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Supporting Online Material for

The Cascadia Initiative: A Sea Change In Seismological Studies of Subduction Zones

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Science Objectives of the Cascadia Initiative

The science objectives of the Cascadia Initiative (CI) are wide-ranging and were developed by a National Science Foundation (NSF)-supported, community workshop convened in Portland, Oregon, in October 2010 (http://www.oceanleadership.org/wp-content/uploads/2010/05/CI_Workshop-Report_Final.pdf).

THRUST INTERFACE AND FOREARC PRISM

Observations of slow aseismic slip and associated seismic tremor at subduction zones are becoming more common as instrumentation capable of recording these phenomena increases (see Shelly et al., 2006; Brudzinski and Allen, 2007; Schwartz and Rokosky, 2007; Shelly et al., 2007; Wech and Creager, 2009; Schmidt and Gao, 2010; Wech et al., 2010; Dragert and Wang, 2011). A picture of how slow slip and tremor are distributed and evolve in space and time around the globe is beginning to emerge, albeit with highly variable resolution. Most observations of slow slip and tremor come from land-based recordings, resulting in location at the down-dip edge of the seismogenic zone that lies directly below instrument coverage. One important question is whether this phenomenon occurs as frequently at the up-dip edge. Their mechanism of slow slip and tremor is poorly known, but it is likely related to the frictional transition from stick-slip to stable sliding, which occurs at both the up- and down-dip edges of the seismogenic zone.

In Cascadia, a distinct band of seismic tremor is located beneath the Coast Ranges (see Brudzinski and Allen, 2007; Wech and Creager, 2009; Wech et al., 2010). Because of the repeated and quasi-periodic occurrence of slow slip and tremor, it has been termed episodic tremor and slip, or ETS, in Cascadia. The CI ocean bottom seismometer (OBS) deployment has been in the water during several episodes of onshore tremor, although detecting signals from these events is difficult. Efforts are underway to determine whether a second band of tremor, low-frequency earthquakes, or slow slip, is occurring near the deformation front, as has been reported from Japan (Obara and Ito, 2005) and Costa Rica (Brown et al., 2005; Walter et al., 2011). If slow slip were occurring in this region in Cascadia, it would help constrain the mechanical response of the outer accretionary prism in a large earthquake and thus contribute to more accurate tsunami simulations.

The Cascadia subduction zone is segmented in many ways, including forearc basin structure (Wells, 2003), location and recurrence of ETS events (Brudzinski and Allen, 2007), occurrence of deep focus earthquakes (McCrory et al., 2012), and rupture zones of paleo-earthquakes (Goldfinger et al., 2008). There is evidence that these segmentation modes coincide, but it is unclear what process produces the segmentation. It is likely that detailed information on crust and mantle structure will be important to understanding this along-strike variability. Comparison of the characteristics of such segmentation with segmentation histories of other subduction zones for which the relationship between slip in large earthquakes and geological segmentation patterns is being determined may help refine development of scenarios for a future Cascadia megathrust earthquake.

The Cascadia OBS deployment will help constrain the spatial variation in both physical properties and the spectrum of deformation events all the way from the deformation front down to the ETS region. These improved constraints are crucial for physical models of the thrust zone and hence for refining estimates of both seismic and tsunami hazard in Cascadia.

SUBDUCTION ZONE STRUCTURE AND DYNAMICS

The CI provides a unique opportunity to study the dynamics of subduction in the context of the structure and evolution of the oceanic plates and the forces acting across the plates.

Subduction zones control the flux of water and other volatiles from the hydrosphere into the mantle, and the release of water in the subduction zone from hydrated minerals is linked to earthquakes and arc volcanism. Hydration of the oceanic plate occurs as a result of hydrothermal circulation near the ridge axis, within the plate interior, and where the plate bends near the trench. There is considerable uncertainty in the water input to subduction zones because the extent of mantle serpentinization is poorly constrained. Quartz veining in the accretionary prism above the slab leads to a change from velocity strengthening to velocity weakening rheology that can support large earthquakes. Some studies suggest extensive hydrous alteration and serpentinization of the mantle forearc, indicating that much water is released at shallow depths, but further work is needed. As the slab descends, thermal models predict that dehydration reactions will occur at shallower depths in Cascadia than in most other subduction zones where the slabs are older (Wada and Wang, 2009; Hyndman, 2013). This shallow fluid release may play an important role in creating favorable conditions for ETS and other slow slip modes (Audet et al., 2008; Wada et al., 2008). Hydration has a strong effect on seismic velocities, so seismic imaging has great potential for constraining the effects of water transport.

Several studies indicate that the structure of the underthrusting oceanic plate can influence subduction zone segmentation. The process of crustal creation segments oceanic plates. It has been postulated that segment boundaries in the subduction zone coincide with the position of subducted pseudofaults that are formed by propagating rifts and/or very large overlapping spreading centers on the Juan de Fuca and Gorda Ridges. Seamounts and fault lines formed by the breakup of the plate as it approaches the subduction zone are other potential sources of discontinuities within the subducting plate. In Cascadia, along-strike variations in sediment thickness and basement temperatures may lead to systematic changes in the recurrence interval of large earthquakes.

JUAN DE FUCA PLATE AND PLATE BOUNDARIES

Improved understanding of the loading of the Juan de Fuca plate is important to the modeling of stress and coupling at the Cascadia subduction zone. The stresses acting across the Juan de Fuca Plate result from a combination of ridge push, slab pull, viscous drag from the mantle, loading of the plate from mantle buoyancy, and transfer of stresses across plate boundaries (Wang et al., 1997; Govers and Meijer, 2001). All of these sources of stress will be estimated by combining seismic imaging and observations of seismicity and deformation along the plate boundaries and within the plate interior.

Plate-scale seismic imaging will also help address longstanding questions about the role of mantle flow in the Juan de Fuca-Cascadia system. The Juan de Fuca and Gorda Ridges have similar spreading rates but very different morphologies that are attributed to the interaction of the Juan de Fuca Ridge with the Cobb hotspot and other melting anomalies (Davis and Karsten, 1986; Hooft and Detrick, 1995). The mantle expression of these interactions is unknown, but it has been postulated that the Cobb hotspot is linked to anomalously slow velocities in the mantle indicative of buoyant mantle beneath the Juan de Fuca Plate. Another question of interest—one that impacts dynamic models of plate stresses—is the depth to which mantle flow is coupled to the motion of oceanic plates; alternate models predict that this is related either to the relatively shallow depth of the thermal boundary layer or to the depth at which the onset of melting beneath the ridge extracts water from the mantle rock and increases the viscosity (Morgan et al., 1995; Hirth and Kohlstedt, 1996). Because oceanic plates transport material from ridges to trenches, they must be underlain, most likely in the asthenosphere, by a counter flow that preserves mass balance (Morgan et al., 2007). The Juan de Fuca Plate may be too small for such flow to be well developed, but dynamic plate stresses are likely affected by the westward motion of the North American Plate caused by trench rollback, mantle flow around the ends of the subduction zone, and/or the interaction of the Cobb hotspot with the asthenosphere (Humphreys and Coblentz, 2007). Finally, the segmentation of the subduction zone may be linked to the deep structure and flow of the mantle beneath the subducting plate.

In addition to constraining local and regional stresses, observations of regional seismicity will contribute to a wide range of studies. The maximum focal depths of earthquakes will reflect the thermal structure of the Juan de Fuca Plate (McKenzie et al., 2005). The earthquake records from the Blanco and Mendocino transforms can be used to study slow earthquakes, and the experiment may be long enough to observe the earthquake cycle on smaller fault patches (Boettcher and McGuire, 2009). Offshore seismic observations of earthquakes are essential for understanding the origin of intraplate seismicity within the Juan de Fuca Plate and the nature of the deformation of the Gorda Plate (Chaytor et al., 2004) and its linkages to mantle flow and subduction earthquakes. Finally, there is substantial evidence of a temporal correlation of seismic activity within the Juan de Fuca Plate and earthquakes at significant distances (Fox and Dziak, 1999). The plate-scale observations of seismicity will allow a systematic study of these phenomena.

OFFSHORE TEMPORARY SEISMIC ARRAYS

A number of seismometers that are independent of the CI have been temporarily deployed in recent years or simultaneously with the CI. These instruments provide additional data for a variety of structural studies that can be integrated with CI data.

Central Oregon Locked Zone Array (COLZA)

COLZA was an amphibious network operated by Oregon State University (OSU) to monitor seismic activity across a segment of the Cascadia forearc from the deformation front landward of the expected locked zone. The network ran from September 2007 to June 2009 and was composed of 16 ocean bottom and six onshore stations in an array with ~ 30 km between instruments (Williams et al., 2011). The array covered from 44°–45°N and extended from the deformation front to the eastern edge of the Oregon Coast Range. Onshore data are publicly available through the IRIS Data Management Center (DMC), and OBS data is also available there (http://www.iris.edu/dms/nodes/dmc/data).

2010 SeaJade Experiment

SeaJade is an experiment that measures the level of seismicity offshore of Vancouver Island to better understand the extent of locking on the mega-thrust subduction interface. Scientists from the Pacific Geoscience Center (PGC) of the Geological Survey of Canada, University of Victoria, Japan Marine Science and Technology Center (JAMSTEC), and Woods Hole Oceanographic Institution (WHOI) conducted the experiment. Its initial phase consisted of 35 JAMSTEC short-period OBSs, two Ocean Networks Canada broadband OBSs, and 10 WHOI broadband OBSs. The WHOI data are available through the IRIS DMC and the JAMSTEC data through JAMSTEC's online data center (http://www.godac.jamstec.go.jp/dataportal/index_eng.html).

2012–2014 Blanco Transform and Gorda Plate Experiment

This OBS experiment, led by Oregon State University and the University of Florida, is an NSF-funded project with the aim of studying plate boundary evolution and physics at an oceanic transform fault system and the internal deformation of the Gorda Plate. The experiment includes deployment of 55 OBSs of which 30 are wide-band (providing useful data to ~ 100 s) and 25 are short-period instruments, all equipped with differential pressure gauges. The experiment began in August 2012, and the PIs have agreed to make data from many OBS sites available to allow full integration into the CI data set.

Active-Source Seismic Experiments

Contemporaneous with the CI, two active-source seismic experiments in 2012 collected transects that provide high-resolution images of the crust and uppermost mantle that complement the CI data and science objectives.

2012 Ridge 2 Trench Experiment

This NSF-funded experiment focused on the evolution of the Juan de Fuca Plate from the ridge to the trench. WHOI and Lamont-Doherty Earth Observatory (LDEO) scientists conducted a two-dimensional multichannel seismic (MCS) and active-source OBS experiment to characterize the evolution of the crust and shallow mantle along complete transects of the Juan de Fuca Plate, from formation at the ridge, through alteration and hydration within the plate interior, to subduction at the Cascadia margin. This was a two-ship experiment (R/V *Langseth* and R/V *Oceanus*) that used an 8 km long MCS streamer and 41 short-period OBSs. OSU and LDEO also deployed linear and two-dimensional arrays of seismometers onshore to record the offshore shots.

2012 COAST Experiment

The Cascadia Open-Access Seismic Transects (COAST) was an offshore and onshore active-source seismic program to address the location, physical state, fluid budget, and associated methane systems of the subducting plate boundary and overlying crust. NSF-funded scientists from the University of Wyoming, the University of Nevada, Oregon State University, the University of Oklahoma, and the University of Washington acquired a grid of two-dimensional MCS profiles in the high-priority GeoPRISMS corridor off Grays Harbor, WA. This was an open-participation, open-access cruise, with an organized shipboard education and training program as well as immediate, full release to the community of all geophysical data.

REFERENCES

Audet, P., M.G. Bostock, J.P. Mercier, and J.F. Cassidy. 2008. Morphology of the Explorer-Juan de Fuca slab edge in northern Cascadia: Imaging plate capture at a ridge-trench-transform triple junction. *Geology* 36:895–898, http://dx.doi.org/10.1130/G25356A.1.

Boettcher, M.S., and J.J. McGuire. 2009. Scaling relations for seismic cycles on mid-ocean ridge transform faults. *Geophysical Research Letters* 36, L21301, http://dx.doi.org/10.1029/2009GL040115.

Brown, K.M., M.D. Tryon, H.R. DeShon, L.M. Dorman, and S.Y. Schwartz. 2005. Correlated transient fluid pulsing and seismic tremor in the Costa Rica subduction zone. *Earth and Planetary Science Letters* 238:189–203, http://dx.doi.org/10.1016/j.epsl.2005.06.055.

Brudzinski, M.R., and R.M. Allen. 2007. Segmentation in episodic tremor and slip all along Cascadia. *Geology* 35:907–910, http://dx.doi.org/10.1130/G23740A.1.

Chaytor, J.D., C. Goldfinger, R.P. Dziak, and C.G. Fox. 2004. Active deformation of the Gorda plate: Constraining deformation models with new geophysical data. *Geology* 32:353–356, http://dx.doi.org/10.1130/G20178.2.

Davis, E.E., and J.L. Karsten. 1986. On the cause of the asymmetric distribution of seamounts about the Juan de Fuca ridge: Ridge-crest migration over a heterogeneous asthenosphere. *Earth and Planetary Science Letters* 79:385–396, http://dx.doi.org/10.1016/0012-821X(86)90194-9.

Dragert, H., and K. Wang. 2011. Temporal evolution of an episodic tremor and slip event along the northern Cascadia margin. *Journal of Geophysical Research* 116, B12406, http://dx.doi.org/10.1029/2011JB008609.

Fox, C.G., and R.P. Dziak. 1999. Internal deformation of the Gorda Plate observed by hydroacoustic monitoring. *Journal of Geophysical Research* 104(B8):17,603–17,615, http://dx.doi.org/10.1029/1999JB900104.

Goldfinger, C., K. Grijalva, R. Bürgmann, A.E. Morey, J.E. Johnson, C.H. Nelson, J. Gutiérrez-Pastor, A. Ericsson, E. Karabanov, J.D. Chaytor, and J. Patton. 2008. Late Holocene rupture of the northern San Andreas Fault and possible stress linkage to the Cascadia subduction zone. *Bulletin of the Seismological Society of America* 98(2):861–889, http://dx.doi.org/10.1785/0120060411.

Govers, R., and P.T. Meijer. 2001. On the dynamics of the Juan de Fuca Plate. *Earth and Planetary Science Letters* 189:115–131, http://dx.doi.org/10.1016/S0012-821X(01)00360-0.

Hirth, G., and D.L. Kohlstedt. 1996. Water in the oceanic upper mantle: Implications for rheology, melt extraction and the evolution of the lithosphere. *Earth and Planetary Science Letters* 144:93–108, http://dx.doi.org/10.1016/0012-821X(96)00154-9.

Hooft, E.E., and R.S. Detrick. 1995. Relationship between axial morphology, crustal thickness, and mantle temperature along the Juan de Fuca and Gorda Ridges. *Journal of Geophysical Research* 100(B11):22,499–22,508, http://dx.doi.org/10.1029/95JB02502.

Humphreys, E., and D. Coblentz. 2007. North American dynamics and western US tectonics. *Reviews of Geophysics* 45, RG3001, http://dx.doi.org/10.1029/2005RG000181.

Hyndman, R.D. 2013. Downdip landward limit of Cascadia great earthquake rupture. *Journal of Geophysical Research* 118:5,530–5,549, http://dx.doi.org/10.1002/jgrb.50390.

McCrory, P.A., J.L. Blair, F. Waldhauser, and D.H. Oppenheimer. 2012. Juan de Fuca slab geometry and its relation to Wadati-Benioff zone seismicity. *Journal of Geophysical Research* 117, B09306, http://dx.doi.org/10.1029/2012JB009407.

McKenzie, D., J. Jackson, and K. Priestley. 2005. Thermal structure of oceanic and continental lithosphere. *Earth and Planetary Science Letters* 233:337–349, http://dx.doi.org/10.1016/j.epsl.2005.02.005.

Morgan, J., J. Hasenclever, M. Hort, L. Rupke, and E. Parmentier. 2007. On subducting slab entrainment of buoyant asthenosphere. *Terra Nova* 19:167–173, http://dx.doi.org/10.1111/j.1365-3121.2007.00737.x.

Morgan, J.P., W.J. Morgan, Y.-S. Zhang, and W.H.F. Smith. 1995. Observational hints for a plume-fed, suboceanic asthenosphere and its role in mantle convection. *Journal of Geophysical Research* 100(B7):12,753–12,767, http://dx.doi.org/10.1029/95JB00041.

Obara, K., and Y. Ito. 2005. Very low frequency earthquakes excited by the 2004 off the Kii peninsula earthquakes: A dynamic deformation process in the large accretionary prism. *Earth Planets and Space* 57:321–326, http://www.terrapub.co.jp/journals/EPS/pdf/2005/5704/57040321.pdf.

Schmidt, D.A., and H. Gao. 2010. Source parameters and time-dependent slip distributions of slow slip events on the Cascadia subduction zone from 1998 to 2008. *Journal of Geophysical Research: Solid Earth* 115(B4), B00A18, http://dx.doi.org/10.1029/2008JB006045.

Schwartz, S.Y., and J.M. Rokosky. 2007. Slow slip events and seismic tremor at circum-Pacific subduction zones. *Reviews of Geophysics* 45, RG3004, http://dx.doi.org/10.1029/2006RG000208.

Shelly, D.R., G.C. Beroza, and S. Ide. 2007. Non-volcanic tremor and low-frequency earthquake swarms. *Nature* 446:305–307, http://dx.doi.org/10.1038/nature05666.

Shelly, D.R., G.C. Beroza, S. Ide, and S. Nakamula. 2006. Low-frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip. *Nature* 442:188–191, http://dx.doi.org/10.1038/nature04931.

Wada, I., and K. Wang. 2009. Common depth of slab-mantle decoupling: Reconciling diversity and uniformity of subduction zones. *Geochemistry, Geophysics, Geosystems* 10, Q10009, http://dx.doi.org/10.1029/2009GC002570.

Wada, I., K. Wang, J. He, and R.D. Hyndman. 2008. Weakening of the subduction interface and its effects on surface heat flow, slab dehydration, and mantle wedge serpentinization. *Journal of Geophysical Research* 113, B04402, http://dx.doi.org/10.1029/2007JB005190.

Walter, J.I., S.Y. Schwartz, J.M. Protti, and V. Gonzalez. 2011. Persistent tremor within the northern Costa Rica seismogenic zone. *Geophysical Research Letters* 38, L01307, http://dx.doi.org/10.1029/2010GL045586.

Wang, K., J. He, and E.E. Davis. 1997. Transform push, oblique subduction resistance, and intraplate stress of the Juan de Fuca Plate. *Journal of Geophysical Research* 102(B1):661–674, http://dx.doi.org/10.1029/96JB03114.

Wech, A.G., K.C. Creager, H. Houston, and J.E. Vidale. 2010. An earthquake-like magnitude-frequency distribution of slow slip in northern Cascadia. *Geophysical Research Letters* 37, L22310, http://dx.doi.org/10.1029/2010GL044881.

Wech, A.G., K.C. Creager, and T.I. Melbourne. 2009. Seismic and geodetic constraints on Cascadia slow slip. *Journal of Geophysical Research* 114, B10316, http://dx.doi.org/10.1029/2008JB006090.

Wells, R.E. 2003. Basin-centered asperities in great subduction zone earthquakes: A link between slip, subsidence, and subduction erosion? *Journal of Geophysical Research* 108, 2507, http://dx.doi.org/10.1029/2002JB002072.

Williams, M.C., A.M. Tréhu, and J. Braunmiller. 2011. Seismicity at the Cascadia plate boundary beneath the Oregon continental shelf. *Bulletin of the Seismological Society of America* 101:940–950, http://dx.doi.org/10.1785/0120100198.