holocene time, with an average recurrence interval of about 500 years (Goldfinger, 2011). The most recent great earthquake (estimated magnitude 9) occurred in 1700, causing widespread tsunami damage in Japan (Atwater et al., 2005). Global Positioning System (GPS) measurements document northeastward compression above the megathrust, indicating that it is presently locked and accumulating interseismic strain and is in the late (high stress and low strain rate) stage of the subduction cycle. Geological studies suggest that there is a 25-40% probability of a magnitude 8+ megathrust earthquake on the subduction zone in the next 50 years (Goldfinger et al., 2012).

South of Vancouver Island, convergence is oblique with a dextral shear across the plate boundary. On land, the GPS velocity field (McCaffrey *et al.*, 2007) documents a regional clockwise rotation of the upper plate at about 1°/Ma, which causes the upper plate to break up into blocks, and causes margin-parallel shortening and tectonic segmentation of the margin (Figure 2). This segmentation, along with westward increasing dextral shear toward the plate boundary may cause seismic segmentation and complex strike slip faulting of the shallow megathrust.

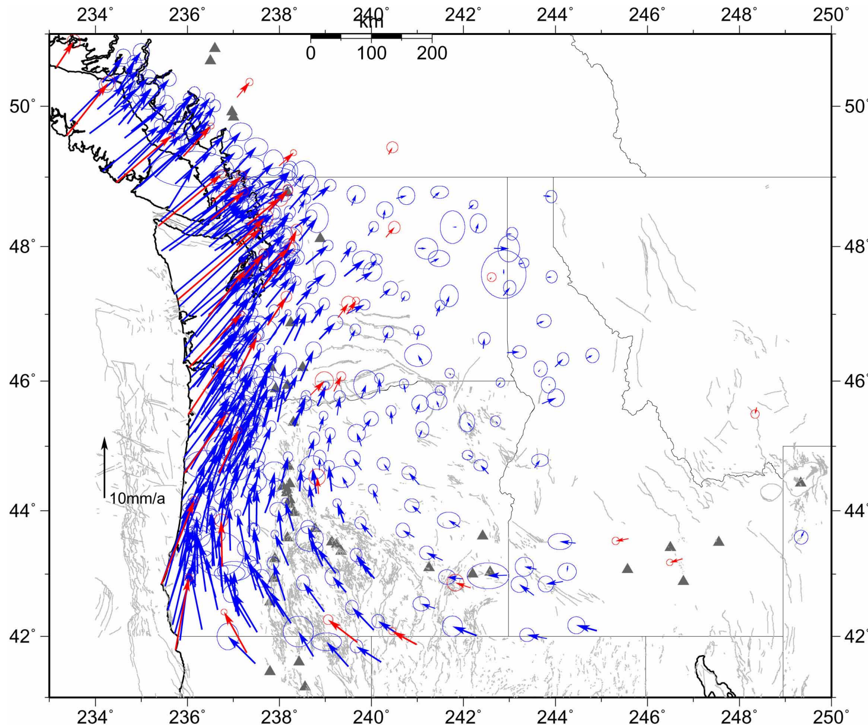

Figure 2. GPS velocities and 70% confidence ellipses in the North American reference frame for continuous (red) and campaign (blue) sites (from McCaffrey *et al.*, 2007).

Motivation for Offshore Geodesy

Seafloor geodetic measurements on the incoming plate, trench, and accretionary prism would contribute in many ways to understanding the subduction zone because they have the potential to resolve a variety of deformation sources. In global plate tectonic kinematic models, the motion of the Juan de Fuca plate is only constrained indirectly. Direct measurements of the motion of the Juan de Fuca plate relative to North America provide a first-order constraint on the convergence and shear across the plate boundary. Measurements of plate motion have been obtained at three locations on the Juan de Fuca plate using GPS-acoustic techniques (Chadwell and Spiess, 2008). Interestingly, the measurement obtained 150 km offshore central Oregon reveals that the plate motion is 50% slower and rotated 25° more easterly than predicted by the geomagnetic anomalies that constrain current kinematic models. It appears that the oceanic plate may be deforming in this region due to a combination of regional plate forces acting within the subduction zone between the obliquely converging and weaker downgoing slab and the stronger accreted terrains of the forearc. However, globally very little is known about interseismic deformation of incoming plates at subduction zones, which makes this lone observation difficult to interpret.

Over interseismic time scales, convergence between the Juan de Fuca and North American plates accumulates in the locked zone (Burgette *et al.*, 2009), a region that will eventually rupture in a megathrust earthquake (Figure 3). The up-dip limit of the locked zone is unconstrained by onshore observations. Offshore measurements of long-term vertical and/or horizontal deformation above the shallow slab would constrain the updip extent of locking with important implications for the size and tsunamigenic potential of a megathrust earthquakes. Slow slip and tremor have been identified beneath the outer accretionary prism of the Nankai Subduction zone (Obara and Ito, 2005) seaward of the locked zone. If present in Cascadia, these transient events would further constrain the extent of the locked zone. We know that the Cascadia subduction zone is segmented, but because the complex deformation of the forearc masks the megathrust locking signal, it is hard to know whether some segments are silently creeping. Seafloor geodetic measurements that spanned the trench at multiple locations along the subduction zone could address this question. If near trench transient events in Cascadia were associated with the deep episodic tremor and slip events that are abundant in Cascadia, it might indicate regions in which the megathrust is incompletely locked.

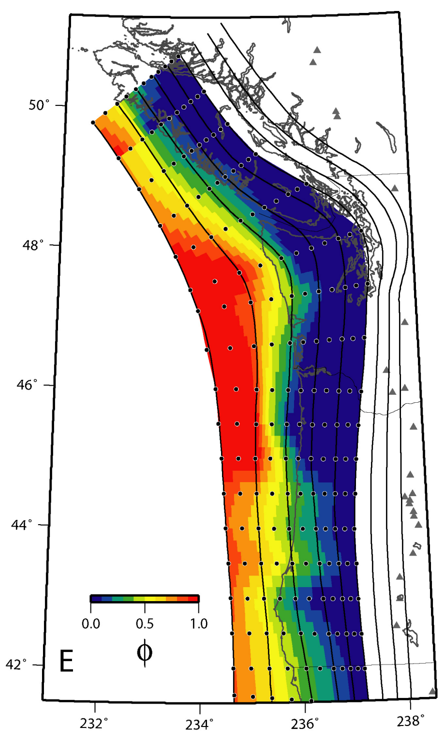

Figure 3. A model of the slip deficit fraction ϕ (locking) on the Cascadia subduction zone derived from land GPS measurements (from McCaffrey *et al.*, 2007)

The convergence between the plates is accommodated across the plate margin by geologic structures in the forearc (Goldfinger *et al.*, 1996). Geodetic observations across the prism would constrain the partitioning of strain across prism and the distribution of active faults. Offshore observations would constrain how the northward migration of the forearc is linked to the northward component of along-strike motion of the Juan de Fuca plate (Wells *et al.*, 1998). The occurrence of very-low-frequency (VLF) events near the trench would elucidate the frictional behavior of splay and detachment structures, and provide insight on the potential for tsunamigenic earthquakes along the margin (Sugioka *et al.*, 2012). Geodetic observations on the prism would also have the potential to resolve submarine landslides and slumps.

When the megathrust fails, seafloor geodetic observations will constrain the co- and post-seismic slip and deformation, which will provide important constraints on mantle rheology (Wang et al., 2012). To the west of the trench, flexural stresses are released by outer rise earthquakes (Clouard *et al.*, 2007). The oceanic plate undergoes internal deformation as it is flexed and pulled to the east. Some of this deformation is accommodated by intraplate earthquakes along inherent weaknesses and fracture zones. External driving forces from the trench or ridge transmit across the plate (Fox *et al.*, 1999) and trigger far-field events or drive transient deformation from viscous coupling with the underlying mantle. Finally, any offshore geodetic array is likely to discover unanticipated deformation sources. Some examples might include premonitory slip on the megathrust (Kato *et al.*, 2012), poroelastic deformation of the prism from fluid flux (Ranero *et al.*, 2008) or the dissociation of gas hydrates, and basin subsidence of the continental shelf from the compaction of sediment or subduction erosion.

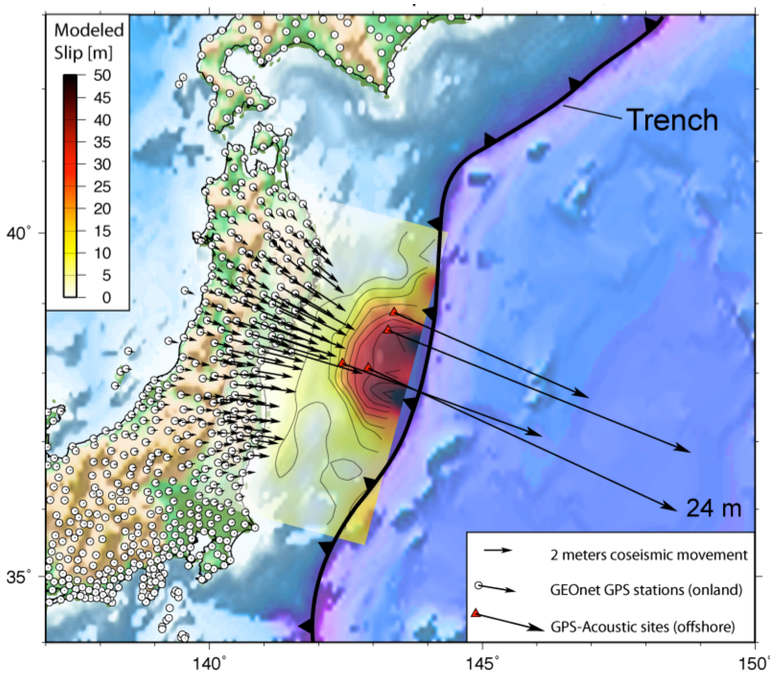

Figure 4. Coseismic displacement and fault slip of the Tohoku-Oki magnitude 9 earthquake based on modeling onshore GPS and seafloor GPS-acoustic observations (from Newman, 2011 with seafloor observations based on Sato *et al.*, 2011)

The importance of geodetic observations in subduction zones was clearly illustrated by the 2011 magnitude 9.0 Tohoku-Oki earthquake in Japan (Figure 4). Here an extensive network of GPS stations on-land would, if used in real time, have easily constrained the full magnitude of the event within 1-2 minutes. Instead, existing systems using only seismic monitoring required ~20 minutes. The Tohoku earthquake occurred in a region where there were also a significant number of seafloor geodetic observations above the rupture zone. Repeat GPS-Acoustic fixes documented the deformation and subsequent restoration of interplate coupling associated with an magnitude 7.2 thrust earthquake in 2005 and show that the co-seismic slip associated with 2011 earthquake exceeded 50 m near the trench, about twice that inferred from modeling data on land. If this data had been available in real time for the 2011 earthquake it would have decreased even further the time necessary to acquire the data to constrain the size of the event. Ocean bottom pressure time series on autonomous instruments recorded vertical seafloor movements associated with both the largest foreshock and the mainshock and are consistent with a model in which afterslip for the foreshock propagated toward the mainshock hypocenter. The seafloor pressure data also revealed a very heterogeneous distribution of after-slip. Based on their experiences, Japan is now investing substantial resources (~$500M) in expanding the number of seafloor geodetic observations and in installing an underwater cable network to obtain seafloor seismic and geodetic data in real time (Figure 5). Discussion at the meeting envisioned the potential for a synoptic monitoring system in Cascadia integrating seafloor and onshore deformation and seismic observations.

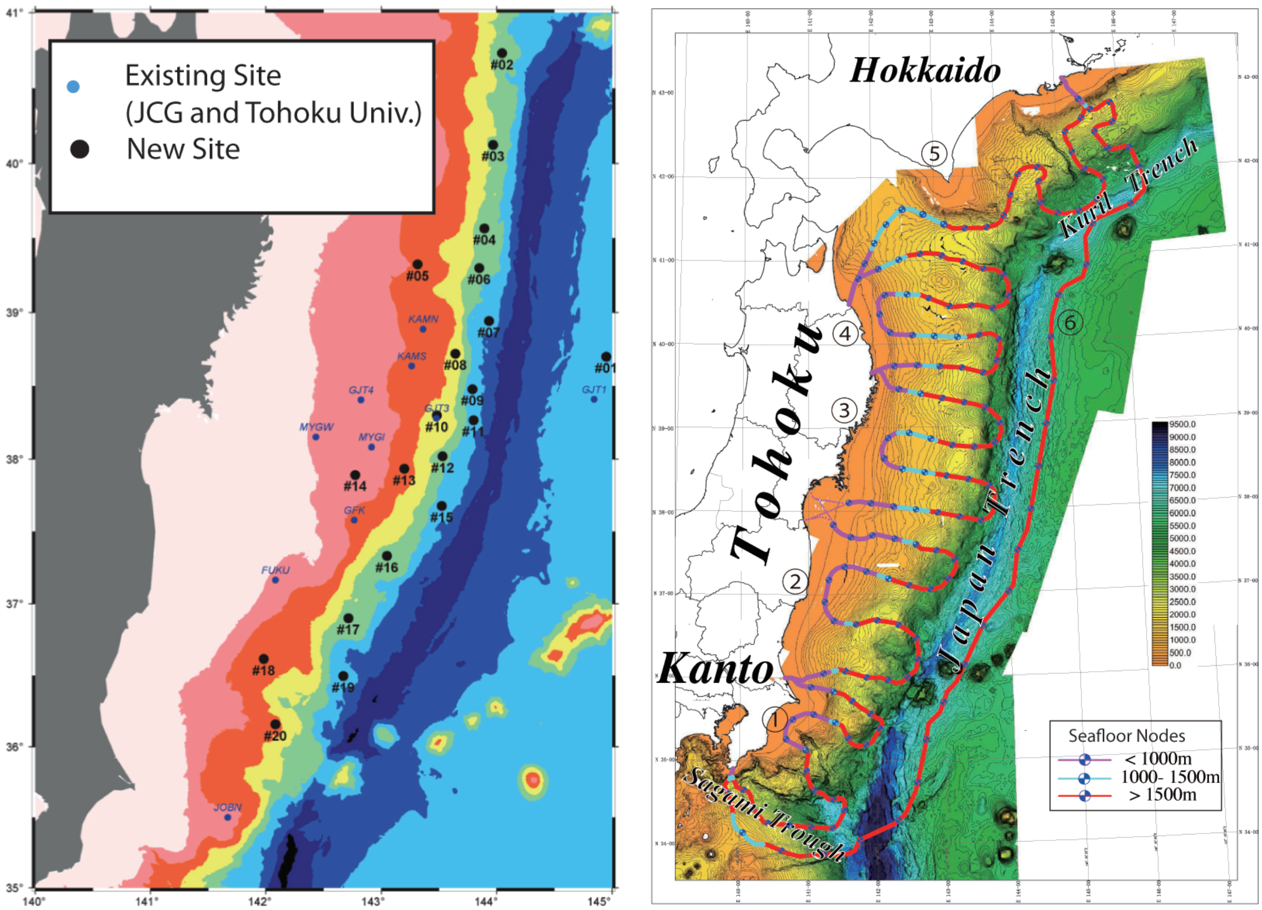

Figure 5. (Left) Pre-Tohoko earthquake acoustic-GPS sites operated by the Japan Coast Guard and Tohoku University and 20 new sites operated by Tohoku and Nagoya Universities (Ishikawa et al., 2012). **(Right)** The Japan Trench Ocean Bottom Seismic and Tsunami Network will be installed by 2015 and comprises 5700 kilometers of cable and 154 nodes (Uehira et al., 2012). Each node comprises a Geospace Technologies three component seismometer, two JAE three component accelerometers, two Paroscientific Nano-Resolution depth sensors and a three-component Nano-Resolution accelerometer. (Also under consideration for Japan is a land-based tsunami warning system that will detect tsunamis through the use of infrasound sensors (Paros et al., 2012)).

Existing Geophysical Infrastructure and Initiatives in the Pacific Northwest

In recent years, the National Science Foundation (NSF) and other agencies have made considerable and ongoing investments in infrastructure for geoscience in Cascadia. For example, NSF GeoPRISMS program recently identified Cascadia as a Primary Site and in April about 150 scientists attended a planning workshop in Portland. This meeting had a broad focus and documented extensive interest in research related to the Cascadia subduction zone.

On land, the Pacific Northwest Seismic Network (PNSN) operates a seismic network of broadband, short period and strong motion sensors with operational support from the United States Geological Survey, Department of Energy and State of Washington. The number of broadband stations has been steadily expanding and now numbers ~100. Most recently 27 temporary sites in the Earthscope USArray transportable network were reinstalled as part of the Cascadia Initiative, 5 in California and the rest in Oregon and Washington, which might convert to permanent broadband PNSN installations. This $2.5M infrastructure investment by NSF was part of the Cascadia Initiative, supported with funds from the 2009 Stimulus or ARRA (American Recovery and Reinvestment Act). ARRA funds are also allowing the upgrade of 18 more stations to broadband capabilities through the USGS. Onshore GPS data in Cascadia is provided by ~470 stations operated (in approximately equal numbers) by both The Pacific Northwest Geodetic Array (PANGA) and the NSF-funded Plate Boundary Observatory (PBO). The Cascadia Initiative provided $2.5M of ARRA funds to upgrade the PBO sites, so that the combined regional network has uniformly high-sample-rate (1-Hz) with real-time continuous telemetry.

The Cascadia Initiative provided $5M for the construction of 60 ocean bottom seismometers (OBSs), including new designs with trawl-resistant enclosures to facilitate shallow-water deployment. Over the years from 2011-15, the Cascadia Initiative OBSs and ten additional instruments will each be deployed four times for one year and will occupy ~160 sites. The deployment pattern comprises a 70-km grid that spans the Juan de Fuca plate, which is designed to extend the US Array transportable grid offshore, a smaller instrument spacing along the subduction zone to detect small earthquakes and dense deployments on the subduction zone off Grays Harbor, Washington; Newport, Oregon; and Cape Mendocino, California.

Both Ocean Networks Canada and the NSF Ocean Observatory Initiative (OOI) are supporting the development of regional cabled observatories on Cascadia margin and Juan de Fuca plate. The NEPTUNE Canada observatory comprises five instrumented nodes on an 800 km cable loop that crosses the continental shelf in two locations and extends to the Juan de Fuca Ridge. The Regional Scale Nodes of the OOI is in the midst of installing extensive networks of cabled seafloor and water column instruments at Axial Seamount on the Juan de Fuca Ridge and at several sites on the margin off Newport, Oregon including Hydrate Ridge. The two systems will initially include 8 broadband seismometers (3 are presently installed on NEPTUNE Canada) and small local short-period seismic networks at Hydrate Ridge, the Endeavour Segment and Axial Seamount. In addition bottom pressure observations are being obtained at multiple locations and the NEPTUNE Canada observatory is connected to one instrumented mid-plate borehole and in addition is set to connect to IODP Hole 1364A on the margin off Vancouver Island for which WHOI has secured funds from the Keck Foundation to install borehole tiltmeters. Borehole fluid pressure monitoring systems (CORKs), presently operating in these holes and in autonomous mode in several other boreholes on the Juan de Fuca plate, respond to seismic and aseismic strain transients and serve as sensitive proxy volumetric strain meters.

On a basin scale, NOAA operates an array of Deep-ocean Assessment and Reporting of Tsunami (DART) buoys as part of national and international efforts to improve capabilities for the early detection and real-time reporting of tsunamis. Three of these buoys are deployed off Cascadia. While the primary function of near shore DART buoys is to constrain the size of outgoing tsunamis that will propagate across the ocean, there is clearly merit to predicting the size of local tsunamis. One of the major challenges is to forecast tsunamis in the near field where the tsunami wave is often overwhelmed by the seismic event. A 17-month experiment at the Monterey Accelerated Research System (MARS) cabled observatory demonstrated the ability to make high resolution pressure measurements of micro-tsunamis, earthquakes, microseisms and infra-gravity waves (Paros et al., 2012).

After a decade-long hiatus in the acquisition of deep seismic reflection data on Cascadia margin, there have been several reflection experiments in the region this year using the *R/V Langseth*. Seismic reflection imaging in subduction zones is an important complement to seismic and geodetic monitoring. For example seismic images are critical for mapping structural features to better assess the extent of megathrust locking and whether the rupture zone extends seaward to the trench. They are necessary to assess the influence of geometrical irregularities on the subducting plate such as seamounts and of structure in the overriding plate in creating megathrust segmentation.

Given all the investments in monitoring infrastructure and scientific initiatives, it is striking that there is not yet a community effort in place to obtain seafloor geodetic data from the Cascadia subduction zone.

Seafloor Geodetic Techniques

On land, the availability of dense networks of GPS stations and maps of ground displacement obtained using interferometric synthetic aperture radar (InSAR) has revolutionized our ability to understand tectonic and volcanic processes. Because the oceans do not transmit the electromagnetic waves that enable these techniques, geodetic measurements on the seafloor are much more challenging. There are a variety of complementary approaches to seafloor geodesy with ongoing technique development efforts focused on improving the accuracy and reducing the costs of observations.

Offshore GPS or GPS-Acoustics combines kinematic GPS with precision acoustic ranging to seabed transponders from a sea surface platform to track the horizontal motion of the seafloor (Figure 6). Conventionally the platform is a ship and acoustic ranging is used to locate the ships horizontal position relative to the center of a small network of seafloor transponders and GPS is used to locate the ship and thus the position of the transponder network. Repeat campaign style measurements over several years can constrain plate motion (or the slip for any intervening earthquake). Because the ship must sit on station for several days to obtain a horizontal position with an accuracy of about a centimeter, the measurements are expensive and time consuming. One approach to reducing costs is to use an alternative sea surface platform. Efforts are underway at SIO to develop systems that use an autonomous wave glider (an aquatic robot) for repeat campaign measurements or a moored buoy for continuous observations. In addition SIO and LDEO are developing a seafloor geodetic benchmark that simplifies the replacement of seafloor transponders when the batteries run out.

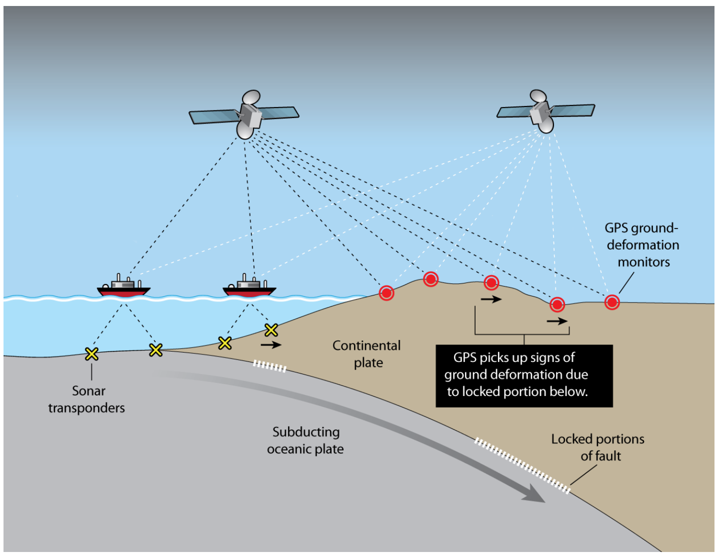

Figure 6. GPS-acoustic methods can extend GPS observation offshore (from Newman, 2011).

An alternative approach to conventional offshore GPS is the Geodetic Acoustic Benchmark Beacon Inverted EchoSounder (GABBIES) being developed at URI. In this method a single acoustic beacon is located on the seafloor both horizontally and vertically by ranging from two accurately navigated ship tracks that cross over the beacon. This method could also be adapted to cheaper autonomous unmanned surface vehicles.

Vertical deformation of the seafloor is measured using absolute pressure gauges that are based on quartz strain gauge technology. The Paroscientific Nano-Resolution Depth Sensors are capable of measuring seafloor pressures with a resolution of 0.0001% and long-term drift rates as low as a few centimeters per year. These drift rates exceed the long-term signal (mm/yr) expected from strain accumulation above the locked zone but would not obscure signals associated with many transient events. At Axial Seamount long term monitoring of volcanic inflation with absolute pressure gauges has been combined with campaign-style measurements using a mobile pressure recorder deployed from a remotely operated vehicle onto seafloor benchmarks to correct for differential drift between stations and obtain relative depth measurements with a repeatability of ~1 cm/yr (Chadwick *et al.*, 2012). The results document long-term uplift at ~15 cm/yr due to inflation of and deflation during eruptions of up to 2-3 m over a week. A similar approach has been used on the East Pacific Rise and is planned for Cascadia subduction zone around

ODP/IODP Sites 889 and 1364 off Vancouver Island. An alterative approach to minimize the effects of pressure sensor drift is to include a means to calibrate observation in situ. In a system under development at SIO, a pair of quartz pressure gauges that record ambient seawater pressure are periodically connected to a piston gauge calibrator. Seafloor pressure measurements can be combined with absolute gravity to infer subsurface density changes; to date this approach has been primarily focused at monitoring production from oil and natural gas reservoirs but it could also be applied to tectonically-induced changes in subsurface density.

Tilt meters usually measure the rotation along two horizontal axes to obtain a local measurement of the gradient in vertical deformation. Conventional short-baseline modern instruments use a pair of spirit levels with electrode sensors and are widely used to monitor volcanic inflation on land. Unfortunately their drift rate can reach 1 μrads/day, which exceeds the long-term signal of ~ 0.1-1 μrads/yr expected above the locked zone. Several such tiltmeters manufactured by LGM Lippman are planned for installation in IODP hole 1364 on the accretionary prism off Vancouver Island, and will be useful for identifying earthquake and slow-slip events. MEMS accelerometer-based tiltmeters have recently been developed by a number of companies for use in industry applications and are attractive for geodetic applications because they should not suffer from instrument drift. Another promising approach for measuring tilt and seismic displacements is the use of interferometry to measure the motion of an inertial mass.

Linear strainmeters measure the change in distance between two points on the seafloor. Conventionally such measurements have been obtained by ranging between acoustic beacons with the precision of measurements limited by our knowledge of changes in the speed of sound. An alternative sensor and deployment system called the Fiber Optic Seafloor Strainmeter has been developed at SIO. The system is presently capable of measuring changes in the length of a 1-km-long buried optical fiber with a precision of 1 mm and may eventually have a sensitivity of about 1 nanostrain.

Measurements of fluid pressures changes in hydraulically isolated boreholes can be used to infer volumetric strain perturbations. Such observations in boreholes on the Juan de Fuca plate have been used to infer the deformation associated with ridge spreading and transform earthquakes. Observations from Costa Rica and the Nankai show that boreholes on the incoming plate and toe of the accretionary prism are capable of monitoring interseismic strain accumulation and a range of episodic deformational events (Davis et al., 2011).

In the absence of seafloor geodetic data or boreholes, fluid flow through the uppermost sediment column in subduction zone forearcs can also be used as a low-cost proxy for strain. Due to the high hydraulic impedance of typical prism sediments, rapid changes in flow rate may indicate deformation of the upper few meters of sediment below an instrument. Results from Costa Rica show that flow-meter-based tracer injection and sampling driven by osmotic pumps is sensitive to the strains associated with slow slip events. With some assumptions, flow rate transients can be used to estimate rupture location, extent, propagation velocity, and duration.

Seafloor Observatories

Traditionally, geophysical times series are obtained on the seafloor using autonomous packages that record data internally for analysis only after the instruments are recovered. If real-time or near real-time data is required, the instruments must be connected to the shore. This can be accomplished either with a submarine cable or using a buoy that communicates to shore by satellite and to the seafloor by an acoustic modem (e.g., DART buoys) or in some newer systems by a cable. Submarine cable observatories provide more power, bandwidth and durability than buoys but are more expensive and cannot be moved. The current infrastructure for the RSN and NEPTUNE Canada observatories provides cabled connections at three along-strike locations above subduction zone. These observatories were designed with expansion in mind; the initial suite of sensors on the RSN will use only ~16% of the power available and 8-10% of the bandwidth. Thus, there is plenty of room on these systems to support the development and installation of geodetic sensors.

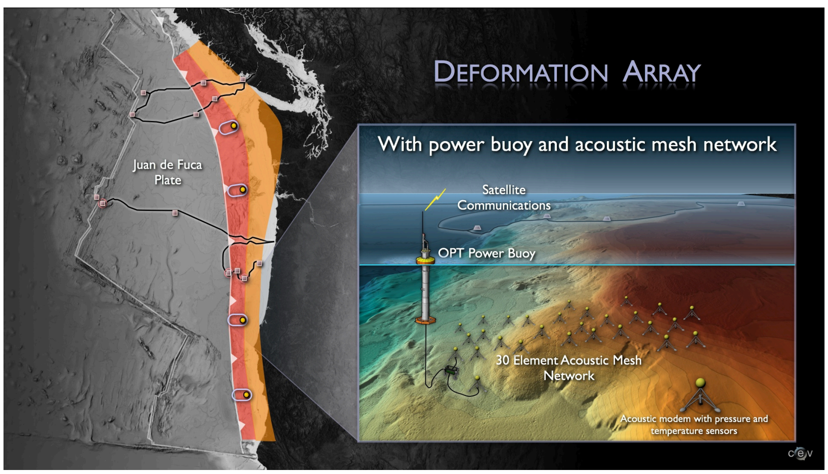

Figure 7. Cabled and buoyed observatories could be combined to monitor the full extent of the Cascadia subduction zone velocities with small-scale instrument networks connected by secondary cables or acoustic meshes (figure created by the Center for Environmental Visualization, University of Washington).

If real time geodetic observations are desired at other locations on the subduction zone, one option is to extend the backbone cable along strike to new nodes. The RSN was designed with a second subduction zone node off Grays Harbor and so this is a potential expansion site. An alternative and complementary approach is to take advantage of modern buoys such as the Ocean Power Technologies PowerBuoy that generate power from wave motion and provide power and connectivity to the seafloor through a cabled connection (Figure 7). These buoys could either be deployed at remote locations with satellite connections used to transfer data back to shore or in networks with a spacing of up to ~15 km centered around a buoy connected to a cabled observatory with high-bandwidth connectivity buoys linked by radio communications. There are two approaches to installing smaller-scale networks of geodetic sensors around each cable node or PowerBuoy site. Instruments can be connected by networks of secondary cables, or alternatively autonomous packages can communicate acoustically (Figure 7). An advantage of the second approach is that the instruments are cheaper to install and a dense scalable network of instruments spaced at ~1 km can form an acoustic mesh with redundant paths for data reliability and self-healing capabilities. For geodetic applications, the time of flight between instruments is in and of itself a geodetic measurement that can be used to monitor displacements with a resolution of ~1-2 cm.

What Next?

On the second day of the meeting the participants split into three breakout groups. The groups were chosen to all have a similar range of expertise and each was asked to address the same set of questions. Although the emphasis of discussions in each group varied they reached similar conclusions. With the exception of the need to monitor tsunamis, there was a consensus that since there have been so few observations of offshore deformation in the Cascadia subduction zone, studies should focus first on obtaining a predictive understanding of the tectonic processes. Key science questions to be addressed include:

- What is the rate of plate convergence?
- What portion of the megathrust is locked?
- Is there along strike variability in width of the locking zone?
- Are some segments creeping?
- Are there shallow transient slow-slip events near the deformation front?
- What is the co- and post-seismic deformation associated with megathrust and other offshore earthquakes?
- Are stresses effectively transmitted across the Juan de Fuca plate?
- How is the internal deformation different between the JDF and its southernmost portion (the Gorda area)?
- What is the rheology of the oceanic mantle and the nature of lithosphere/asthenosphere coupling?

What do we want to measure?

Key measurements on the regional scale include changes in horizontal (and perhaps vertical) velocity using an acoustic GPS technique and pressure for both tsunami detection and vertical deformation, and changes in strain rate using borehole pressure and strain measurements. In areas where transient effects are anticipated or higher spatial resolution is required, tilt, short-baseline linear strain and fluid flux measurements will also be important. Because of the expense of deploying equipment on the seafloor and the need to distinguish observational artifacts from signals, sites should be routinely instrumented for multiple geodetic techniques and redundant observations. Shallow fluid flow observations would benefit from collocation with direct observations to better calibrate this proxy technique. Broadband and strong motion seismometers would complement the geodetic observations.

Given the limited toolkit for seafloor geodesy, there is a pressing need for investment in emerging technologies. Such development efforts should, where appropriate, take advantage of the existing cable infrastructure and boreholes. Good bathymetric maps of the toe of the accretionary prism would be useful in identifying potential source areas for tsunami earthquakes, and would provide a critical baseline in advance of an event. High resolution mapping with autonomous underwater vehicles flying near the seafloor may improve the sensitivity of bathymetry time-differencing techniques to a level where they could detect interseismic deformation.

Where do we want to measure it?

It was agreed that there should be a phased approach to the deployment plan. The first phase would start with an exploratory period, lasting on the order of 5 years, during which various potential sources can be surveyed and instrumentation can undergo technical development. In the second phase, the density of observations would increase with the ultimate goal of matching those on land and with an increased emphasis on monitoring objectives.

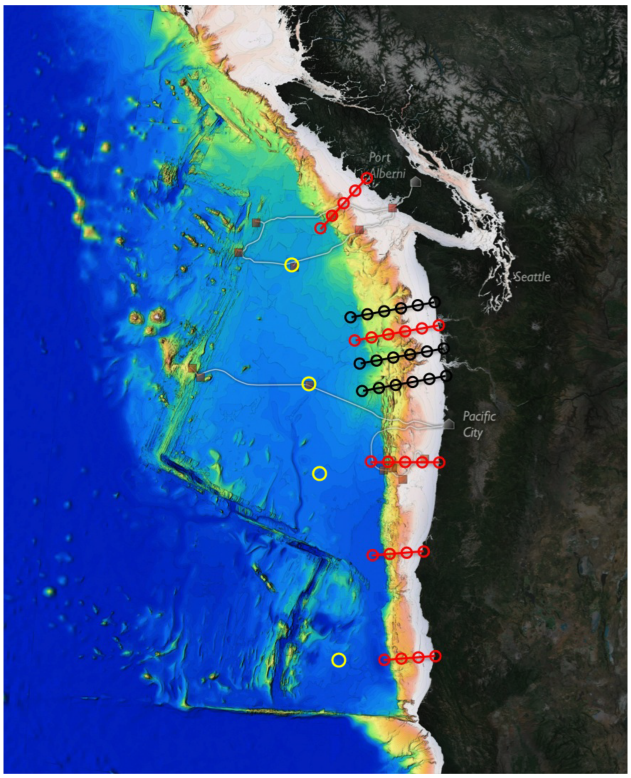

Figure 8. Schematic configuration of an initial seafloor geodetic experiment based on the discussions of one working group. Several measurements (yellow) would be obtained mid-plate to constrain plate convergence rates. Trench-perpendicular geodetic profiles (red) would be obtained at several sites distributed along the entire subduction zone and would use campaign style deployments where cabled observatory infrastructure was presently unavailable. Additional profiles could be obtained with a finer along-trench spacing (black) to investigate segmentation (Base map created by the Center for Environmental Visualization, University of Washington).

Observations should be obtained at several more locations on the Juan de Fuca plate to measure plate motion and convergence rates. Within the subduction zone, there was a consensus that the initial geodetic observations should be obtained on trench perpendicular transects. Each transect should include at least one site on the incoming plate and should extend close to shore so that seafloor observations can be merged seamlessly with land measurements. The optimal spacing of sites should be guided by modeling but would likely be 20-40 km. Each group envisioned between 4 and 10 transects whose location would be informed by the structure of the prism, known seismic activity, and evidence of segmentation (Figure 8). Some transects can take advantage of the cabled observatories but a higher density of measurements is required along and across strike than can be supported exclusively by existing infrastructure. In addition to the transects, a few more dispersed observations will be required on the Juan de Fuca plate to constrain plate motion and internal deformation.

What is the value of campaign versus permanent observations?

There is clearly value to both styles of observation. Given the paucity of existing observations, an incremental approach is required to determine signal levels. Campaign style deployments would be adequate for the first phase of observation at locations away from existing observatory infrastructure. Indeed, they will be necessary to guide the design any expansion of the permanent infrastructure. As the permanent infrastructure is expanded, there will likely always be a desire to supplement permanent observations with campaign experiments to address specific science problems. For many observational techniques, campaign-style deployments will provide continuous data for the duration of the deployment, but GPS-Acoustic and ROV calibrated bottom pressure measurements will be discrete. As our understanding of deformational patterns increases continuous GPS and calibrated pressure will become increasingly important to address science questions.

What is the importance of real time data?

Real time data serve several important functions. First, it is essential for hazards monitoring and thus will be necessary for the later phase of observations. Second it allows scientists to respond to events and increase the density of observations – this may be particularly important to study transient events. Third since much of the processing of geodetic and seismic data streams on land occurs in near real time, the short latency for either a cabled connection or batched satellite transmission will facilitate the integration of marine observations into amphibious data sets.

How do we proceed in the short and long term and who will fund it?

There are a number of NSF-funded efforts underway to develop and enhance marine geodetic techniques and such work is important. This work should continue with a focus on driving down the cost of techniques, improving instrument sensitivities and minimizing measurement drift. However, the technology is sufficiently mature to support an initial phase of exploratory campaign style observations. While PI-driven proposals to existing programs can play a role in such work, it will require a community effort with a financial commitment and organizational structure that is comparable to offshore seismic component of the Cascadia Initiative. The initial observations will need integration with other data sets and modeling efforts to interpret the observations in terms of subduction zone processes. In the longer term, the scientific and hazard communities will need to make the case for a permanent geodetic and seismic monitoring network to cover the length of the subduction zone.

NSF is playing a major role in the development of seafloor geodetic techniques but other funding sources are also contributing, such as NASA for GPS-based techniques, ONR for acoustics and private foundations. Across the border, Canadian government agencies and research programs have parallel efforts. For monitoring applications in the US, marine geodesy overlaps the mandates of NOAA for tsunamis and the USGS for earthquakes, which suggests a collaborative approach. Other agencies such as FEMA, DOE and Homeland Security also have a stake in the products of such efforts.

The logical first step is to build upon the ideas expressed in this meeting and the April GeoPRISMS Cascadia workshop and seek support from multiple agencies for a community-wide workshop that would develop more specific and detailed plans for a community approach to the first phase of geodetic observations in the Cascadia subduction zone.

Conclusions and Recommendations

The primary conclusions and recommendation of this workshop can be summarized as follows:

1. There is strong scientific and hazards monitoring justification for seafloor geodesy in the Pacific Northwest because it provides critical information about the subduction zone that cannot be obtained by other means.

2. There are extensive infrastructure and several initiatives on shore and at sea that would be complemented by seafloor geodesy.

3. Initial objectives of seafloor geodesy should be to address scientific questions related to measuring and understanding:
   a. The motion and deformation of the Juan de Fuca plate.
   b. The spatial extent of the megathrust locked zone and whether some segments of the subduction zone are creeping.
   c. The characteristics of offshore transient deformation events.

4. Initial efforts should focus on obtaining measurements of horizontal and vertical deformation along trench perpendicular profiles at 4-10 locations along strike using a combination of autonomous and observatory-hosted instruments.

5. The long-term objective should be real time monitoring along the whole subduction zone.

6. A community workshop supported by multiple agencies would be the most productive mechanism to build interest and develop plans for the initial phase of observations.

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Appendix B: Meeting Agenda

Ocean Sciences Building Room 425

Monday, June 11

Introduction and Motivation

8:30	Meeting Goals	William Wilcock
8:40	The Cascadia Subduction Zone – An Introduction * (p. 27)	Ray Wells
9:00	Offshore Structure	Anne Tréhu
9:20	Known and Unknown Deformation* (p. 28-30)	David Schmidt
9:40	Lessons from Tohoku* (p. 31)	Ryota Hino

10:10 Break

Existing Infrastructure

10:30	Pacific Northwest Seismic Network	Paul Bodin
10:40	Pacific Northwest Geodetic Array	Tim Melbourne
10:50	Canadian Land Networks	Herb Dragert
11:00	Cascadia Initiative* (p. 32)	Doug Toomey
11:10	Ocean Observatory Initiative	Deborah Kelley
11:20	Neptune Canada* (p. 33)	Martin Scherwath
11:30	DARTs for tsunami source definition	Vasily Titov

What is Missing?

11:40	What is missing from the big picture?	Kelin Wang
11:50	Discussion	

12:30 Lunch

Geodetic techniques

1:30	Acoustic GPS and Ranging* (p. 34-36)	David Chadwell
1.45	Geodetic Acoustic Benchmark Beacon Inverted Echosounder (GABBIES)	Yang Shen
1:55	Seafloor Pressure	Spahr Webb
2:10	Deformation at Axial Seamount* (p. 37-38)	Bill Chadwick
2:25	Pressure, Gravity and Optical Strain* (p. 39-40)	Mark Zumberge
2:40	Tilt Measurements* (p. 41)	Andrew Newman
2:55	Borehole Hydrological Methods* (p. 42-43)	Earl Davis
3:10	Seafloor Hydrological Methods	Evan Solomon

3:25 Break

3:40 Discussion of Geodetic Techniques

Seafloor Observatories and Networking

4:20	Potential of Observatories	John Delaney
4:40	Cables versus Buoys	Pete Barletto
4:50	Acoustic Meshes	Dana Manalang
5:00	Discussion	

5:30 Adjourn to drinks and barbeque dinner on Marine Sciences Building deck

Tuesday, June 12

More Motivation

8:30	Need for Underwater Observations* (p. 44)	Andrew Newman
8:45	Monitoring versus Science	John Vidale

What Next?

9:00 Breakout Groups

We split into 3 breakout groups each of which addressed the following:

What do we want to measure?
Where do we want to measure it?
What is the value of campaign versus permanent observations?
What is the importance of real time data?
How do we proceed in the short and long term?
Who will fund it?

Discussion Leaders:	Group A	Jeff Freymueller
	Group B	Adam Schultz
	Group C	Meghan Miller

11:00 Plenary Discussion
Breakout group reports
What are the next steps?

12:00 Meeting Adjourns

* *Abstract included in Appendix C (page number in parentheses)*

Appendix C: Selected Abstracts

The Cascadia subduction zone - An introduction

Ray Wells
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The Juan de Fuca (JDF) plate subducts beneath North America along the Cascadia subduction zone, which extends 1100 km from Cape Mendocino, CA to northern Vancouver Island. Convergence is oblique to the NE, ranging from 30 mm/yr off N. CA to 50 mm/yr off Vancouver Island. Subduction of the young warm JDF slab (~5-10 Ma beneath the shelf) produces 1) a characteristic physiography consisting of a coast range and an inland sea, and 2) relatively shallow locking on the megathrust, inferred to be offshore from thermal models. The Cascadia subduction zone is accretionary – a sedimentary blanket on the incoming plate up to 5 km thick is offscraped to form an active accretionary prism and deformation front. The active prism lies outboard of the rock framework of the margin, which consists of three older, accreted terranes: 1) amalgamated Mesozoic terranes, 2) Siletzia, oceanic basalt accreted to N. America in the Eocene, and 3) the Olympic accretionary complex, which is thrust beneath Siletzia along the continental slope and exposed in the Olympic Mountains. An active volcanic arc extends the full length of the subduction zone.

Current seismicity on the subduction zone is largely confined to intermediate depth, in-slab events in the down going JDF plate, largely beneath the Puget Lowland and around the Mendocino Triple Junction. Current seismicity on the shallow megathrust is almost non-existent. However, the geologic record of episodic coastal subsidence and offshore turbidites confirm that the megathrust has produced numerous great earthquakes and tsunamis in Holocene time, with a recurrence interval of about 500 years. The most recent great earthquake (estimated M9) occurred in 1700, based on widespread tsunami damage in Japan. Global Positioning System measurements (GPS) document northeastward compression above the megathrust, indicating that it is presently locked and accumulating interseismic strain.

The Pacific Northwest GPS velocity field also documents a regional clockwise rotation of the upper plate at about 1°/Ma, which causes the upper plate to break up into blocks, causing margin-parallel shortening and tectonic segmentation of the margin. This segmentation, along with westward increasing dextral shear toward the plate boundary appears to cause seismic segmentation and complex strike slip faulting of the shallow megathrust.

Known and unknown deformation in the offshore environment

David Schmidt

The offshore environment of the incoming plate, trench, and accretionary prism provide a variety of deformation sources with distinct spatial and temporal signatures. At the broadest scale, the motion of the Juan de Fuca plate relative to North America provides a first-order constraint on the convergence across the plate boundary. Acoustic GPS has provided limited, but informative, constraints (Chadwell and Spiess, 2008). This convergence is then accommodated across the plate margin by geologic structures in the forearc (Goldfinger et al., 1996). On the southern half of the subduction zone, convergence is oblique to the strike of the trench. However, offshore instrumentation could better match the northward migration of the forearc relative to the northward component of plate motion (Wells et al., 1996). Over interseismic time scales, convergence between the Juan de Fuca and North American plates accumulates in the locked zone (Burgette et al., 2009), a region that will eventually rupture in a megathrust earthquake. The up-dip edge of the locked zone is unconstrained by onshore instrumentation, while offshore observations would provide critical constraints.

Several potential deformation sources have been observed on other subduction systems, but not fully documented in Cascadia. Slow slip and tremor have been identified beneath the outer accretionary prism of the Nankai Subduction zone (Obara and Ito, 2005). Although it has not been detected in Cascadia, it would not be surprising to find a similar transient signal near the trench. The occurrence of very low frequency (VLF) events near the trench would elucidate the frictional behavior of splay and detachment structures, and provide insight on the potential for tsunamigenic earthquakes along the margin (Sugioka et al., 2012). To the east of the trench, flexural stresses are released by outer rise earthquakes (Clouard et al., 2007). The oceanic plate undergoes internal deformation as it is pulled to the east. Some of this deformation is accommodated by intraplate earthquakes along inherent weaknesses and fracture zones. External driving forces from the trench or ridge can transmit across the plate (Fox et al., 1999), and trigger far-field events or drive transient deformation from viscous coupling with the underlying mantle. Finally, any offshore geodetic array is likely to discover unanticipated deformation sources. Some examples might include premonitory slip on the megathrust (Kato et al., 2012), poroelastic deformation of the prism from fluid flux (Ranero et al., 2008) or gas hydrates, and basin subsidence of the continental shelf from the compaction of sediment or subduction erosion.

These signals can be measured using a variety of instrumentation, including acoustic GPS, absolute pressure gauges, borehole strain, tilt, or pore pressure (volumetric strain). In designing the mix of instruments, the community has to consider the temporal and spatial signature of the anticipated signal. Any deployment plan needs to have clear scientific objectives that are designed for targeted study, monitoring, or discovery.

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Source	Potential	Spatial	Duration	Max Displacements	Instrumentation	Scientific Value
Plate Motion	Known	Very broad	Long-lived	~cm/yr horizontal	GPS-A	Constrain Convergence
Plate Locking	Known	50-200 km across prism	Long-lived	~mm/yr vertical	GPS-A; differential APG	Define up-dip edge of locking
Strain partitioning in the prism	Known	50-200 km across prism	Long-lived	~cm/yr horizontal	GPS-A	Identify active structures in prism; accommodation of oblique convergence
Interplate Earthquakes	Known	10’s to 100’s km	Short-lived	mm’s to 10’s of meters	APG; tilt; strain; pore pressure	Identify active plate interface; foreshocks
Submarine landslides	Known	5-20 km	transient	variable	?	evolution of prism; sediment loading
Slow slip and tremor at the trench	Likely	50-100 km	transient	<cm per event	APG; tilt; strain; pore pressure	Resolve the nature of strain release nearest the trench
Tsunami Earthquakes	Likely	100’s km	Short-lived	meters	APG; tilt; strain; pore pressure	Rupture behavior nearest the trench
Outer Rise Earthquakes	Likely	100’s km	Short-lived	cm to meters	APG; tilt; strain; pore pressure	Release of flexural stress; state of the plate prior to subduction
Internal deformation in JDF; Intraplate earthquakes	Likely	100’s km	Long-lived or short-lived	cm vertical; meters horizontal	GPS-A	strength of oceanic slab; internal weakness
Plate-scale interactions across the JDF	Likely	100’s km	transient	mm-cm	GPS-A	Transmission of stresses across the plate
Premonitory slip	Speculative	10’s ro 100’s km	transient	<cm	APG; tilt; strain; pore pressure	Triggering processes and fault preparation
Poroelastic deformation of the prism	Speculative	Dispersed and localized	transient	mm’s vertical	APG; tilt; strain; pore pressure	Fluid flux from compaction and dehydration
Basin subsidence from compaction and subduction erosion	Speculative	10-100 km	Long-lived	<mm/yr vertical	GPS-A	Geologic construction of prism and sedimentation

Lessons from Tohoku

Ryota Hino (Tohoku Univ., Japan)

The 2011 Tohoku-Oki earthquake occurred just beneath a network of seafloor geodetic measurements maintained by Japan Coast Guard and Tohoku University. The observed deformation data provide strong constraint on the source model of the mainshock of M 9.0 as well as that of the largest (M7.3) foreshock. In this presentation, I will summarize what we observed in the Tohoku forearc region by means of GPS-Acoustic (GPS/A) seafloor geodetic survey and ocean bottom pressure (OBP) monitoring. Prior to the occurrence of the Tohoku-Oki earthquake, GPS/A time series showed that co- and postseismic deformation associated with the 2005 thrust earthquake (M 7.2) were followed by restoration of interplate coupling. At the occurrence of the M-9 mainshock, huge horizontal displacements were observed and those observations are regarded as the strong evidence of extremely large coseismic slip near the trench axis. Continuous OBP data detected temporal change of vertical seafloor movement associated with both the mainshock and the largest foreshock. The OBP data between the foreshock and the mainshock can be explained by assuming that aseismic afterslip of the foreshock propagated from near the foreshock hypocenter toward the mainshock hypocenter. The OBP data suggest that the afterslip distribution was very heterogeneous; substantial slip occurred on the plate interface downdip of the hypocenters and along the trench axis, whereas there was only minor slip around the two hypocenters. Horizontal displacement vectors delineated by recent GPS/A campaigns are also strongly variable in space, suggesting heterogeneous afterslip distribution.

Status of the Ocean Bottom Seismology Component of the Cascadia Initiative

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The Cascadia Initiative (CI) is an onshore/offshore seismic and geodetic experiment that takes advantage of an Amphibious Array to study questions ranging from megathrust earthquakes to volcanic arc structure to the formation, deformation and hydration of the Juan de Fuca and Gorda plates. This diverse set of objectives are all components of understanding the overall subduction zone system and require an array that provides high quality data that crosses the shoreline and encompasses relevant plate boundaries. In October 2010, an open community workshop was convened in Portland, Oregon that produced a series of recommendations to maximize the scientific return of the CI and to develop deployment plans for the offshore component of the experiment. The NSF Cascadia Initiative Workshop Report[1] presents the scientific objectives of the CI, the resources involved and the community-defined ocean bottom seismometer (OBS) deployment plan. Over its planned 4-year data acquisition period, the offshore portion of the Cascadia Initiative will involve the deployment and recovery of ~280 OBSs at ~160 different sites and a total of about 14 cruises. In addition, the 2010 CI workshop envisioned a significant education and outreach component that would be integrated into the operational plans. The Cascadia Initiative Expedition Team (CIET) is a group of scientists who are leading the seagoing expeditions to deploy and recover OBSs and are developing related Education and Outreach modules. The CIET is knowledgeable about the science and operational objectives of the CI, includes individuals with chief scientist experience, ones who have not yet been to sea and representatives from both the EAR and OCE communities. It is anticipated that there will be berths for students, post-docs and other scientists to participate in either deployment or recovery legs, thus providing the seismological community with opportunities to gain valuable experience in planning and carrying out an OBS experiment. The CIET maintains a web site for the community where information regarding CI expeditions is provided[2]. The CIET presentation will report on the 2011 field season, ongoing E&O efforts and the schedule for OBS operations in 2012.

[1] http://www.oceanleadership.org/2010/nsf-cascadia-initiative-workshop/
[2] http://pages.uoregon.edu/drt/CIET/

NEPTUNE Canada Update

Martin Scherwath

NEPTUNE Canada regional cabled ocean network, located in the Northeast Pacific, is part of the Ocean Networks Canada Observatory. This network provides online access for the international research community to conduct ocean-based experiments. This subsea infrastructure, linked by an 813 km cabled network off the coast of Vancouver Island, enables scientists and the general public a unique way of monitoring the ocean environment. Data are transmitted via high-speed fiber optic communications from the seafloor to a data management and archiving system at the University of Victoria.
The network consists of five instrumented nodes, one near shore, two on the continental slope of which one provides access to the shelf, one on the abyssal plane, and the furthest site out on the Endeavour segment of the Juan de Fuca Ridge. An additional node site that has not yet been made active is a sedimented spreading ridge.

Seismological, tectonic experiments include broadband seismometers and bottom pressure recorders (BPRs) installed at all active nodes except Folger (although Endeavour's broadband seismometer is not yet installed), with future extension planned to expand across the Explorer and Pacific plates as well as the installation of arrays of short-period seismometer and BPRs, furthermore existing boreholes with Circulation Obviation Retrofit Kit (CORK), one of which is currently connected and one ready for connection plus several planned to be connected in the future, and finally a seafloor compliance apparatus that includes a gravimeter, originally installed at the continental slope and currently to be moved to Endeavour.

One new geodesy project is now funded, with Woods Hole Oceanographic Institution's Jeff McGuire and John Collins as lead principal investigators, entitled "Understanding of the upcoming magnitude 9 Cascadia earthquake before it happens." This $1 mio Keck funded project plans to install a tilt meter in the continental slope CORK hole IODP 1363A in addition to an array of eight absolute pressure gauges distributed between the continental slop and the deformation front.

Potential contributions of Seafloor Geodesy to understanding slip behavior along the Cascadia Subduction Zone

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We propose an experiment to measure crustal deformation along Cascadia that crosses the entire region of a subduction zone from the incoming plate, the offshore continental slope and the sub-aerial continent (See Figure). There are two primary objectives to address with seafloor geodetic monitoring of Cascadia. What is the stick-slip behavior along the subduction thrust fault from the deformation front toward the coast where land geodetic data are controlling? Where is this offshore behavior located? Generally there are three possibilities. Stable sliding could occur from the deformation front to landward, i.e., no stick behavior and no transfer of elastic strain to the upper plate. This has a low probability as elastic strain is observed onshore along Cascadia, except at approximately 44°40′ where *[Burgette et al., 2009]* observe no significant uplift along a leveling line and note that no stick or locking is required on the thrust fault to fit their data.

The second possibility is reported in most of the published models *[Fluck et al., 1997; Wang et al., 2003; McCaffrey et al., 2007; Burgette et al., 2009]*. They assume stick behavior from the deformation front to some distance landward where it decays linearly or exponentially to completely stable sliding. Land geodetic data are too far from the deformation front to resolve whether or not stick starts at the front. Likewise, though land geodetic data are best fit with a transition from fully stick or locked to a decay and ultimately fully stable sliding, this boundary occurs offshore and is not strongly resolved leading to variability among the published models. Seafloor geodetic data located directly above the thrust fault where the changes in slip behavior occur should be able to resolve more strongly their magnitude and location.

The third possibility is a variation of the second where at the toe material is assumed to require some time and space to consolidate before supporting stick-like behavior. The situation is a subtle one because even though the material at the toe may not be under elastic strain it most likely moves with the material that is just downdip and locked. *Wang [2007]* has shown three scenarios. *Gagnon et al., [2005]* observed the toe offshore Lima Peru contracting significantly. This suggests it is reasonable to conclude the toe is not stationary with respect to the upper plate, but that generally it must move either under elastic strain or simply kinematically with the material downdip. Though the difference is small between frictionless and locked it could be detected with sufficient duration of seafloor geodetic monitoring. This would address the question directly as to the state of stick slip behavior out near the front as noted by *[Avouac, 2011]*.

An additional target for seafloor geodesy is measuring any interseismic elastic deformation of the incoming plate and what role this may have in understanding the stick slip behavior on the thrust fault near the deformation front. This topic has received scant attention to date primarily due to a lack of observations. There are two recent examples, however, that suggest that some amount of the elastic strain due to convergence is accumulated in the incoming plate. *Lay et al. [2009]* observed in the Kuril Islands a subduction thrust fault earthquake in 2006 followed by a normal fault earthquake in 2007 in the incoming plate. They suggest that about half of the interseismic strain accumulation was accommodated elastically within the incoming plate. *Chadwell [2007]* reported an observation with GPS-Acoustics at 44°40´ offshore central Oregon that is about half the expected long-term rate based on the geomagnetic anomaly reconstructions. A likely interpretation is that a significant amount of the convergent motion is accumulated as elastic strain in the plate offshore. Interestingly, this would be consistent with *Burgette et al., [2009]* finding that no stick (or locking) is required to fit the leveling data at this same latitude along the CSZ.

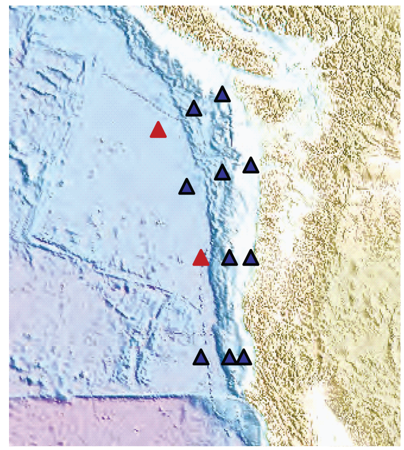

Figure 5: Notional array seafloor array (black triangles). Red existing, but presently inoperable GPS-A sites that could be reactiviated.

Geodetic arrays in place before a subduction thrust earthquake provide more direct measurements of slope response than relying on land geodetic data alone. This was first demonstrated by *Matsumoto et al. [2006]* offshore Japan and of course most recently following the Tohoku-Oki Earthquake where 24 m was observed at one GPS-A site and 31 at another *[Sato et al., 2011; Kido et al., 2011].* These measurements on the sea floor along with modeling of tsunami waves passing over deep sea pressure sensors imply 40-50 m displacement on the thrust fault. Early result based solely on land geodetic data estimated only about 25 m of shift along the thrust fault. The direct observation of the co-seismic displacement is unprecedented. However, the more important contribution from seafloor geodesy may be measurements of interseismic strains in the slope and incoming plate and using these observations to map the behavior of stick-slip for estimating more precisely the rupture potential. Figure shows a notional design of a seafloor geodetic array for Cascadia to be further refined with community input.

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Seafloor Geodesy at Axial Seamount

Bill Chadwick, Oregon State University/NOAA

We have used pressure sensors to detect vertical displacements of the seafloor at Axial Seamount, an active submarine volcano on the Juan de Fuca Ridge in the NE Pacific. Continuously recording bottom pressure recorders (BPRs, similar to the DART tsunami detection systems operated by NOAA, but without the surface buoy for realtime communication) can detect sudden, short-term seafloor displacements that last seconds to days. At Axial, this includes signals from dike intrusions and deflation events during intrusions or eruptions. In Cascadia, such short-term deformation signals might include co-seismic displacements on the overriding plate that are important for seismic source-modeling (like the results recently published from the 2011 Japan earthquake by Ito et al. [2011] in GRL). BPRs can be deployed as autonomous moorings for up to several years at a time, or can be connected to a cable (for example, on the planned OOI/RSN cabled observatory with a node at Axial Seamount). However, BPRs typically have long-term drift that can amount to up to 1 m/yr.

To get around this problem and to measure gradual long-term volcanic inflation at Axial Seamount, we make ROV-based campaign-style pressure measurements at an array of seafloor benchmarks with a mobile pressure recorder (MPR). This method gives accurate relative depth measurements with a repeatability of about 1 cm/yr, but requires that there be a reference station that is assumed to be stable as part of the measurement array (which works well for focused volcano deformation, but would be more limiting for trying to measure regional deformation in Cascadia). At Axial, the MPR measurements are made every 1-3 years, during one 2-3 day ROV dive, at an array of 6 benchmarks spanning ~10 km, and have documented inflation rates of 5-15 cm/yr. At Cascadia, long-term gradual deformation signals of interest would include inter-seismic deformation of the continental margin, which would be important for modeling the extent of the locked zone. However, our MPR method would probably have to be modified for use in Cascadia, because of its limitations of: (1) only giving depth differences relative to a reference station, and (2) the limited distances that can be covered during one ROV dive. For Cascadia, modified methods for long-term geodetic monitoring might include: (1) MPR measurements at a more wide-spread array of benchmarks during multiple ROV dives (this would relax the spatial restriction, but would introduce more measurement error due to hysteresis), (2) use of absolute pressure sensors (for example, as developed by Mark Zumberge), or (3) GPS-acoustic ranging (for example, as developed by Dave Chadwell). All of these alternatives would be more expensive than the methods we use at Axial Seamount.

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Pressure, Gravity and Optical Strain

Mark Zumberge

Self Calibrating Pressure Recorder

One method to detect vertical crustal deformation of the seafloor is to monitor changes in the ambient seawater pressure, whose value is governed primarily by depth. Modern pressure sensors based on quartz strain gauge technology can detect the pressure shift associated with subsidence or uplift of the seafloor by as little as 1 cm. Such signals can be caused by tectonic or volcanic activity, or by hydrocarbon production from an offshore reservoir. However, most gauges undergo a slow drift having unpredictable sign and magnitude, which can be misinterpreted as real seafloor height change. To circumvent this problem, we have developed an instrument that calibrates the pressure gauges in place on the seafloor. In this autonomous system, a pair of quartz pressure gauges recording ambient seawater pressure are periodically connected to a piston gauge calibrator. In a 104 day test in 664 m of water off the California coast, a precision of about 1 cm in depth variation was achieved after removal of drift determined from calibrations occurring for 20 minutes every ten days.

Seafloor Gravity and Pressure

Changes with gravity over time have proven to be a valuable means to infer subsurface density changes associated with tectonic processes as well as the production from oil and natural gas reservoirs. Such inferences allow the monitoring of moving fluid fronts underground. Our group began making time-lapse seafloor gravity and pressure measurements in 1998 in collaboration with the Norwegian oil company Statoil. To date we have surveyed six different fields offshore Norway, making with repeated surveys at all of the them to reveal time-lapse changes. We incorporated a land gravity sensor into a remotely operated seafloor housing. Three such relative gravity sensors mounted in a single frame are carried by a Remotely Operated Vehicle (ROV) to concrete benchmarks permanently placed on the seafloor. Reference benchmarks sited outside the survey region are assumed to provide stable fiducial points. Typical surveys last a few days to a few weeks and cover 8 to 80 benchmarks with multiple observations of each. In our recent surveys we have been achieving 3 μGal repeatability in gravity and about 5 mm in benchmark depth (deduced from simultaneously recorded ambient seawater pressure).

Seafloor Optical Fiber Strain Sensor

We are developing a new type of seafloor strainmeter that will have sensitivity much higher than has been available previously for seafloor use. We plan to install the sensor on the seafloor and establish its noise floor, response, and sensitivity by observing the solid Earth strain tides, which have an amplitude of approximately 50 nanostrain. Many scientific targets, including slow earthquakes (episodic tremor and slip), volcanic inflation and deflation, mid-plate strain signals, spreading center events, and possible seafloor slide precursors, can be addressed by successfully developing this instrument.

Over the past several years, a sensor and deployment system called the Fiber Optic Seafloor Strainmeter have been developed. This consists of an optical fiber cable stretched between two anchors on the seafloor – an electro-optic system on one of them periodically measures the optical length of the stretched cable. As the Earth strains, so does the cable and its optical length. Previous versions had a displacement precision of around 1 mm (over a length ranging up to 1 km). A new optical scheme has been identified that improves the sensitivity by at least three orders of magnitude. The new seafloor strainmeter design is capable of continuously monitoring strains with a sensitivity of about 1 nanostrain.

BP (formerly British Petroleum), an international oil company interested in developing new technologies in marine sciences useful to the oil industry, provided funding to develop the technology and a system to deploy the sensor cable on the seafloor. In earlier versions of the sensor, the cable remained exposed, subject to damage from debris and noise from temperature and current fluctuations. The new deployment system, which has been tested but needs modification to be successful, allows the sensor cable to be buried 15 to 30 cm below the sediment. Initial tests at sea with the new deployment sled were successful up to the point at which the second anchor in the system is deployed. A problem in the current release mechanism can cause the sensor cable to break. We have a new plan to eliminate the need for automatic release of the critically sited second anchor and perform that task with an ROV.

Optical Tiltmeter

A new technology has been developed and tested that uses interferometry in place of the traditional electronic displacement transducer to measure the motion of an inertial mass. This technology offers significant advantages over the conventional feedback tiltmeters and seismometers in wide use today. These advantages include:

- The sensor is a linear, high-resolution digital displacement detector, which measures displacement referenced to the wavelength of the laser light and provides a 30-bit resolution digital output without the need for a high-resolution analog-digital converter;
- The bandwidth and resolution are sufficient to resolve the Global Seismic Network (GSN) low noise model from DC to > 15 Hz with a dynamic range sufficient to record the largest teleseisms and most regional and local earthquakes, as well as tidal tilt records;
- Unlike standard feedback seismometers and tiltmeters whose response and calibration are dependent upon numerous electronic and mechanical components, the calibration and response of sensors utilizing the new technology are simple using only three free parameters that can be determined at any time through examination of the data.

Tilt Measurements: Data, instruments, and limitations

Andrew Newman
Georgia Institute of Technology

Tilt meters measure the rotation usually along two horizontally oriented axes, to obtain a local measurement equivalent to the spatial derivative of vertical deformation. The tool is widely used both in volcano monitoring and in industry for the observation of deformation associated with fluid extractions or slope stability. Tilt signals associated with long-term strain accumulation along the subduction interface are expected to yield rotations of only a few microradians/yr, focused primarily at transitions in locking. Most modern instruments use a pair of spirit levels with electrode sensors, known as short-baseline tiltmeters, to identify changes in rotation as small as 0.01 microradians, theoretically sufficient for interseismic studies. Unfortunately, these measurements are only valuable for short period observations such as rapid volcanic inflation or coseismic deformation, as these tools have significant drift that can be as high as 5 microradian/day. Tests performed along the seafloor with long-baseline telemeters that measure changes in hydraulic head have proven difficult, yielding similar drift issues as current short-baseline instruments.

Using Micro-machine technologies, MEMS accelerometer-based tiltmeters have recently been developed by a number of companies for use in industry applications. These new instruments are attractive because the fundamentally measure the orientation of the earth's gravitational pull, and should theoretically not suffer from instrument drift. However, published specifications for these instruments report sensitivities that are currently about an order of magnitude too high for long-term interseismic studies. Though collaborations with such companies, it may be possible to significantly increase the sensitivity, and perform detailed tests to establish the true drift of these instruments.

Finally, the real value of tilt measurements, assuming drift problems have been resolved, comes from spatially dense observations. Making such measurements using sensor network designs has the potential for yielding full-field vertical signals once integrated across the network (assuming instruments extend beyond the deformation front).

Formation pressure as a proxy for volumetric strain: ODP/IODP CORK borehole monitoring across the Juan de Fuca plate and Cascadia subduction zone

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Keir Becker, Rosenstiel School of Marine and Atmospheric Science, University of Miami

The primary goals of early ODP "CORK" hydrologic observatory efforts were to determine the natural thermal state and driving forces for fluid flow through oceanic crust and subduction-zone accretionary prisms, and to obtain pristine pore-water samples in the absence of drilling and open-hole perturbations. Some installations have been operational continuously for over 16 years, and the long records have provided a variety of additional "fringe benefits". For example, the formation response to variable loads imposed on the seafloor by seasonal ocean circulation, tides, tsunamis, and wind-generated ocean waves have provided constraints on elastic and hydrologic properties (compressibility, shear modulus, permeability, storage compressibility), with inferred properties being representative at a formation scale, i.e., one that is much greater than that characterized by standard borehole or laboratory measurements.

Another originally unanticipated application of CORK hydrologic monitoring has been the use of formation pressure as a proxy for crustal strain. Pressure changes have been observed at the times of many discrete episodes of seafloor spreading and fault slip along the Juan de Fuca Ridge and adjacent transform faults, and at the times of seismogenic and aseismic slip along the Nankai, Mariana, and Middle America (Costa Rica) subduction zones (e.g., Fig. 1). In each case, quantitative estimates of strain have been made with the elastic properties estimated from seafloor loading response. Post-slip pressure transients have also been observed, as well as secular interseismic strain accumulation at Costa Rica and Nankai.

Various improvements to CORK hardware since the first deployments in 1991 now provide a means for monitoring pressure at multiple isolated formation levels, and for including other sensors such as seismometers and strain meters. Improvements to pressure monitoring electronics allow high resolution (e.g., 10 ppb full-scale pressure, or 0.4 Pa at 4000 m) reaching up to seismic frequencies (1 Hz). The combination of this measurement capability and the sensitivity of pressure to strain in low-porosity (40%) sediment and igneous oceanic crust - typically 5 kPa/μstrain - makes this observational technique viable and valuable for geodetic studies. A total of ten borehole observatories are currently operational in the northern Juan de Fuca plate region. One has been connected to the NEPTUNE Canada cable network for real-time monitoring since 2009, and several others are scheduled for connection in the next few years. Unfortunately, only one has been established at the Cascadia prism, so the work of establishing a transect for subduction zone strain monitoring has only begun.

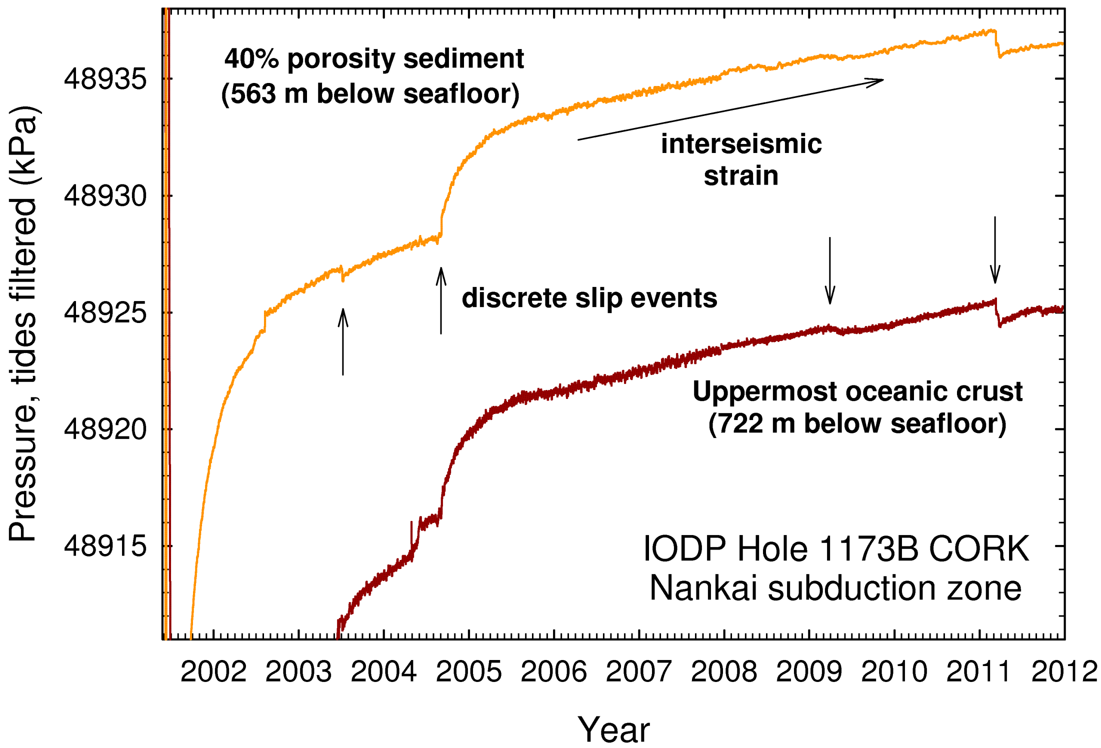

Fig. 1. Pressures at two formation levels measured in IODP Hole 1173B in the subducting Philippine Sea plate, Nankai subduction zone. Complementary signals are observed in the accretionary prism 13 km landward in Hole 808I (after Davis, Becker, Wang, and Kinoshita, Earth Planets Space, 61, 649-657, 2009).

The Need for underwater Observations

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Though 90% of plate boundaries are underwater, the geodetic community remains focused primarily on land because of the relative ease, and low cost of making such measurements. The unbalanced observations of events such as the Tohoku-Oki earthquake highlights that though dense on land GPS is invaluable for evaluating the details of locking or release along the deeper sections of the seismogenic interface, such data are inadequate for constraining the build-up or release in the near-trench region that is responsible for most damaging tsunami behavior. In addition to better constraining both interseismic and coseismic strain from major underwater, and primarily subduction zone earthquakes, measurement of modern sea floor displacements are necessary for constraining plate motions of some plates that are entirely underwater, including the Juan de Fuca, and internally deforming Gorda sea plates. Such measurements are necessary for adequately constraining the long-term loading forces that drive major earthquakes.

As a community, we should be working to not only make much more expansive measurements of the seafloor using current technologies, including GPS-Acoustic, pressure, and tilt, but should be working to advance our technologies. Technological focus should be on both driving down the cost of manufacturing, deploying and maintaining instrumentation, but also to be improving instrument sensitivities and removing dreaded long-term drift signals that destroy our ability to make valuable interseismic locking assessments. We need to work with our local government as well as international organizations, including the World Bank, to fund workshops to focus our science needs and establish our true technological and possibly financial limitations. Then funding is necessary for the development and deployment of new tools as mentioned above. Finally funding is necessary to perform adequate quality research on the observed signals in order to truly constrain the kinematic environment along the majority of our yet, unmeasured plate boundaries.