A focused study of Cascadia upper-plate structure and its impact on subduction-zone segmentation

Megan Anderson[1], Paul Bedrosian[2], Richard Blakely[3], Brian Sherrod[4], and Ray Wells[3]
[1]Colorado College, Colorado Springs; [2]USGS, Denver; [3]USGS, Menlo Park; [4]USGS, Seattle

GeoPRISMS Science Plan Questions Addressed:
1) What governs the size, location, and frequency of great subduction zone earthquakes, and how is it related to the spatial and temporal variation of slip behavior observed along subduction faults? 2) How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?

Goal: Develop a 3-D structural map of upper-plate, upper crustal tectonic structures spanning an entire proposed subduction-zone segment.

Data infrastructure utilized/established: New aeromagnetic survey; existing LiDAR data; ongoing USGS trenching and geologic mapping studies; new targeted magnetotelluric (MT) and gravity transects; existing EarthScope/Amphibious Array seismic data and regional MT data.

Key investigation efforts: Analysis of new aeromagnetic data will help identify and extend newly-discovered and known faults within forearc and arc upper crust of SW Washington and NW Oregon, roughly between Grays Harbor and Tillamook. Supporting analysis of LiDAR data will define neotectonic activity. These efforts will target new MT, ground-magnetic, and gravity transects across structures of interest, constrained by existing geologic mapping and seismic data, all leading to detailed 2-D models across important forearc structures. Combining 2-D models and map view interpretations will lead us to a 3-D model of upper-crustal structure. We will compare our structural map to indicators of subduction interface segmentation (e.g. tremor density, free-air gravity, offshore structure) to determine the causal association of upper-plate structure and interface segmentation/variations.

The Project:
Segmentation of the Cascadia subduction zone interface appears to manifest in the distribution of seismicity and slow slip along the interface. This type of segmentation is a multifaceted target of interest for many reasons: it may bear on the length of rupture during megathrust earthquakes and hence the maximum magnitude of future great earthquakes, and it may bear on the geographic limits of ETS behavior during interseismic intervals. Many aspects likely control the spatio-temporal segmentation of slip along the subduction interface including (but not limited to) the spatial distribution of materials along the interface, changes in plate geometry and hence physical and thermal state of interface materials, temporal placement within the seismic cycle, migration of fluids through the subduction interface, and the location of preexisting weak (or strong) zones within the subducting and overriding plates. We are particularly interested in the upper plate and understanding its geologic and tectonic structure, its segmentation both normal and parallel to the trench, and how that structure affects the distribution of stress during and after megathrust earthquakes. The research community hypothesizes that segmentation of slip on the subduction interface is triggered or stalled by interactions with the overriding plate, but we cannot understand these relationships without a complete picture of structural segmentation of

the overriding plate. In Cascadia, trench-parallel structural heterogeneity of the upper plate is evident in data ranging from surface topography to deep geophysical imaging, all indicating that forearc strain is heterogeneous and accommodated in three dimensions: parallel to the trench, perpendicular to the trench, and down the dip of the subduction interface.

To address these issues, we propose a systematic geophysical investigation of the Cascadia forearc and arc across a complete subduction zone "segment" in western Washington and Oregon. This segment falls between two proposed boundaries for segmentation of the subduction interface (near Grays Harbor and Tillamook) as defined by spatio-temporal tremor distributions, free-air gravity data, and offshore basin structure after Wells et al. (2003; Figure 1). Internally, this segment is marked by features signifying that the overriding crust is broken by numerous faults, including the Doty fault and faults responsible for the Mt. St. Helens and West Rainier seismic zones (Figure 2). These features are identified by aligned seismicity, enhanced electrical conductivity, gravity and low-resolution aeromagnetic anomalies, and geologic mapping. Yet, little is understood about the deep structure of this segment or the connectivity of tectonic elements within it. We propose to integrate existing and new airborne magnetic, gravity, seismic, and MT data to produce structural models of the upper crust consistent with geologic mapping, LiDAR, and available subsurface information. Our overarching goal is to define forearc and arc heterogeneity in relation to a proposed Cascadia subduction-zone segment, and through this process determine the relationship between proposed predictors of subduction interface segmentation and concrete physical segmentation of the forearc upper crust. Lessons learned about what defines a segment in the absence of large, historical earthquakes will apply to segmentation elsewhere along the Cascadia subduction zone and at other subduction margins.

We will attempt to answer a number of specific questions about the structure of the forearc/arc and fault connectivity in the crust of SW Washington and NW Oregon using various geophysical methodologies: 1) The Doty fault is an important, trench-normal crustal structure arguably extending to Willapa Bay. Does the Doty fault extend offshore, and does it influence megathrust seismicity? If so, what are the causal reasons? 2) How laterally extensive are other faults within this segment, and what is the geometry of their deep structure? 3) How do faults and other tectonic features connect with each other on the surface and at depth, if at all? 4) Which faults exhibit neotectonic activity? 5) The Mt. St. Helens and West Rainier seismic zones bound crust of unique magnetic and electrical properties. What is the physical nature of this crustal block and does it influence arc seismicity and tremor distribution? 6) How does the spatial distribution of mapped faults and lineations compare to 'markers' of subduction zone segmentation (ETS distribution and recurrence intervals, heterogeneity in the gravity field, forearc rotation boundaries, along-strike changes in fluid release)?

New 3-D structural models of SW Washington and NW Oregon will help identify crustal faults that contribute their own seismic hazard, as well as influence subduction-interface events. Our project thus will inform two major geohazard concerns: subduction interface events and shallow crustal earthquakes. New aeromagnetic data (Figure 2) should be acquired and interpreted early in the GeoPRISMS process to define upper plate fault geometry within the forearc. This interpretation will facilitate early development of structural models that can serve as *a priori* constraints in geodetic models (e.g. McCaffrey et al., 2007), models derived from other newly acquired geophysical datasets (e.g. broadband seismic), and 3-D kinematic or dynamic models that test hypotheses for the interconnection between upper-plate structure and subduction interface segmentation.

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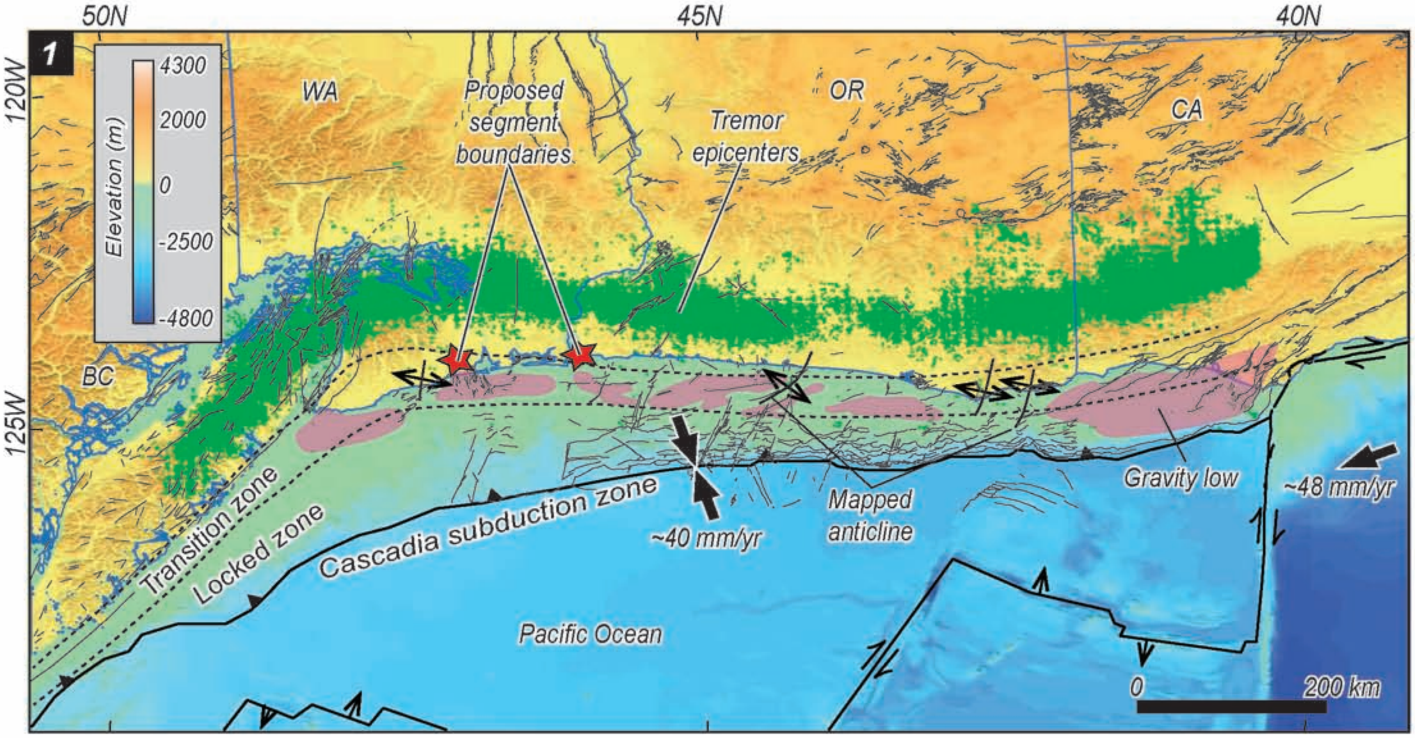
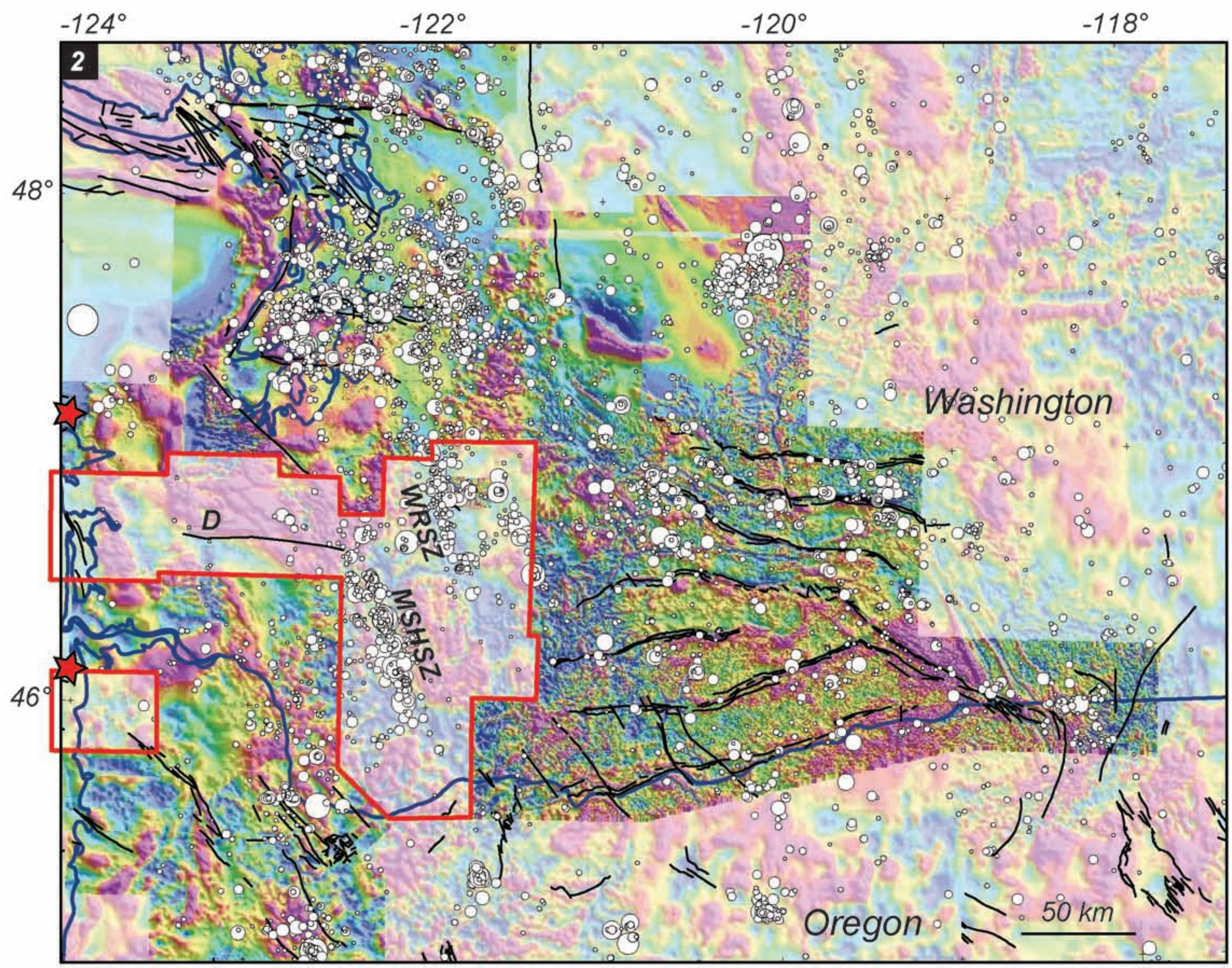
Figure Captions

Figure 1. Upper- and lower-plate structure and the distribution of episodic tremor. Green dots indicate episodic tremor epicenters (Pacific Northwest Seismic Network). Gray lines are Quaternary faults (USGS Quaternary Fault Database, digital geologic map of British Columbia, Geologic Survey of Canada). Offshore pink areas indicate gravity lows interpreted as forearc basins, possible indicators of greatest slip during past great earthquakes (Wells et al., 2003). Red stars show north-south limits of study area.

Figure 2. Magnetic anomalies, earthquakes, and quaternary faults of Washington and northern Oregon. Subdued rainbow colors are magnetic anomalies based on low-resolution airborne surveys older than 1995. Bright rainbow colors are high-resolution magnetic surveys acquired by the USGS since 1995. Warm colors indicate positive anomalies, cool colors are negative anomalies. Black lines, Quaternary faults (USGS Quaternary Fault Database). White circles, upper-plate earthquakes sized proportional to magnitude (Pacific Northwest Seismic Network). Red polygons, boundaries of proposed aeromagnetic survey. D, Doty fault; WRSZ, west Rainier seismic zone; MSHSZ, Mt. St. Helens seismic zone.



50N
45N
40N
120W
125W
1
4300
2000
0
-2500
-4800
Elevation (m)
WA
OR
CA
BC
Proposed segment boundaries
Tremor epicenters
Transition zone
Locked zone
Cascadia subduction zone
~40 mm/yr
Mapped anticline
Gravity low
~48 mm/yr
Pacific Ocean
0
200 km



-124°
-122°
-120°
-118°
48°
46°
2
Washington
Oregon
D
WRSZ
MSHSZ
50 km

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

C. David. Chadwell[1], Spahr C. Webb[2], Scott L. Nooner[2]

[1]*Scripps Institution of Oceanography, University of California San Diego*

[2]*Columbia University Lamont-Doherty Earth Observatory*

Emails: cchadwell@ucsd.edu, scw@ldeo.columbia, snooner@ldeo.columbia.edu

Proposed site: Cascadia Subduction Zone

Themes addressed: (GeoPRISMS [1]Draft Science Plan; [2]Draft Implementation Plan)

4.1[1] What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?

4.2[1] How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?

2.3.4.B[2] Cascadia Margin-Critical research efforts for GeoPRISMS studies: Seafloor Geodesy

Key existing and forthcoming data/infrastructure: 1) Moored-buoy for continuous GPS-Acoustic measurements of horizontal deformation and continuous seawater pressure measurements at the seafloor with a low-drift sensor and in-situ physical oceanographic measurements for sounds speed and density. 2) Autonomous sea-surface platforms for collecting campaign-style GPS-Acoustic data. 3) Seafloor benchmarks for long-term horizontal and vertical deformation measurements. 4) Earthscope, Plate Boundary Observatory, Ocean Observatories Initiative-Regional Scale Nodes (seafloor cable) and -Endurance Array (buoys), Cascadia Initiative Ocean Bottom Seismometer array. (See Poster for details).

Discussion:

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 (Figure 1). 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.

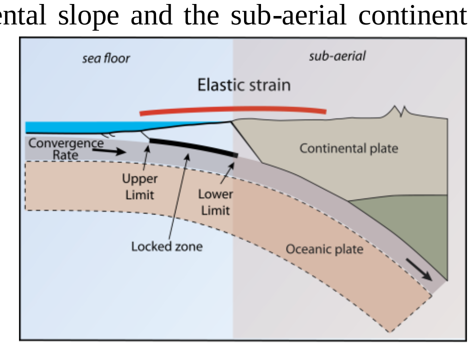


Figure 1: Subduction Profile showing offshore and onshore strain.

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 as shown in Figure 2. 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.

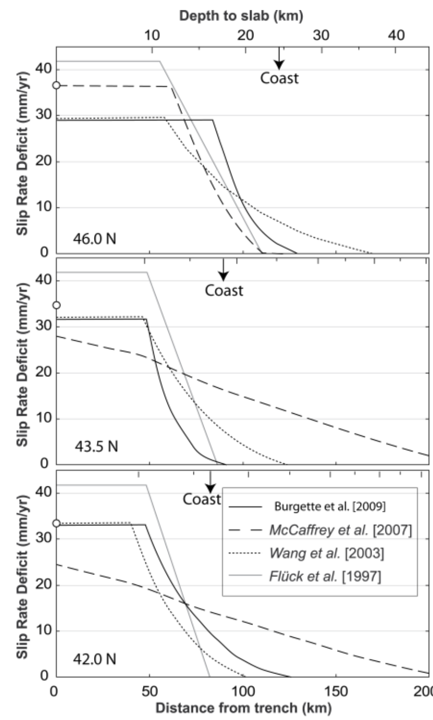


Figure 2: Slip at profiles along Cascadia [Burgette et al., 2009].

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 (Figure 3). *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]*.

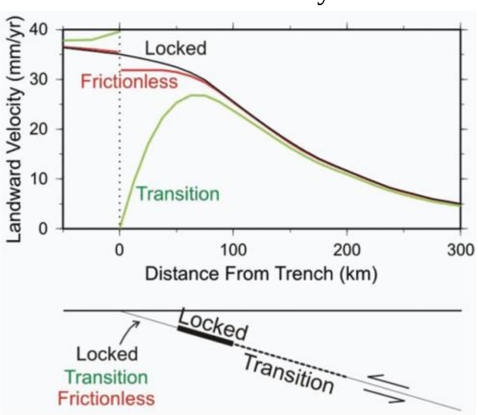


Figure 3: Possible slip behavior models [Wang, 2007]

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 (Figure 4). *Chadwell [2007]* reported an observation with GPS-Acoustics at 44°40´ offshore central Oregon that is about half the expected long-term rate based

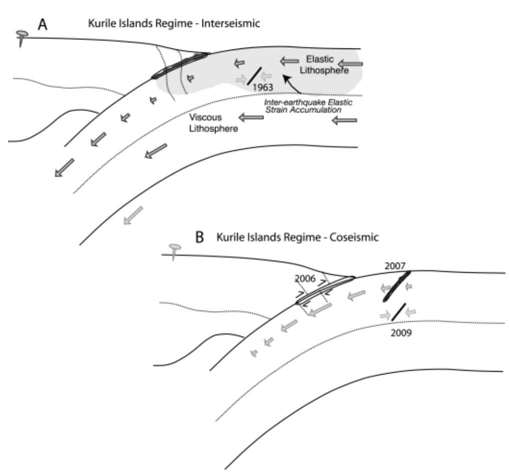


Figure 4: Incoming plate elastic strain cycle [Lay et al., 2009]

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.

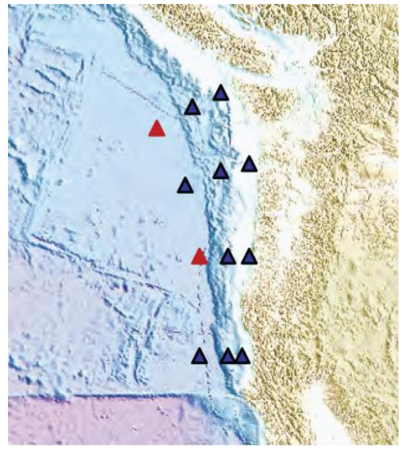


Figure 5: Notional array seafloor array (black triangles). Red existing, but presently inoperable GPS-A sites that could be reactiviated.

In closing, 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 5 is a notional design of a seafloor geodetic array for Cascadia to be further refined with community input.

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Long-term simultaneous imaging of slow and fast quakes using small-aperture seismic arrays

Abhijit Ghosh[1] (aghosh.earth@gmail.com), Kenneth C Creager[2], John E Vidale[2]
[1]Dept of Earth & Planetary Sciences, University of California Santa Cruz
[2]Dept of Earth & Space Sciences, University of Washington

Plate boundary faults experience both fast and slow slip. Fast slip dominates the locked seismogenic zone, the nucleation zone of large megathrust earthquakes. Slow slip and associated tremor, on the other hand, mainly occur directly downdip of the locked zone. Fast and slow slips likely interact with each other. It is even suggested that slow slip might have preceded the dynamic rupture of the recent great megathrust earthquake in Japan [*Kato et al.*, 2012].

Cascadia witnessed great megathrust earthquakes. It is characterized by frequent tremor episodes along the entire margin and slow earthquakes as large as Mw ~7.0. The relationship between slow slip and associated tremor with fast slip (regular earthquakes), however, remain unknown. Addressing this issue requires high-resolution long-term imaging of the seismicity, associated with both fast and slow slip, with enhanced detection capability. Existing regional seismic networks are not designed to capture this level of details in the seismic activity. Small-aperture seismic arrays are successfully used in Cascadia to image slow and fast earthquakes in unprecedented resolution [e.g., *Ghosh et al.*, 2010a; *Vidale et al.*, 2011], and greatly enhanced detectability compared to conventional methods using existing network data.

We propose to install two small-aperture seismic arrays in strategic locations in northern Cascadia, part of which we previously imaged using array techniques [*Ghosh et al.*, 2009]. The proposed arrays will reoccupy the sites of two previous similar arrays (Figure 1) operating in this area until recently as a part of an EarthScope project (CAFE). This will allow us to combine newly collected data with the existing ones to study the seismicity pattern for a relatively longer time period, which would be useful to reliably interpret the observations. Moreover, these two locations are suitable to image a very active part of the fault where repeating tremor patches with dimension of 20-30 kms have been identified, several LFEs are located and several large slow earthquakes appeared to have nucleated.

The arrays would provide a close look of the activities in and around the tremor patches, which appear to control the evolution of slow earthquakes [*Ghosh et al.*, 2012]. This will enable us to study possible spatiotemporal changes in the activities of tremor and regular earthquakes and explore connection between them. The arrays would track several repeating LFEs already identified in this area [*Sweet et al.*, 2010], and will be used to find more LFEs to get a more complete spatial coverage. Tracking LFE activity over a long time-period is essential to study variability in the recurrence behavior of LFEs in time and along the dip of the tremor zone. This would help understand the frictional regime of the conditionally stable part of the subduction fault. Based on the previous activity of slow earthquakes in this area, the arrays would likely record initiation of many small, several moderate-size and couple of large slow earthquakes. High-resolution imaging of initiation of multiple slow earthquakes of different size might be critical to understand how they nucleate, grow and start rupturing. Why do some event grow larger while others don't? Rapid tremor migration over short time scales, known as tremor streaks [*Ghosh et al.*, 2010b], provides a unique view of the complexities in the evolution of the slip during slow earthquakes. So far, only a handful of streaks are identified, inadequate for useful statistical analyses. The arrays would help grow our streak catalog allowing us to study the interplay between stress and fault structure during slow earthquakes. The arrays would also be helpful for the existing tremor and earthquake monitoring mechanism providing data with high signal-to-noise ratio using array-stacking techniques.

Long-term high-resolution imaging of seismicity, associated with both fast and slow slip, with small aperture seismic arrays in strategic locations will provide an opportunity to study spatiotemporal evolution of fault slip in a level beyond the capability of any existing regional network. This study will address some of the key issues underlying the generation, evolution and termination of slow earthquakes, possible connection between slow and fast earthquakes, and help better understand the physics of fault slip and its implications in the subduction zone dynamics.

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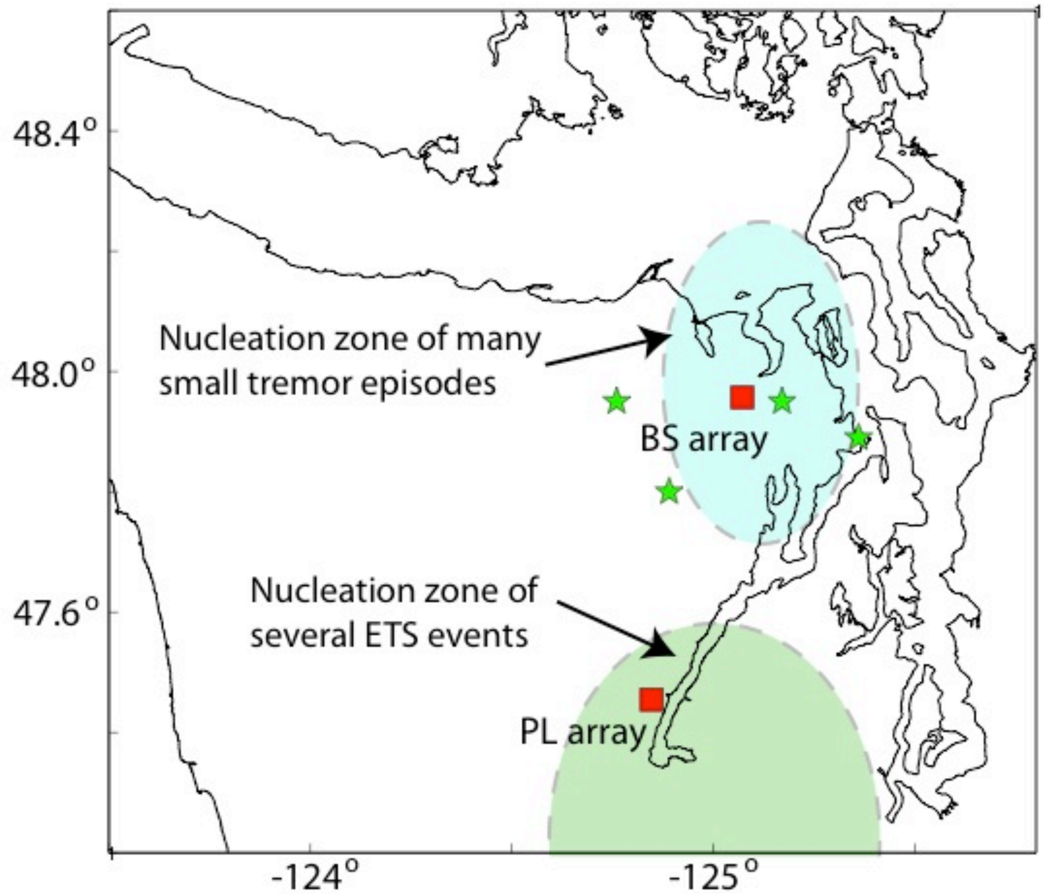

Figure 1: Map showing the arrays (red squares) we are proposing to reoccupy. The light blue area hosts three patches that experience repeated tremor episodes, and appears to be the nucleation zone of frequent small to moderate-sized tremor episodes. The light green area marks the zone from where several ETS events got started in the last few years. Green stars represent the locations of the low-frequency earthquake identified so far using array analysis.

PALEOSEISMOLOGY AT THE CENTRAL CASCADIA SUBDUCTION ZONE

Ben Horton, Simon Engelhart, Andrea Hawkes, Alan Nelson, Kelin Wang, Pei-Ling Wang and Rob Witter

Paleoseismology at the Cascadia subduction zone addresses two questions guiding the GeoPRISMS SCD Initiative:

1. *What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?*
2. *How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?*

Coastal paleoseismology addresses amounts and rates of Cascadia megathrust deformation throughout complete earthquake cycles, that is, over periods of hundreds to thousands of years. We measure subduction-zone strain accumulation and release indirectly by inferring coastal land-level changes from small (<2m) changes in relative sea level (RSL) that occur both instantaneously (coseismic) and gradually (interseismic). Measuring how and when the Cascadia plate boundary deforms facilitates our understanding of subduction at other plate boundaries and improves assessments of earthquake and tsunami hazards in western North America.

Some consider Cascadia to be the type area of subduction-zone paleoseismology. Its coasts harbor an extensive archive of land-level changes that are inferred from stratigraphic evidence. Regional sea-level rise at rates of ~1 mm/yr along the central Cascadia margin since 5-6 ka has resulted in largely continuous records of tidal sedimentation. This creation of accommodation space allows for the preservation of the sedimentary record. As inferred from couplets of interbedded organic and muddy sediment beneath tidal wetlands, the Cascadia coastal stratigraphy may record up to twelve great earthquakes that ruptured much of the central and southern subduction zone since 6.5 ka. By comparison, the Holocene sedimentary and/or morphologic record of coseismic and interseismic land-level changes at many other subduction zones is incomplete. For example, south-central Chile has only fragmentary evidence for earthquake-induced land-level movements because of falling sea level since 6 ka combined with probable near complete postseismic recovery following great earthquakes. Southern coastal Alaska has a potentially extensive sedimentary record but constructing a megathrust history for this region has been hampered by large tidal ranges, high sedimentation rates, logistical challenges, and problematic ^{14}C ages. In Sumatra, U-Th-dating of coral heads yields an extraordinarily precise and detailed record of land-level changes, but only for the past two centuries. In Hokkaido, tidal stratigraphy above deep parts of the Kuril megathrust shows evidence for repetition of slow postseismic uplift over 2.8 ka.

And yet the potential quantitative record of land-level changes during many earthquake cycles at Cascadia remains largely unexamined. Although several recent studies of the history of tsunami inundation are quite detailed, most paleoseismic fieldwork completed prior to 1995 understandably focused on overall stratigraphic framework and ^{14}C dating of buried soils interpreted as evidence for sudden subsidence. A common approach was to describe the stratigraphic evidence of the most recent AD 1700 earthquake, now estimated at magnitude M8.8-9.2, and then assume that earlier earthquakes were similar. All but the most recent estimates of the amount of coseismic subsidence at Cascadia are too imprecise (errors of >±0.5 m) to distinguish, for example, coseismic from postseismic land-level movements, or to infer differences in amounts of subsidence or uplift from one earthquake cycle to the next.

One of the most precise ways of re-dressing this deficiency is to apply recently developed statistical transfer functions to microfossils, such as foraminifera and diatoms, collected from Cascadia estuarine sediments. Similar studies of sea-level change on other continents have obtained an unprecedented vertical resolution of ±0.2 m.

We propose that the improved vertical resolution of land-level reconstructions throughout multiple earthquake cycles will: (1) yield more precise measures of coseismic and interseismic deformation over timescales of decades to centuries; (2) improve comparisons with the earthquake history inferred from offshore turbidites; (3) test hypothetical rupture segmentation boundaries; (4) provide some of the first measures of post-earthquake vertical deformation for prehistoric earthquakes; (5) examine evidence for or against precursory deformation just prior to great earthquakes; (6) help constrain regional slip models of Cascadia megathrust rupture for tsunami simulations; and (7) test hypotheses of slip-predictable, time-predictable, and slip-time-unpredictable strain accumulation.

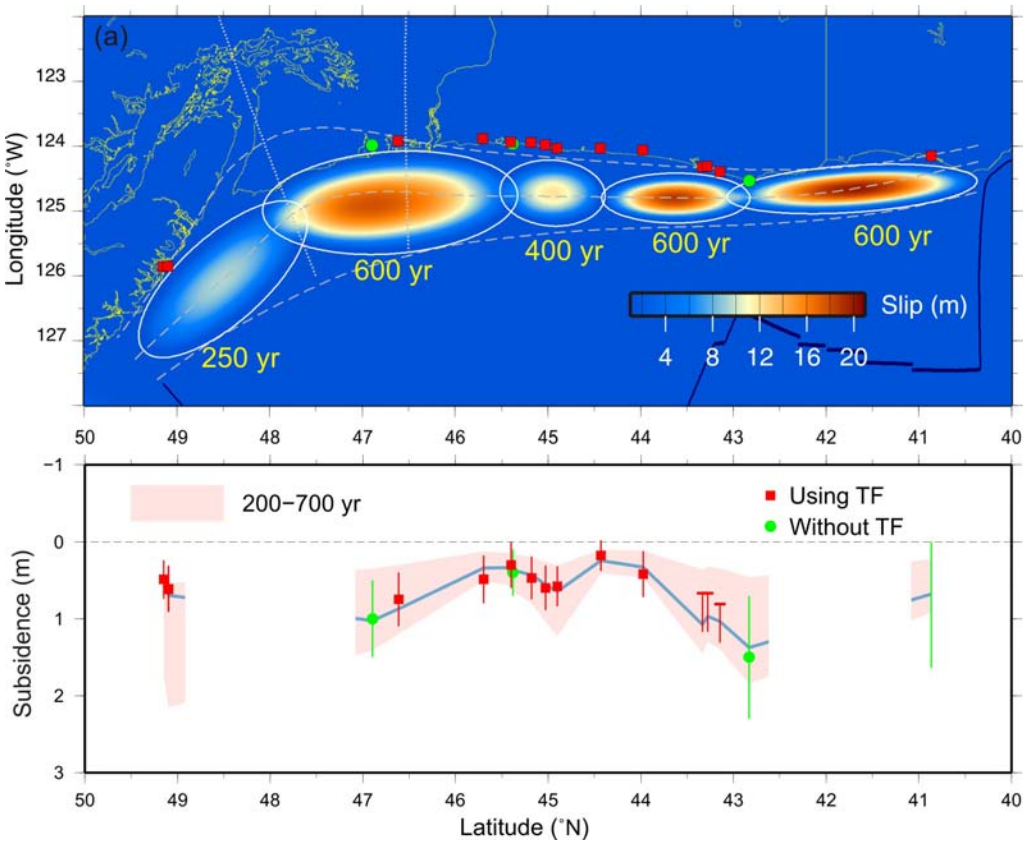

Figure 1: A preliminary dislocation model of the 1700 Cascadia earthquake to illustrate how paleoseismic data can help constrain rupture heterogeneity and what critical data are still missing. The model uses 3-D fault geometry and spatially variable slip distribution. (a) Slip distribution consisting of high-moment slip patches, with patch boundaries delineated by white lines. Peak slip (reddest point) for each patch is measured in terms of equivalent time of plate convergence. (b) Model-predicted coseismic subsidence in comparison with paleoseismic observations. TF: transfer function. The shaded band is bounded by results for uniform slip of 200 yr and 700 yr. Uncertainties in the paleoseismic data are described as follows: symmetric error bars indicate normal distribution, one-sided error bar indicate minimum subsidence estimate, and a bar with no symbol indicates uniform distribution.

Determining Temperatures of the Eastern Edge of the Cascadia Subduction Zone: Shallow Water Heat Flow Measurements in Puget Sound

H. Paul Johnson[1], Kelin Wang[2], Tor Bjorklund[1], Tim McGinnis[3]
[1]Oceanography, UW, [2]Pacific Geoscience Centre, PGC, [3]Applied Physics Lab, UW

Abstract: Temperature in the sub-surface is the primary controlling parameter for most of the physical and chemical processes associated with a subduction zone. Within the Cascadia Subduction Zone, the young, heavily sedimented Juan de Fuca plate subducts obliquely at about 40 mm/year beneath Washington, Oregon and British Columbia, and is one of the warmest subduction zone slabs in the world. Large magnitude megathrust earthquakes have been shown to rupture the entire fault zone from Mendocino, CA to northern Vancouver Island on several hundred-year time scales. In addition, less dramatic but still dangerous intraslab seismicity beneath the heavily populated Puget Sound region extends to 60-km depth, with some small seismic events reaching depths as great as 100 km. Knowing the distribution of subsurface isotherms is critical for understanding these active tectonic processes, including those that 'lock' the relative motion of the plates, cause the large megathrust earthquakes, produce the intra-slab seismic activity, and induce deep fluid flow attributed to the episodic tremor and slip (ETS). However, within Western Washington, models of the sub-surface isotherm distribution are based largely on extrapolation of heat flow data from distant areas that may represent fundamentally different thermal environments. We propose a pilot study of shallow water heat flow stations within the larger Puget Sound area, to develop a technique that can eventually produce a complete E-W profile of sub-surface temperatures - from the Washington coast to the western slopes of the Cascade Mountains.

Rationale: The up-dip (seaward) and down-dip (landward) limits of future rupture zone of the Cascadia megathrust have been proposed to be the intersection of the décollement and the 100°C and 350°C isotherms, respectively (Hyndman and Wang, 1993). The position of the down-dip limit controls the intensity of ground shaking in the heavily populated forearc region. There are large uncertainties in the location of this critical eastern limit beneath western Washington because of the lack of reliable heat flow data from the area. Heat flow measurements from the shallow inland waters of Western Washington would provide the critical vertical thermal gradients necessary for downward projection of isotherms to the décollement that underlies the region. The shallow water heat flow experiments proposed in this White Paper would provide the necessary vertical thermal gradients, and when combined with seismic data from the region, would allow identification of the intersection of the critical 350°C and the décollement.

In addition to the catastrophic mega-thrust earthquakes associated with the CSZ, which occur infrequently at intervals of hundreds of years, mid-plate earthquakes associated with the subducting slab occur much more frequently (i.e., the Nisqually earthquake of 2001). Even though localized to smaller regions than mega-thrust seismic activity, these earthquakes can be destructive with significant societal impact. These smaller intraslab earthquakes also appear to be temperature controlled, although perhaps indirectly through the dehydration embrittlement of the subducting plate. Thermally controlled metamorphic dehydration and hydration processes are expected to be responsible for episodic tremor and slip (ETS) (Wech and Creager, 2008; Abers et al, 2009). Whether the focus is on mega-thrust earthquakes of M_w9, intraslab quakes of smaller magnitude, or ETS events which may provide fundamental insight into subduction zone plate coupling, it is clear that the sub-surface thermal environment will be a primary variable in any model of Cascadia Subduction Zone seismicity.

Specific Questions Addressed by the Experiment: The primary question addressed by the experiment proposed by this White Paper is "*what is the vertical distribution of isotherms beneath Western Washington – from the coast to the foothills of the Cascades?*" The scale of this question is too large and the methodology too uncertain to be answered by a single experiment. We propose a pilot study that would test the feasibility of measuring heat flow in shallow in-land waters which, if successful, would allow us to measure heat flow along a full E-W profile, from the continental margin to the Cascades.

Methodology: Previous terrestrial heat flow studies of the Pacific NW have used wells drilled into aquifers as their primary data set (Blackwell et al, 1990). However, there are few such measurements in Western Washington, and aquifers with mobile ground water may not provide the most accurate vertical thermal gradients. We propose to use the thick impermeable pelagic mud cap present in (a) Puget Sound, (b) Hood Canal and (c) some freshwater lakes as our experimental heat flow measuring sites. While this impermeable mud provides an excellent media for the measurement of geothermal gradients, the shallow water (~200 m) and seasonal temperature variations of these sites provides a major noise source for the extraction of the relatively small geothermal gradient. However, prior studies in the Western Pacific (Hamamoto et al., 2005, 2011) have demonstrated that by measuring the thermal gradient continuously over the period of a year permits removal of the high frequency bottom water variations. Further, selecting sites where bottom water temperatures have previously been measured for periods of 5 to 10 years (in Puget Sound, Hood Canal and on the Washington margin) for other un-related experiments would allow the removal of long-period seawater variations (i.e., ENSO). We have identified several sites where semi-continuous bottom water measurements have been made over long intervals, some since 1998, and propose to deploy test probes <u>at one of those sites</u> as a pilot study for eventual measurement of the full E-W profile. After careful removal of the bottom water variations with both long (5 to 10 years) and short (monthly/annual) periods, the geothermal gradient obtained would be downward continued into the subsurface, using thermal conductivities derived from seismic velocity (EarthScope) and electrical resistivity proxies (Patro and Egbert, 2008); methods which have been shown to be effective in the deep Kola Superdeep Borehole.

Proposed Pilot Study: We plan to use standard piston core technology to insert a thermal probe at 200 meters water depth into pelagic mud, probably at the Hood Canal site, where bottom water temperatures have been monitored continuously since 2005. The thermal probes will use multiple autonomous temperature loggers (Antares) at 0.5 m intervals and have a planned probe insertion depth of 4 to 6 meters. We first plan a short period (12 hours) test deployment prior to the long-term experiment, followed by a possible 'mid-course strategy modification' based on that short-period data and then insertion of <u>two probes at a single site</u> for a period of a year before recovery. Two probes deployed at the same site would both allow for instrument failure after a year-long deployment, and if both are successful, provide additional confidence in the data acquired.

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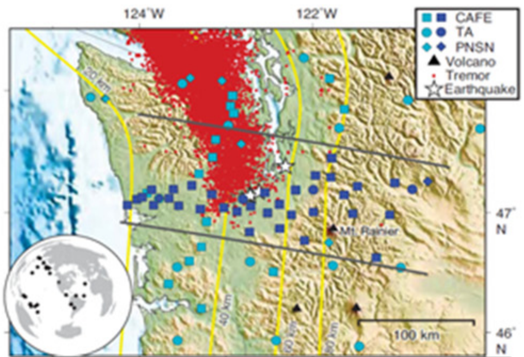
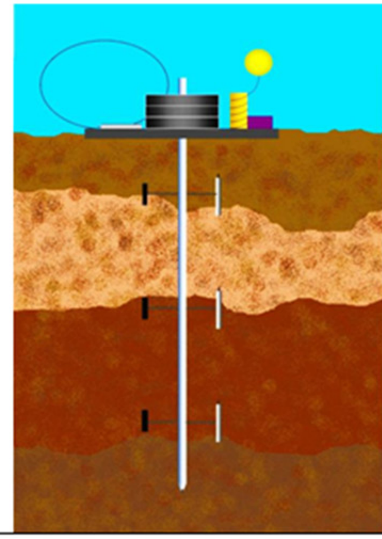
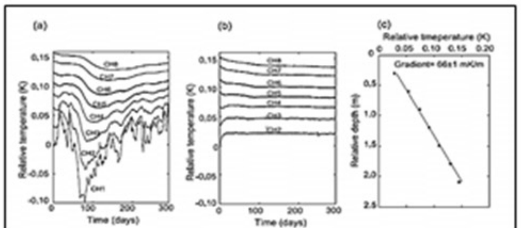


Red dots are ETS locations; blue squares seismometers, yellow contours are slab depth, stars are epicenters of 3 M_w>6.5 intraslab quakes. Abers et al, Geology, 2009

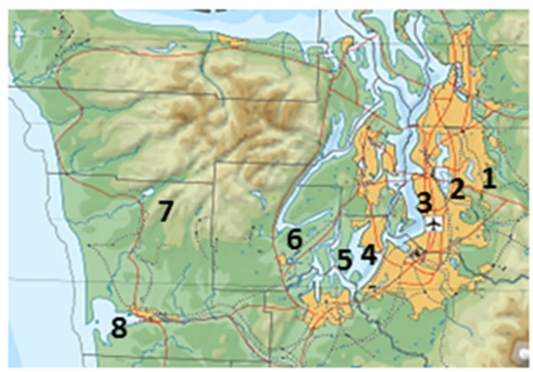


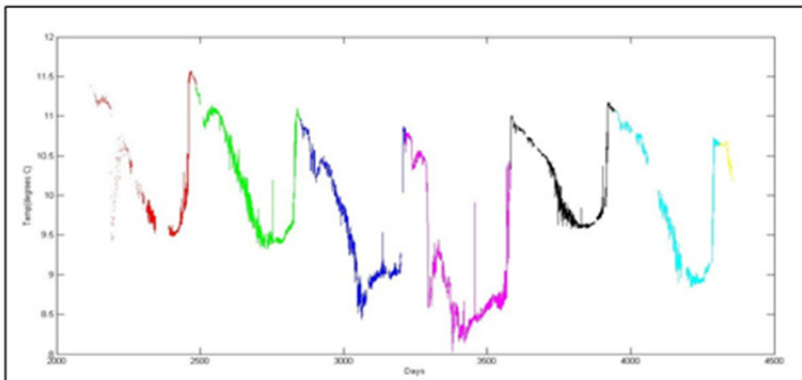
Proposed 4 m long probe for insertion at sites where prior long-term bottom water temperature records exist.



Shallow water Heat Flow from Nankai showing corrections for bottom water temperature variations; Hamamoto et al, 2011.

Right: Potential sites for E-W heat flow profile 1. Lake Sammamish. 2. Lake Washington, 3. Puget Sound central basin, 4 and 5. South Puget Sound. 6 Hood Canal. 7. Lake Quinault. 8. Grays Harbor.





Left: CTD bottom water temperatures from Hood Canal (site #6) from 2005 to present time (A.Devol, pers. comm., 2012).

Thermal Structure of the Cascadia Subduction Zone on the Washington Margin

H. Paul Johnson, Evan A. Solomon and Marie Salmi, School of Oceanography, University of Washington

Abstract: We will be conducting a comprehensive study of the thermal environment of the Cascadia Subduction Zone (CSZ) off the Washington margin in 2013 during a 24-day field program with Jason II. This study site overlaps geographically with the North Cascadia OBSIP array and the 2-D MCS survey of the R/V LANGSETH. The goal of this GeoPRISM/NSF funded study is to determine the temperature structure of the overlying accretionary prism sediments of the CSZ deformation zone with a transect of systematic heat flow and fluid flux profiles off the Washington Coast near Grays Canyon. The CSZ is a targeted Discovery Corridor within the new GeoPRISM Program, where an abundance of geophysical, geochemical, biological and physical oceanographic investigations are planned for the next decade. Temperature is a primary controlling factor of many subduction zone processes, particularly at active margins subject to large magnitude, megathrust earthquakes such as the CSZ offshore Washington State, and basic heat flow and fluid flux studies of the Cascadia Corridor are fundamental data required by the GeoPRISM Program.

Rationale: The Cascadia Subduction Zone has generated a large number of high-magnitude M_w9 earthquakes, and **poses the greatest single source of seismic hazard to the northwestern United States**. In spite of an intense scientific focus on the CSZ, there have been no systematic heat flow measurements on the margin over an along-strike distance of 800 km – from south of Vancouver Island to southern Oregon. Existing data demonstrate that while the 100 km along-strike section of the CSZ adjacent to Vancouver Island has densely-spaced heat flow profiles, MCS surveys and ODP/IODP drill holes, the segments of the CSZ off-shore WA and OR have only sparse heat flow stations made during programs focused on other scientific goals. We will acquire systematic profiles of heat flow and fluid flux data along a corridor of the accretionary prism on the Washington margin at 47°N, from west of the deformation front on the abyssal plain to just below the shelf edge at 500 m depth – in order to make the first quantitative estimates of the thermal structure of the 'locked zone' of the Cascadia megathrust.

Specific Questions Addressed by This Experiment:

1. *What is the temperature of the basement-sediment interface at the deformation front prior to entering the CSZ?* Prior data suggests a strong latitudinal gradient in basement temperatures in Cascadia Basin, from hot igneous basement beneath Vancouver Island to a cooler plate offshore Oregon. This N-S temperature gradient appears due to differences in sediment thickness and in exposure of basement outcrops on the incoming plate, but the processes are poorly understood.
2. *Is there a correlation between isotherms within the sediment column and the vertical position of the décollement at the up-dip limit of the mega-thrust fault interface?* If the décollement 'steps down' to basement depth as the CSZ deepens landward - as implied by MCS data elsewhere, is there a corresponding change in the temperature distribution of the overlying sediment column?
3. *What is the temperature at the up-dip limit of the seismogenic zone at the CSZ, and does it correlate with known diagenetic reactions and dehydration temperatures of primary clays?* Mineralogy exerts a first-order control on fault frictional properties, including strength and sliding stability. Temperature is a primary control on the seismogenic zone location, as the up-dip limit consistently occurs between 100°C to 150°C. These temperatures coincide with clay dehydration reactions important for controlling the up-dip limit, and the release of mineral-bound water reduces the shear

strength of faults by decreasing the effective stress. Authigenic minerals precipitating at these temperatures may have a higher coefficient of friction and exhibit velocity-weakening behavior, directly influencing the frictional behavior of the décollement.

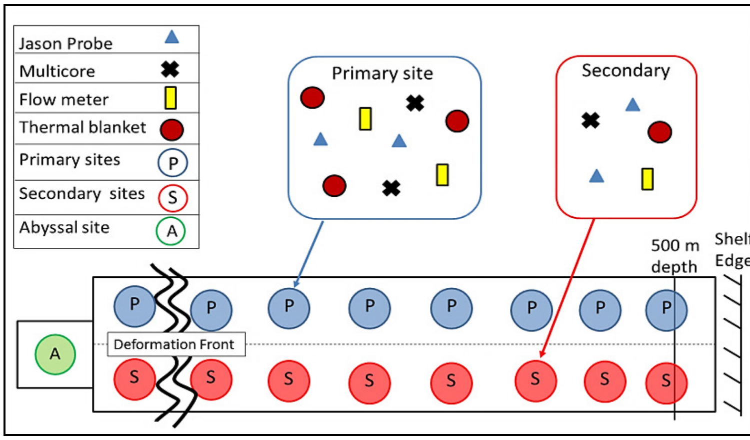
4. Prior CSZ models based on data from off-shore Vancouver Island suggest that subduction zone isotherms are correlated with slab dip, which is well-defined seismically (Hyndman and Wang, 1995; Wang et al, 1995; Oleskevich et al, 1999; McCrory et al, 2002). *However, on the Washington margin, there are only sparse terrestrial heat flow data, and <u>almost no marine heat flow data along the entire WA/OR segments</u> with which to test this model.*

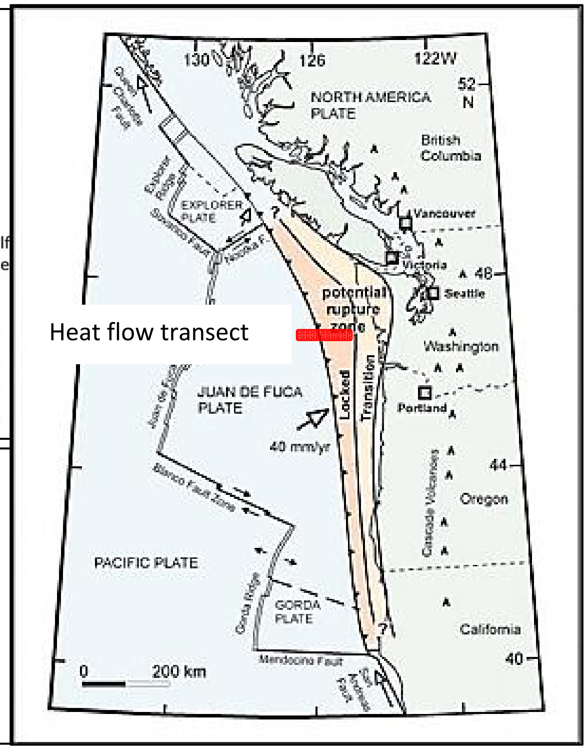
Methodology: For accurate estimates of heat flux from the challenging environment of the accretionary prism, we plan redundant methods of both thermal and fluid flux measurements along a 2.5-D profile of the margin at a single latitude. In this profile we would use thermal blankets suitable for impenetrable sub-stratum, continuous fluid flow meters, multi-core deployments for both pore fluid chemistry and thermal gradient data, and ROV heat flow probes, and concentrate our efforts at 10 equally-spaced depth intervals. Our proposed heat flow profile will coincide spatially with other large-scale NSF programs planned for the Washington corridor at 47°N, including the OBSIP (Ocean Bottom Seismometer) deployments, Endurance Array moorings for OOI, and two Open Access MCS programs (2-D in 2012, 3-D proposed for 2014) using the R/V LANGSETH. The mutual benefit of our proposed heat flow surveys to (and from) these existing programs/proposals in the same area would be substantial. The goal would be to obtain data of sufficient quality that downward projection of the surficial thermal gradients to the CSZ décollement and igneous basement could be done with reasonably high level of confidence.

Bottom water temperatures (BWT) vary seasonally, particularly in the shallower portions of the margin. This variability must be removed to extract the heat flow signal from the sub-surface, but can easily be accomplished if the BWT variations at the site are recorded over a sufficient period (i.e., >8 months; Hamamoto et al, 2005; 2011). The sub-surface variability of seasonal bottom water temperature changes on the WA margin will be determined by the addition of Antares temperature sensors externally to the OBSIP OBS instruments during their simultaneous 1-year deployment in 2012 (Andrew Barclay, pers. comm. 2011) and again during our proposed 2013 Grays Canyon field program. Further, historical CTD moorings and sea glider data on the Washington margin, deployed almost continuous since 1998, will provide additional constraints on bottom water temperatures.

Seafloor fluid flow meters are critical to assessing the presence and magnitude of upward fluid advection at the heat flow stations, and we will be deploying continuous fluid flow meters (Mosquitos) in the sediments at the same sites where heat flow measurements are made (Solomon et al., 2008). In addition, we will be estimating flow rates from sediment pore fluid profiles collected at each station, using the OSU multi-corer samples dedicated to fluid geochemistry. The sediment geochemical profiles provide redundancy with the Mosquito flow rates, information on fluid-rock reactions and the source of the fluids, and constraints on the spatial variability and mean values of flow at each station.

Data Access: The Open Data Access strategy recently adopted by the MCS community is the new paradigm of rapid release of data and cruise reports with both wide community and NSF support. Consistent with this policy, our ship-board data sets and cruise reports are planned to be available to the GeoPRISM community ~6 months post-cruise.





GeoPRISM Heat Flow Transect off Grays Canyon, WA in 2013. Our heat and fluid flow program will be a 2.5-D profile oriented orthogonal to the margin with multiple instrument deployments at 10 discrete water depths. E-W profile extends from west of the deformation front to 500 meters depth below the shelf edge.

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Constraining Fluid Sources and Fluxes Through the Cascadia Accretionary Prism - Impact on Volatile Cycling, Physical State, and Microbiology

Evan A. Solomon, School of Oceanography, University of Washington (esolomn@uw.edu)
Miriam Kastner, Scripps Institution of Oceanography, UC-San Diego (mkastner@ucsd.edu)

This white paper addresses aspects of the GeoPRISMS SCD questions, in particular, what are the connections between thermal structure, fault zone composition, metamorphic dehydration, pore-pressure, fault strength, and fault slip behavior; and what is the cycling of volatiles in a young and hot subduction zone. It also addresses the 3rd SCD process-based theme on "Fore-arc to Back-arc Volatile Fluxes.

Fluid flow and fluid pressure in subduction zones have a profound impact on the shallow thermal structure and fluid content of the subducting plate and upper plate (e.g. Hyndman and Wang, 1993; Langseth and Silver, 1996; Spinelli and Saffer, 2004; Harris et al., 2010), fault zone stability and seismogenesis (e.g. Hubert and Rubey, 1959; Davis et al., 1983; Scholz, 1998), and the transfer of elements and isotopes to the oceans, volcanic arc, and mantle (e.g. Moore and Vrolijk, 1992; Martin et al., 1996; Fryer et al., 1999; Chan and Kastner, 2000; Solomon and Kastner, 2011). The cycling of solutes and volatiles in the forearc of subduction zones (SZs) supports a deep biosphere and should have a profound impact on global chemical and isotopic budgets, affecting the chemistry of seawater, arc and back-arc volcanoes, mantle, and the atmosphere.

At the Cascadia SZ, which represents an extreme thermal end-member SZ, fluid expulsion occurs at non-uniform rates from the deformation front to the arc, and, as observed on the IODP Expedition 311, produces variable fluid geochemical signatures along the W-E transect (e.g. Riedel et al., 2010). At sites near the deformation front, the pore fluids are primarily influenced by *in situ* reactions and porosity reduction, whereas the landward, more mature portion of the margin is influenced by advection/diffusion of diluted fluids generated at depth by mineral dehydration reactions (Riedel et al., 2010).

Changes in physical and mineralogical properties with depth and the associated evolution of fluids in SZs are intimately linked to the transition from aseismic to seismic slip along the plate boundary (e.g. Moore and Saffer, 2001). Fluids advected along fault zones, at the plate boundary, and in the upper plate may record mineral reactions occurring at depths marking the onset of seismogenesis (e.g. You et al., 1996; Moore and Saffer, 2001; James et al., 2003; Hensen et al., 2004). Fluid chemistry is predictably altered with increasing temperature and pressure, assuming fluid-rock equilibrium at various temperatures and knowledge of the mineralogy-lithology of the subducted and accreted materials. Thus, the chemistry and isotopic compositions of the fluids provide information on the fluid origin at depth, the temperature at the source, as well as the role of in situ diagenetic versus deeper-sourced reactions in the fluid production. Some of these diagenetic and low-grade metamorphic reactions release fluid, change the rocks frictional characteristics, and could alter fault zone rheology. Fluid pressure and fluid advection may affect localization of faulting and locking at subduction zones, and return flow in the subducting oceanic basement also influences pore fluid pressures and temperatures deeper within the subduction zone.

At higher temperatures and pressures within the seismogenic zone, a new suite of hydrous minerals forms as others break-down, inducing fluid recycling within the system, that leads to the formation of hydrous phases such as chlorite, serpentine, and amphiboles. Ultimately fluids are released, further altering both the pore fluids and solid geochemistry. Constraining the interplay between the key dehydration reactions at depth, including retrograde reactions during fluid ascent, along the plate boundary and other faults, and microbiological overprinting in the upper sediment column, is crucial for interpreting the chemical anomalies found in fault zones and other flow pathways in SZs. These reactions also impact the delivery of fluid-soluble elements and volatiles to greater depths in the SZ with implications for fluxes beneath the volcanic arc.

The key fluid-rock reactions and mineralogical changes impacting the fluid chemistry at Cascadia can be constrained through sampling of fluids at a predetermined array of sites that will be chosen based on existing and new geophysical surveys, and on a synthesis of results from the three Cascadia scientific drilling expeditions (ODP Legs 146 and 204; IODP Exp. 311). These chemical and isotopic compositions will aid in understanding the evolution of fluid rock reactions deeper within the subduction zone, as discussed above.

Hence, through detailed geochemical fingerprinting and numerical modeling of the chemical and isotope profiles, it will be possible to:

1. Characterize the fluid-rock reactions, fluid sources, and flow rates in fault zones and other fluid flow horizons in the Cascadia accretionary prism.
2. Constrain the temperatures at the fluid sources, how they relate to the up-dip limit of seismicity, and whether they differ from those at erosional margins.
3. Trace key diagenetic and low-grade metamorphic hydration/dehydration reactions that may be responsible for seismic behavior along the plate boundary.
4. Construct mass balance models to estimate the flux of fluids, solutes, and isotopes back to the ocean, and the residual flux to greater depths within the subduction zone.

These objectives could be achieved by:

1. Additional drilling, coring and logging. The new sites will be determined through synthesis of the data from the existing Cascadia prism sites
2. Long-term monitoring and connection to NEPTUNE-Canada and the future OOI-RSN cable system will allow co-documentation and understanding of the relationships between between tectonics, hydrogeology, geochemistry, and microbiology at an accretionary margin.

For all the above, the incoming sediments must as well be fully characterized along-strike at representative sites that reflect the main variations in sedimentology-lithology (both composition and thickness) and the thermal regimes.

If sampling is focused offshore Grays Canyon, it would coincide spatially with other large-scale NSF programs planned for the Washington corridor at 47°N, including the OBSIP (Ocean Bottom Seismometer) focused deployment site, Endurance Array moorings for OOI, high resolution EM302 bathymetry surveys, two Open Access MCS programs (2-D in 2012, 3-D proposed for 2014) using the R/V LANGSETH, and a proposed comprehensive study of the thermal environment of the Cascadia Subduction Zone (CSZ) off the Washington margin in 2013 during a 24-day field program with Jason II (Johnson, Solomon, Salmi white paper).

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Volcanic arcs through time: High-resolution transects across 40 million years of arc evolution in the Oregon Cascades

Streck, M., Department of Geology, Portland State University, Portland, OR, 97207 (StreckM@pdx.edu)
Rowe, M.C., Conrey, R., School of the Environment, Washington State University, Pullman WA 99164 (mcrowe@wsu.edu; geolab@mail.wsu.edu)
Duncan, R., College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331 (rduncan@coas.oregonstate.edu)

Key Sites: McKenzie River Drainage, Rogue River Drainage (Oregon Cascades)
Theme: Arc Evolution
Primary Data: ^{40}Ar-^{39}Ar age dates; whole rock geochemistry, mineral and melt inclusion geochemistry (including sulfur and halogens).

Long-lived arc systems can provide a deep time perspective on the evolution of single arcs through their magmatic record deposited over millions of years of activity. With data on arc output and magmatic composition through time, fundamental questions about the dynamics of magma generation at active convergent plate margins can be addressed. These questions include whether observed changes in the output are due to arc longevity and thus caused by mantle and/or crustal modifications through time, or whether they are controlled by changes in the tectonic regime as well as by changes in the subduction inputs. Suitable arc systems for obtaining the necessary data for assessing such relationships are rare because either arc activity was rather short lived (<10-20 m.y.), the existent long-lived arc has lost the context of its original subduction setting, or there is an insufficient rock record due to erosion, burial by younger strata, metamorphic overprint, or the arc is inaccessible due to remoteness or being submarine.

Since initiation of the Cascades around 45 Ma, the arc has been more or less in the same place with the same subduction setting. Yet the arc has progressively migrated slightly eastward in Oregon so that older rocks were not covered by younger activity (Fig. 1) (Verplanck and Duncan, 1987; Priest, 1990; Sherrod and Smith, 2000; Du Bray et al., 2006, Du Bray and John, 2011). This has produced an essentially continuous volcanic record from initiation to the modern, active High Cascades arc. Thus the Cascades represent a rare example of ~45 m.y. of nearly cospatial magmatism of a continental arc within a well understood tectonic framework (e.g.,Verplanck and Duncan, 1987; Severinghaus and Atwater, 1990; Du Bray and John, 2011) in an on-land setting that can be readily accessed.

We propose a project geared towards generating high-resolution records of the magmatic output of the ancestral (45-5 Ma) Cascades of Oregon. Here, geological and accessibility preconditions for study of the temporal evolution of a continental arc are particularly well met, and study conditions are further enhanced by the availability of a great deal of prior regional reconnaissance and locally detailed map and chemical data, plus auxiliary data such as LIDAR imagery. We propose to obtain geological as well as state-of-the art compositional and age data on select transects across the ancestral Cascades, building on available regional reconnaissance data as well as on prior detailed local studies. Transects will follow drainages that generally cross the volcanic stratigraphy perpendicular to strike. Our first target is the McKenzie River drainage that crosses the ancestral Cascades at the latitude of Eugene, OR. This will be complemented by a second transect farther south, along the Rogue River near the latitude of Grants Pass, OR. Additional transects are planned when results of the first two are available. The transect approach was chosen in order to capture the entire volcanic record of the ancestral Cascades at select latitudes and to obtain results on specific stratigraphic packages within a reasonable, 2-3 year, time frame that can be used to identify subsequent targets for study.

It is clear from existing data that rocks of the ancestral Cascades are not as well preserved as rocks from the young High Cascades. This is not an issue exclusive to our study but is encountered wherever older volcanic stratigraphies are needed to provide important data for evaluating processes of arc evolution. However, a careful sampling approach as well as modern instrumentation (X-ray Fluorescence (XRF), Inductively-Coupled Plasma Mass Spectrometry (ICP-MS), Portable XRF (pXRF), Electron Probe Micro Analysis (EPMA), Laser ablation Multicollector ICP-MS, Ta furnace and UV laser heating gas source Mass Spectrometry) can produce unequivocal, high quality data.

With the new transect data we will improve knowledge of magmatic fluxes and compositional changes over this forty million year age span of Cascade arc evolution. With these improved data sets, we will explore correlations and their implications for how the mantle wedge and arc crust evolved with time, whether changes varied smoothly or were more abrupt, and also the sensitivity of flux rates and compositions to changes in subduction and tectonic parameters (e.g. Verplanck and Duncan, 1987; Severinghaus and Atwater, 1990; Priest, 1990).

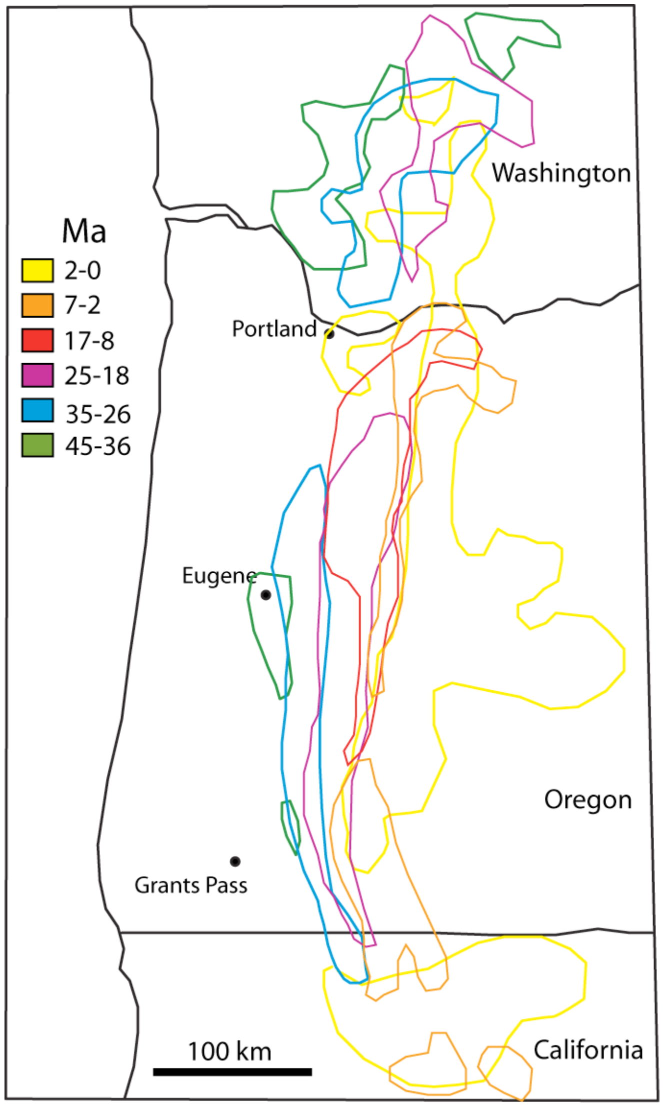

Fig 1: Age distribution of volcanic rocks along the Cascade arc in Washington, Oregon and northern California (after Du Bray and John, 2011, simplified).

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