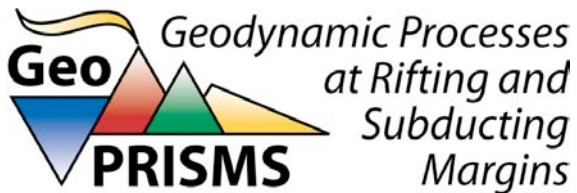




GeoPRISMS / EarthScope
Cascadia Science Workshop

April 5-6, 2012
Portland, OR

Abstract Volume



Resolving mantle structure beneath the Pacific Northwest

Darold, Amberlee; Humphreys, Eugene; Schmandt, Brandon; Gao, Haiying

University of Oregon, Eugene, OR, United States.

Cenozoic tectonics of the Pacific Northwest and the associated mantle structures are remarkable, the latter revealed only recently by EarthScope seismic data. Over the last ~66 Ma this region experienced a wide range of tectonic and magmatic conditions: Laramide compression, ~75-53 Ma, involving Farallon flat-slab subduction, regional uplift, and magmatic quiescence. With the ~53 Ma accretion of Siletzia ocean lithosphere within the Columbia Embayment, westward migration of subduction beginning Cascadia, along with initiation of the Cascade volcanic arc. Within the continental interior the Laramide orogeny was quickly followed by a period of extension involving metamorphic core complexes and the associated initial ignimbrite flare-up (both in northern Washington, Idaho, and western Montana); interior magmo-tectonic activity is attributed to flat-slab removal and (to the south) slab rollback. Rotation of Siletzia created new crust on SE Oregon and, at ~16 Ma, the Columbia River Flood Basalt eruptions renewed vigorous magmatism.

We have united several EarthScope studies in the Pacific Northwest and have focused on better resolving the major mantle structures that have been discovered. We combine an ambient-noise surface wave model with body wave models to resolve structures continuously from the surface to the base of the upper mantle. Specifically, we tomographically modeled the body waves with teleseismic, finite-frequency code under the constraints of ambient noise tomography and teleseismic receiver function models of

Gao et al. (2011), and teleseismic anisotropy models of Long et al. (2009). We now have clear imaging of two episodes of subduction: Juan De Fuca slab deeper than ~250 km is absent across much of the PNW, and it has an E-W tear located beneath northern Oregon; Farallon slab (the “Siletzia curtain”) is still present, hanging vertically just inboard of the core complexes, and with a basal tear causing the structure to extend deeper (~600 km) beneath north-central Idaho than beneath south-central Idaho and northern Washington (~300). Lying just west of the Siletzia curtain, beneath NE Oregon, is a prominent high-velocity body centered on 250 km depth. Its nearly circular plan view corresponds with the area of intense Columbia River Basalt eruptions and with the circular topographic bull’s eye centered on the recently uplifted (post CRB) Wallowa Mountains. Finally, we are investigating a very low-velocity volume of mantle present between the E-W Juan de Fuca tear and the high-velocity body beneath the Wallowa Mountains. At 250 km depth this is the strongest low-velocity anomaly beneath the western U.S. Presently we are completing resolution testing on the structures revealed through our imaging in order to resolve their structural details. These synthetic resolution tests along with the high resolution imaging of the crust and upper mantle will clarify several previously cited structures as well as strengthen our conclusions on the tectonic history and geodynamical evolution of the mantle while aiding in putting together a comprehensive story for the area.

Upper-plate structure and its impact on subduction-zone segmentation

Megan Anderson¹, Paul Bedrosian², Richard Blakely³, Brian Sherrod⁴, and Ray Wells³

The spatio-temporal segmentation of slip along the subduction interface is controlled in part by 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. It is generally agreed that interactions with the overriding plate trigger segmentation of slip on the subduction interface, 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 all dimensions.

We propose to conduct 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. The overriding crust along this segment is broken by numerous faults, including the Doty fault, Gales Creek fault, and faults responsible for the Mt. St. Helens and West Rainier seismic zones. 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.

¹Colorado College, Colorado Springs; ²USGS, Denver; ³USGS, Menlo Park; ⁴USGS, Seattle

Estimated Shallow Crustal Shear Velocity Structure Off the South Island, New Zealand from Seafloor Compliance Measurements

Justin S. Ball and Anne F. Sheehan

CIRES and the Department of Geological Sciences, University of Colorado, Boulder

Ocean surface gravity wave energy at sufficiently long periods can propagate to the seafloor producing a time-varying pressure load. The transfer function between applied pressure and resulting displacement fields at the seafloor is known as the seafloor compliance and depends strongly on the shear structure beneath the measurement site. The Marine Observations of Anisotropy Near Aotearoa (MOANA) experiment deployed 30 broadband ocean bottom seismometers (OBS) with collocated differential pressure gauges (DPGs) off the South Island of New Zealand in 2009-2010. The MOANA experiment aims to employ regional anisotropy measurements to quantify the strain field at depth and elucidate the mantle rheology. Teleseismic methods of resolving anisotropy such as receiver function analysis and shear-wave splitting depend on high signal-to-noise ratios that are difficult to achieve at OBS sites due largely to the effects of low-velocity sediments. Methods of removing sediment effects from teleseismic data typically require accurate estimates of sediment column velocities, to which seafloor compliance is sensitive. Preliminary compliance curves were calculated from pressure and acceleration power spectra at periods between 33-500s and normalized by the coherence between pressure and vertical acceleration signals to suppress non-infragravity noise sources. The resulting compliance values range from 10^{-10} - 10^{-8} Pa⁻¹ and are sensitive to changes in basement shear modulus at depths that increase with forcing period. Data uncertainties increase with depth to approximately 5% at 7km. 1D forward velocity models with a depth range of 100-7000m are used to calculate synthetic compliance curves and the best-fitting model for each station is presented. The use of these models and associated synthetic seismograms to remove undesired sediment-converted S phases from OBS receiver functions is investigated.

Sub Bottom Profile Based Correlation of Cascadian Seismogenic Turbidites

Bran Black

Individual seismogenic turbidites visible in Cascadian sub bottom profile data have been tracked from the northern San Andreas up to the southern edge of the Astoria Fan off of northern Oregon, as well as in isolated basins north of the Astoria Fan off the southern and central Washington coast. The number of visible turbidites within the sub bottom profile data ranges from 30-40 off northern California and southern Oregon to the 10 or so events still discernable at the edge of the Astoria Fan. The comparison between the placement and extents of the events illustrated in the sub bottom profile data to the earthquake event correlation based off of this region's sediment cores produced by OSU's Active Tectonics and Seafloor Mapping Lab (ATSML) show a high degree of agreement between both these separate approaches.

Potential Contributions of Seafloor Geodesy to Understanding slip behavior along the Cascadia Subduction Zone

D. Chadwell

ABSTRACT: We propose an experiment to measure the crustal deformation along Cascadia that crosses the entire region of the subduction zone from the incoming plate, the offshore continental slope and the sub-aerial continent. Presently, onshore geodesy has determined that the locked region lies almost entirely offshore. However, these data lack proximity and poorly resolve details of the stick-slip behavior near the deformation front and the location of the boundary from full stick to some component of stable sliding. To date GPS-Acoustic measurements have been collected infrequently using ships with special capabilities and seafloor acoustic transponders with finite life-spans. Developments underway include moored-buoys for continuous collection of GPS-Acoustic data, small autonomous platforms that use less expensive ships or no ship at all, and permanent 3-D benchmarks on the seafloor to extend the time series of seafloor position measurements for years to decades.

Magmatic evolution within the lower arc crust: Insights from crystal zoning in the Tenpeak pluton, North Cascades crystalline core, Washington

C. Chan

Deep-crustal plutons are important for understanding heat, melting and mass transfer processes in the lower crust. Our comprehension of these processes influences perspectives of crustal growth and how magma ascends to form large volume batholiths in the upper crust. Despite the importance of these systems, it is difficult to study deep-crustal plutons in many terranes due to insufficient exhumation and modification by regional metamorphism and deformation. For this study we focus on the Tenpeak pluton, intruded at 7–10 kbar between 92.3–89.7 Ma in the Northern Washington Cascades crystalline core, which is part of a continental magmatic arc. The Tenpeak is a well-exposed and relatively unmodified composite pluton consisting predominantly of tonalite with zones of mingled and sheeted gabbro, tonalite, and hornblendite. The objectives of this study are to: (1) document how composition and compositional zoning of major and minor phases vary between different episodes of magma influx; (2) constrain formation mechanisms for the pluton; and (3) investigate the role of diffusive processes in controlling mineral zoning patterns. A combination of field mapping, geochronology, whole rock geochemistry (XRF and ICP-MS), and mineral chemistry (LA-ICP-MS and EMPA) has been used to help reconstruct the magmatic and thermal history of the pluton. Our initial studies focus on a 91.8 Ma sheeted complex near the southwest margin of the batholith, which has been previously interpreted to reflect numerous pulses of magma with different chemical histories. Preliminary data show distinct chemical differences between felsic and mafic sheets, both at the whole-rock and mineral scale. Bulk rock compositions show overlap in Mg # (range: 0.57–0.70) but lower abundances of incompatible trace elements (e.g. La, Zr) and higher compatible trace elements (e.g. Cr, Ni) in the mafic magmas. Mafic sheets also have greater depletion of LREE and higher HREE contents. Significant differences are also apparent in phenocryst compositions. Plagioclase phenocrysts in mafic sheets are characterized by lower Ba and Ti and higher Sr relative to the felsic zones. Mafic magmas also have amphiboles with higher Zr and Sr, and lower Ce compared to those in the felsic magmas. These chemical variations suggest that a number of processes, including fractionation, mixing and crystal exchange are potentially important in controlling the compositions of mafic and felsic magmas and their contained phenocryst phases.

Some Fundamental Problems in Oregon Western Cascade geology and petrology
R. Conrey

The Western Cascade Range in Oregon comprises Cascade arc volcanism from circa 40 Ma to 5 Ma. Regional reconnaissance scale and locally detailed mapping and sampling have increased our knowledge of the older arc but several fundamental issues remain unresolved. The modern High Cascade arc occupies an intra-arc graben that formed beginning some 5 myo. However, the western margin of that graben is located 10-15 km east of a pronounced gravity anomaly (work of Rick Blakely and others), suggesting the possibility of an older Western Cascade intra-arc graben margin west of the younger one. Mapping indeed supports this hypothesis: both the Cougar Reservoir FZ (mapped by George Priest and colleagues) along the South Fk McKenzie R., and the Hoover FZ along the North Fk. Breitenbush R., offset circa 15-25 Ma rocks downward to the east. The gravity anomaly is shadowed by drainages that trend N-S in contrast to the E-W trend expected from volcanic materials flowing westward from an ancestral N-S oriented arc highland. Topographic analysis (work of Wei Luo and colleagues) suggests much more dissection west of this apparent boundary and changes in regional slopes across the boundary. Priest has mapped an angular unconformity west of the Hoover FZ, consistent with an interpretation that older east dipping rocks were buried by west dipping volcanics derived from an increased eruption flux prior to formation of a graben. This is similar to the relationship known for the younger High Cascade graben. The time period 20-25 Ma seems to be characterized by significant volumes of Fe-rich tholeiitic lava (initial work by Craig White), suggesting extension may have allowed magma evolution at shallower crustal levels than typical during that time. In comparison, the High Cascade intra-arc graben is associated with the eruption of significant Fe-rich lavas. Only more detailed mapping, sampling, and dating can further our understanding of this problem.

The petrology of mafic lava in the Western Oregon Cascades is also not well known. The phenocryst mineralogy is commonly olivine-augite dominated, suggesting much wetter magma on average than the typical plagioclase-olivine dominated High Cascade mafic magmas. Chemical trends such as increasing Al_2O_3 with declining MgO support the interpretation that augite and olivine were the predominant crystallizing phases in Western Cascade mafic magmas. Anorthitic plagioclase is known from the Western Cascades, consistent with the presence of significant water in the melts. The presence of evolved Fe-rich mafic lavas as noted above complicates the picture. Until more of their eruption timing and evolution is known, petrogenetic relationships between these magma types will remain speculative.

The work of fault growth within the sandbox and within accretionary prismsMichele L Cooke¹, Justin W Herbert¹ and Bertrand Maillot²¹ University of Massachusetts at Amherst² Universite de Cergy-Pontoise

Fault systems may evolve to minimize the total work on the system. The work budget of fault systems includes frictional heating, internal work, tectonic work (external to the system), work against gravity, and seismic work. More enigmatic than these is the work required to propagate faults. While this term may be smaller than other terms in the work budget, observations of long-lived faults suggest that W_{prop} is not negligible. Direct measurements of external work from sandbox experiments show drop in work associated with both the growth of new thrusts and the reactivation of older faults. The thrusts develop when the total work savings of having the fault exceeds the cost of the new fault. The drop in work with new fault formation scales with the area of new fault surface created. This relationship can thus be used to estimate the cost of fault growth in the sandbox. While the relative amounts of work consumed in different processes changes between the sandbox and accretionary prisms, the controls on fault growth are consistent. We might use the pattern of recent backthrust development within the southern Cascadia wedge to constrain the work required to grow these faults and to produce future backthrusts.

Tracking Hydrosphere Dynamics with Borehole Strainmeters: One Person's Noise = Another Person's Signal

*H. Dragert and E. Davis
Geological Survey of Canada (Pacific)
Natural Resources Canada, Sidney, BC, V8L 4B2*

Observations from the Gladwin borehole strainmeters deployed in Cascadia as part of the Plate Boundary Observatory have demonstrated a precision better than 1 nanostrain and have resolved transient strain signals generated by slow slip on the deep subducting plate interface. Often, such seismo-tectonic signals are obscured by "noise" stemming from changes in the hydrosphere and processes involving the water cycle. On land, examples of such processes, with time scales of days to months, include natural discharge/recharge of drainage basins or rapid water table drawdown due to large-scale agricultural pumping. At coastal locations, the strain signals associated with earthquake-generated tsunamis and smaller scale meteo-tsunamis, with characteristic time scales of minutes to hours, are clearly resolved. 1Hz strain data can also contain strain signals with periods of the order of 5-20s that are generated by ocean waves and swell that load the coastline (i.e., single-frequency microseisms). Understanding these signals constitutes a first step towards removing unwanted "noise" for tectonic studies. Such signals may also be useful for estimating local elastic and hydrologic formation properties.

Coastal subsidence during late Holocene great megathrust earthquakes beneath Cascadia tidal marshes, Siletz Bay, Oregon

Simon E. ENGELHART¹, Benjamin P. HORTON¹, Alan R. NELSON², Robert WITTER³, Andrea D. HAWKES⁴, and Christopher H. VANE⁵

¹ Sea-Level Research, Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, PA, USA.

² Geologic Hazards Science Center, United States Geological Survey, Golden, CO, USA

³ Oregon Department of Geology and Mineral Industries, Newport, OR, USA.

⁴ Woods Hole Oceanographic Institution, Woods Hole, MA, USA.

⁵ British Geological Survey, Keyworth, UK.

Coastal marshes bordering the Cascadia subduction zone archive a stratigraphy of great Holocene plate-boundary earthquakes. However, most estimates of the amount of vertical deformation from marshes during past great earthquakes are imprecise (errors $>\pm 0.5$ m) and lack the precision needed to obtain unique solutions for geophysical models of plate-boundary deformation. In response, we apply foraminiferal-based transfer functions (TF) with a resolution of ± 0.2 m, supported by $\delta^{13}\text{C}$ values (‰), to reconstruct coseismic subsidence.

Foraminiferal assemblages ($n=75$) along elevational gradients at four sites in Siletz Bay show a strong relationship with elevation. The low marsh/tidal flat is dominated by *M. fusca* (Zone 1), middle to high marsh by *J. macrescens*, *B. pseudomacrescens*, *T. inflata* and *Haplophragmoides* spp. (Zone 2) and a higher high marsh assemblage of *T. irregularis* (Zone 3). Subdividing the $\delta^{13}\text{C}$ data based on these foraminiferal defined zones indicates that values become increasingly negative with elevation (Zone 1 = -24.2 ± 1.7 ; Zone 2 = -25.7 ± 2.1 ; Zone 3 = -29.0 ± 0.3). We developed a TF by combining the Siletz data with 83 samples collected from marshes in Oregon (Hawkes et al., 2010). The modern data are applied to 4 peat-mud couplets that record sudden subsidence during a great megathrust earthquake. Reconstructions suggest that 3 of the 4 earthquakes produced subsidence of 0.5 – 0.8 m, as shown by a shift from foraminiferal assemblages dominated by middle to high marsh species to low marsh and tidal flat species. In contrast, the 2nd most recent earthquake is associated with a change from *B. pseudomacrescens* to *T. inflata*, indicating <0.3 m of subsidence; both middle to high marsh species. Our subsidence estimates will help constrain elastic and viscoelastic models of Cascadia earthquake deformation cycles and improve assessments of seismic and tsunami hazards throughout central western North America.

Ignimbrite Volcanism of the Deschutes Formation

Daniel W. Eungard, Adam J. R. Kent, Anita L. Grunder

College of Earth Ocean and Atmospheric Science

026 Wilkinson Hall

Corvallis OR, 97331

eungardd@onid.orst.edu

The silicic deposits of the Deschutes Formation of Central Oregon provide a record of the explosive output of the modern High Cascade arc following the transition from Western to High Cascade volcanism at ~8 Ma. To provide insight into the nature of magmatism and volcanism at this time two large silicic eruptive deposits, the Lower Bridge Tuff and McKenzie Canyon Tuff, were chosen for detailed study. We present data on deposit thickness, clast size and type, and results from XRF, EMPA, and LA-ICP-MS analysis of glass and mineral compositions. Minimum eruptive volumes of 5.5 and 3.8 Km^3 DRE were calculated from thickness isopachs of the Lower Bridge and McKenzie Canyon Tuff respectively, which places these eruptions at VEI 5 or greater. Imbrications of clasts in the McKenzie Canyon Tuff indicate a southwesterly source near the present day location of the Three Sisters Volcanic Complex. The Lower Bridge Tuff represents eruption of a homogeneous rhyolitic magma with restricted glass composition of 72-75 Wt% SiO_2 and with relatively evolved mineral compositions as seen in plagioclase of An_{15} to An_{54} and augite with Mg number of 47-67. In contrast, the McKenzie Canyon Tuff has two populations of glass having silica contents ranging from 55-61 and 71-75 wt% and bimodal mineral compositions. The eruption started as a rhyolite and became progressively more mafic with time as it tapped a compositionally zoned magma reservoir. Mineral compositions coincide with this trend as they progress from evolved to more mafic compositions as seen in plagioclase compositions ranging from An_{20} to An_{87} and augite having Mg# of 50-74. Olivine of Fo 79-83 also occurs in the uppermost portions of the unit. The Lower Bridge and McKenzie Canyon Tuff are two out of more than a dozen distinct ignimbrites in the Deschutes Formation. The age span of the Deschutes Formation is 7.6-4 Ma based on Ar-Ar dates by Smith (1986). We estimate that explosive silicic volcanism of VEI 5 and greater occurred at an overall rate of at least one eruption per 300 ka.

Seismic surface wave observations of the structure and anisotropy of mid-ocean ridges and Cascadia

Donald W. Forsyth

The propagation of Love and Rayleigh waves provides constraints on the shear velocity structure of the lithosphere and asthenosphere, giving clues to the distribution of melt and the temperature structure. The azimuthal anisotropy of Rayleigh waves yields information on the possible flow patterns in the mantle by constraining the depth distribution of seismic anisotropy. This poster summarizes some of the previous observations of upper mantle structure and anisotropy in Cascadia and on spreading centers to indicate what type of resolution might be obtained using the regional arrays of land and sea seismographs in the Cascadia Initiative.

Seismic evidence for 3D decompressional melting at the Cascadia subduction zone

Haiying Gao and Yang Shen

University of Rhode Island

Melt generation and volcanism in subduction zones may result from several possible processes: hydration of the mantle wedge by fluid released from the slab, reheating of downgoing sediments/crust, and upwelling induced by subduction. Each process predicts a different pattern of melt generation and can thus be distinguished with high-resolution seismic imaging. Here we construct a comprehensive crustal and upper mantle structure of the Cascades with a full-wave tomographic method. We use continuous seismic data recorded by about 600 stations between 1995 and 2011 in an area covering from northernmost California to northern Vancouver Island, Canada. The empirical Green's functions are extracted from inter-station cross correlation at periods of 7-200 seconds. We simulate full-wave propagation within a 3D reference velocity model. The travel time anomalies are measured from the observed and synthetic Green's functions. The shear and compressional velocities are inverted jointly as Rayleigh waves are sensitive to both V_p and V_s . The solution from inversion is used to iteratively update the 3D reference model. Our model shows that there exist segmented low shear-wave velocity (~ 3.8 km/s) volumes beneath the back-arc at depths of 80-115 km and are ~ 250 km away from the Cascades arc. The very low-velocity anomalies require existence of partial melt. These back-arc low-velocity volumes extend upward to the volcanic arc in the Cascades, and are spatially correlated with the three volcano clusters along strike. Our seismic findings suggest that decompression melting in the upper mantle wedge is a highly 3D process that defines the segmentation of volcanism along the Cascades.

Quantifying the size of bubbles that burst to produce very fine ash during the May 18, 1980 eruption of Mount St. Helens

Kimberly Genareau, Gopal Mulukutla, Alexander A. Proussevitch,

Dork L. Sahagian, Adam J. Durant

Explosive volcanic eruptions emit large proportions of very fine ash ($< 32 \mu\text{m}$) into the atmosphere, posing hazards to aviation, infrastructure, and human health. Here we present an analysis of bubble size distributions at the point of fragmentation during the 18 May 1980 eruption of Mount St. Helens (MSH). The external surfaces of individual fine ash grains preserve the morphology of the bubbles that burst to form the ash, so bubble sizes can be measured using stereo-scanning electron microscopy. For the study presented here, we examined simple ash particles, defined as ash grains that display the remnants of individual bubble walls or Plateau borders, which separate the imprints of adjacent vesicles. Simple particles are particularly significant because: 1) They represent the most efficiently fragmented portion of the magma; 2) the number density of simple particles dominates in highly explosive eruptions compared to ash grains that preserve the imprints of multiple vesicles (i.e., compound ash particles) and; 3) simple particles comprise the finest ash fraction, which is responsible for the greatest ash-related hazards for aviation safety and human health. BSDs of simple ash particles were obtained from four sample locations at various distal locations (200-700 km) from the vent. All samples display a unimodal BSD with the peak in vesicle volumes between 560 and 5600 μm^3 . Assuming a spherical shape, this peak corresponds to a modal equivalent vesicle diameter of 10-22 μm . Values obtained for the finest ash fraction are consistent between all examined samples, indicating that the modal bubble size in the very fine ash fraction does not vary significantly as a

function of distance from source. Determination of syn-eruptive bubble sizes thus makes it possible to glean information regarding pre-eruptive conduit dynamics from observed ash deposits, to parameterize numerical eruption models in ways not previously possible, and to quantify the size of bubbles that burst to create the ash component most hazardous to the aviation industry and human health.

Patches of asperity in the transition zone control evolution of slow earthquakes

Abhijit Ghosh^{1,2} (aghosh.earth@gmail.com), John E. Vidale¹, and Kenneth C. Creager¹

¹Department of Earth & Space Sciences, University of Washington

²Now at Department of Earth & Planetary Sciences, UC Santa Cruz

Slow earthquakes, characterized by slow slip and associated seismic radiation called non-volcanic tremor, has been observed in major subduction zones worldwide. They release much of the stress from the fault's transition zone, which lie directly down-dip of the locked segment, the nucleation zone of large damaging earthquakes. However, the depth of the tremor in Cascadia, and the factors governing tremor generation and rupture propagation during slow quakes remain enigmatic. We develop a novel multi beam-backprojection (MBBP) method to detect and locate tremor using multiple seismic arrays. We apply this technique to image tremor activity during an entire ETS-cycle including a large episodic tremor and slip (ETS) event in Cascadia with unprecedented resolution. Our results suggest that the majority of the tremor is occurring near the plate interface. We observe strongly heterogeneous tremor distribution with patches in the transition zone that experience repeated tremor episodes and produce majority of the tremor (Figure 1). During the large ETS event, rupture propagation velocity varies at least by a factor of five, and seems to be modulated by the tremor patches. Preliminary results suggest that the 2010 and 2011 ETS events rupture the same patches in the up-dip part of the transition zone. These observations support a model in which transition zone is heterogeneous and consists of patches of asperities with surrounding regions slipping aseismically. The asperities fail quasi-periodically to release stress and appear to regulate rupture propagation and tremor generation during slow earthquakes. This study present new observations revealing the tectonic characteristics of the transition zone controlling the generation and evolution of slow earthquakes.

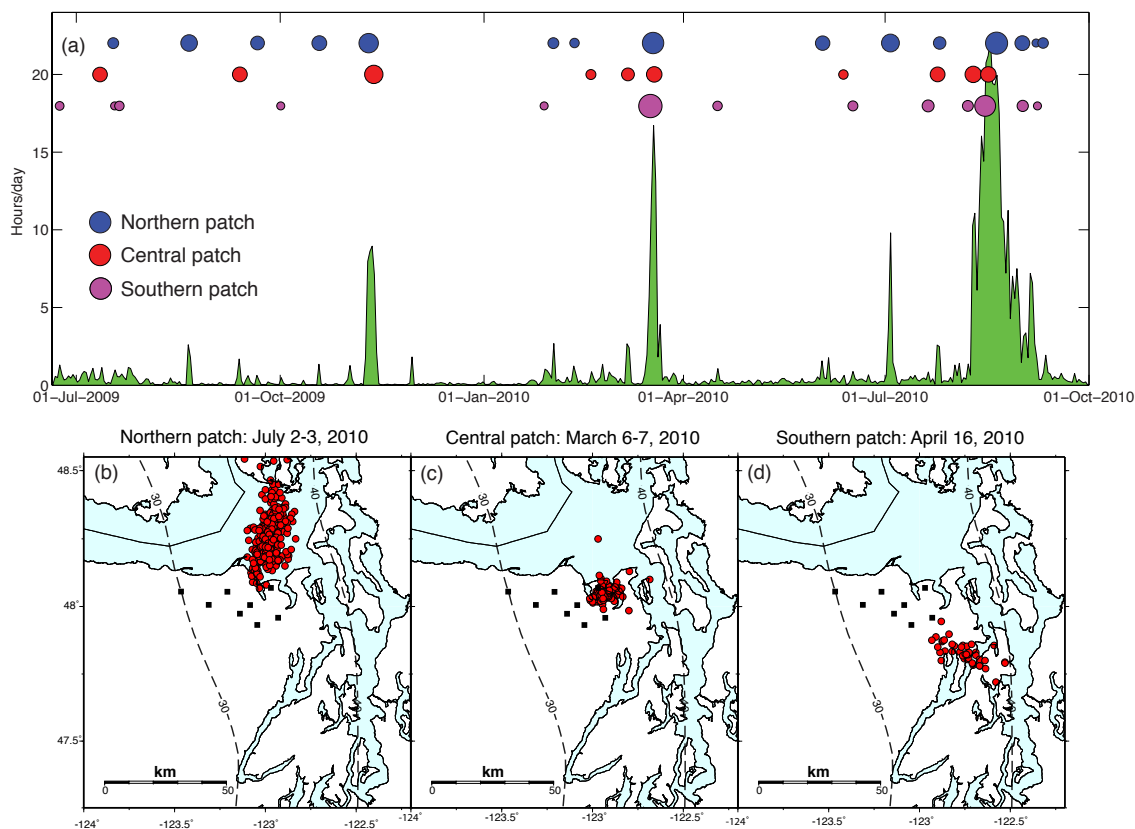


Figure 1: Panel (a) shows tremor activity detected by the MBBP algorithm during the 15.5 months studied here. Colored circles indicate timings and durations of the tremor episodes occur repeatedly in three down-dip patches. Circles are scaled by the duration (the largest 6 days, the smallest 2 hours). Panels (b), (c) and (d) show examples of typical tremor episodes in each down-dip patch.

Late Holocene Paleoseismicity, Tsunamis, and Relative Sea-Level Changes in Yaquina Bay, Central Coastal Oregon

Graehl, N.A.¹, Kelsey, H.M.¹, Witter, R.C.²

¹Humboldt State University Geology Department (nickgraehl@gmail.com)

²Oregon Department of Geology and Mineral Industries

Wetland sediments that border Yaquina Bay and the lower Yaquina River on the central Oregon coast record paleoearthquakes on the Cascadia Subduction Zone (CSZ). We used gouge corers, Russian peat augers and test pits to examine shallow (3-7 m deep) stratigraphy beneath intertidal and freshwater marshes surrounding the estuary. We focused eight weeks of field investigations at Sally's Slough because of the presence of a long and stratigraphically contiguous record of buried peat layers overlain by sheets of sandy silt or tidal mud.

Three approaches were used to determine whether buried soils and associated sandy silt deposits at Sally's Slough record late Holocene Cascadia earthquakes and tsunamis. The first approach involved detailed descriptions of subsurface stratigraphy gathered from closely spaced cores in order to correlate buried soils among sites and assess lateral continuity of buried soil horizons. Correlations were based on lithostratigraphic characteristics and relative elevation of the sharp upper contacts of peat. The second entailed radiometric dating of candidate buried soils using spruce needles and other identifiable detritus to assess correlations between buried soils in adjacent cores and to test the degree of synchronicity of regional Cascadia megathrust earthquakes. The third employed diatom biostratigraphic data to assess paleoenvironmental changes across peat-mud and peat-sandy-silt contacts and to estimate the amount of land-level change (relative sea-level rise) based on changes within in-situ diatom assemblages.

Great earthquakes on the CSZ dropped Yaquina Bay and surrounding tidal marshes and freshwater spruce bogs to low marsh conditions at least twelve times during the last 4,500 yrs B.P. Furthermore, nine of the twelve buried soils were accompanied by an overlying sandy-silt deposit that gradually fined up section into an estuarine mud. If the soils are buried by subsidence accompanying a subduction zone earthquake, we infer that the mechanism transporting sandy silt to the site is tsunami. Diatoms within the sandy silt material indicate that the material was sourced from a tidal flat (Yaquina Bay) and that buried soils developed in a high to upland freshwater marsh environment before being abruptly subsided to low marsh conditions.

The chronology of subduction related earthquakes recorded at Sally's Slough in the Yaquina River estuary is in part consistent with paleoseismological investigations along other parts of the CSZ. Ages of buried soils closely match the chronology of earthquakes from adjacent estuaries. One possible interpretation based on comparing subduction zone earthquake chronologies in adjacent estuaries is that a central segment of the CSZ (Yaquina Bay to Cannon Beach) may have ruptured between ~500-700 yrs B.P. If this interpretation withstands further work in central Oregon estuaries, then the Yaquina Bay paleoseismic record provides evidence that the CSZ can rupture in segments.

3D Multichannel Seismic Imaging of Off-Axis Melt Lenses at the East Pacific Rise: Potential Heat Sources for Ridge Flank Hydrothermal Fluid Circulation

Shuoshuo Han¹, Suzanne Carbotte¹, Helene Carton¹, John Mutter¹, Juan Pablo Canales², Mladen Nedimović³

1. Lamont-Doherty Earth Observatory. 2. Woods Hole Oceanographic Institution. 3. Dalhousie University.

Water content in the down-going plate strongly affects volcanic and seismic processes at subduction zone. The incorporation of water into oceanic lithosphere begins with high temperature fluid circulation at the axis of mid-ocean ridges driven by heat from magma and hot crustal rocks, continues for millions of years as lower temperature fluid circulation on the ridge flanks, is potentially enhanced at the outer trench rise prior to subduction with active faulting due to plate bending, and may still continue at the trench as the plate descends.

On mid-ocean ridges, it is believed that high temperature hydrothermal flow is confined near ridge axis with its driving force provided by crustal magma chambers found in the mid-crust. However, Haymon et al. (2005) reported the discovery of actively venting fluids (up to 150°C) and mineral deposits associated with an abyssal hill located ~5 km from the East Pacific Rise (EPR) axis at 10°20'N. Recent Multichannel Seismic (MCS) studies have imaged off-axis melt lenses (OAML) outside the axial low velocity zone at Juan de Fuca Ridge (JdFR) (Canales et al. 2009) and East Pacific Rise near 9°N (Canales et al. 2012). Here we present 3D MCS images of a prominent OAML on the eastern flank of EPR around 9°39'N. This OAML is ~3 km x 3 km in size, located ~3-5 km from the ridge axis at 0.7- 0.8 s two-way travel time below the seafloor. The deepened Moho under the OAML on the time migration section suggests a low velocity zone beneath it. The OAML and its associated low velocity zone may serve as potential heat sources for localized high-temperature hydrothermal circulation on the ridge flanks, contributing to the hydration of young oceanic crust. This OAML and other OAMLs imaged in EPR 9°N area and JdFR are located deeper in the crust than the axial magma chamber, which indicate that the high temperature fluid circulation driven by them and the associated crustal alteration may extent deeper in the crust than at the axis.

In order to constrain the hydration of oceanic lithosphere across all the regimes, including the ridge, near ridge, ridge flank, and the trench, using seismic methods, we will conduct an active source seismic study (long-streamer MCS and wide-angle OBS 2D profiles) from the Juan de Fuca ridge across the entire JdF plate to the Cascadia subduction zone in June 2012. Survey plan will be presented in the meeting.

Absolute gravity in the northern Cascadia Subduction Zone: The lighter (and heavier) side of long-term and transient deformation monitoring

J.A. Henton¹, H. Dragert², A. Lambert², S. Mazzotti³, T. James² and N. Courtier²

¹ Geodetic Survey Division, Natural Resources Canada, Pacific Geoscience Centre, 9860 West Saanich Road, Sidney, BC V8L 4B2, Canada

² Geological Survey of Canada (Pacific), Natural Resources Canada, Pacific Geoscience Centre, 9860 West Saanich Road, Sidney, BC V8L 4B2, Canada

³ Géosciences Montpellier, Université Montpellier 2, UMR 5243 - CC 60, Place E. Bataillon, 34095 Montpellier cedex 5, France

On southern Vancouver Island (SVI), situated in the forearc of the northern Cascadia Subduction Zone, absolute gravity (AG) measurements have been made typically three to four times per year for over a decade at four sites. AG observations are sensitive to both vertical motion of the observation site and mass redistribution within (and below) the underlying deforming crust. The deformation gravity gradient (DGG), defined as the ratio of the time rate of change of surface gravity ($\dot{g}$) to vertical crustal velocity ($\dot{h}$), provides insight into the deformation process. For the four AG stations on SVI, earlier comparisons between the observed gravity trends and vertical GPS rates indicated a linear DGG that is appropriate for a subduction zone. In order to further investigate the bias for SVI, we systematically re-processed continuous GPS data from stations of the Western Canada Deformation Array using the NRCan's Precise Point Positioning (PPP) software. To provide a broader comparison, we also analysed three additional long-term AG sites in western Canada. In contrast with the earlier analyses, the DGG is poorly defined and does not show a clear agreement with the subduction model-predicted gradient ($-0.2 \mu\text{Gal}/\text{mm}$). However the offset between the AG trends and GPS uplift rates is confirmed by the new data, with an indication that stations closer to the subduction fault may see a larger mass increase than stations further away. A tentative correlation between positive gravity residual rates and interseismic strain rates is observed, possibly related to deformation of the forearc crust due to the interseismic loading of the subduction fault.

The monitoring of subduction zone Episodic Tremor and Slip (ETS) has been carried out primarily using seismic data for tremor and continuous Global Positioning System (GPS) and strain-meter observations for transient slip. The regularity of ETS episodes in the northern Cascadia Subduction Zone has recently allowed us to schedule a series of absolute gravity (AG) measurements to augment these other data and thereby help in understanding the physical processes involved in the generation of ETS. For the 2010 ETS event in the northern Cascadia, AG observations were carried out at Port Renfrew, British Columbia. The Port Renfrew region was targeted since it has typically had large ($\sim +7\text{mm}$) vertical displacements measured at a nearby GPS site. Additionally this region has experienced large strains during past ETS episodes. The closest PBO borehole strainmeter to Port Renfrew, B004 (Sekiu, WA), typically experiences ETS shear strain transients exceeding 100 nanostrain. Although preliminary, the analysis of the multiple-epoch series of AG observations at Port Renfrew during the 2010 ETS event indicate a gravity decrease larger than expected for observed GPS height change associated with thrust faulting. The residual gravity loss, after accounting for the gravity change predicted from the observed height change, may reflect a loss of fluids and/or a decrease in mean density. Future monitoring of ETS events will be augmented by continuous gravity measurements (*e.g.*, with earth-tide and/or superconducting gravimeters).

THE LANDWARD LIMIT OF CASCADIA GREAT EARTHQUAKE RUPTURE

R.D. Hyndman, K. Wang, J. Cassidy, H. Kao, S. Mazzotti, H. Dragert,
L. Leonard, and G. Rogers

Pacific Geoscience Centre, Geological and Geodetic Survey of Canada
and SEOS, University of Victoria

Abstract

The most critical constraint to ground motions and earthquake hazard from Cascadia great subduction earthquakes is the landward limit of rupture. We review the constraints, the assumptions, the uncertainties, the consistencies, and the inconsistencies from the different methods. We also discuss what these results indicate about great earthquake fault behavior. The methods include: (1) The downdip rupture limit for the 1700 and earlier events from coastal marsh coseismic subsidence, (2) Geodetic constraints to the “locked zone” where elastic strain is accumulating for future rupture, (3) Maximum temperature limit for seismic behaviour on the subduction thrust, (4) Change in thrust seismic reflection characteristics downdip from thin inferred brittle seismic fault zone to thick reflective aseismic shear zone, (5) The updip limit of ETS slow slip on the thrust where little or no long-term elastic strain is concluded to be accumulating, (6) The forearc mantle corner; downdip aseismic serpentinite and talc are expected on the thrust, (7) Geological associations with rupture, i.e., basins just offshore etc. Also important is method calibration from recent great earthquakes elsewhere. The rupture displacement is expected to taper landward over some distance. Taking 50% of full rupture as a reference, the concluded rupture limit is mainly offshore except for a few locations. There are large uncertainties but all of the constraints give consistent downdip limits except for the ETS slow slip and the forearc mantle corner both of which give a landward limit that is approximately 30 km downdip of the other constraints. The constraints provide rupture limit averages. Substantial variability in rupture area is expected for individual earthquakes.

Mantle Flow and Seismic Anisotropy Associated with Plume-Plate Interaction

Garrett Ito, Robert Dunn, Yuanyuan Fu, Alejandro Gallego, Aibing Li, Cecily J. Wolfe
SOEST, 1680 East-West Rd. POST 810, University of Hawaii, Honolulu, HI 096822

Numerical models are used to simulate upper mantle flow and the development of lattice preferred orientation (LPO) of mantle minerals in order to predict seismic anisotropy associated with mantle plumes interacting with the lithosphere. The 3D mantle flow of a steady plume interacting with a lithospheric plate is computed using finite elements, and the LPO and seismic anisotropy are computed by solving the fabric evolution of olivine and enstatite aggregates using Kaminski and Ribe's DRex. For an ideal axisymmetric case of a vertical plume beneath a stationary plate, the plume stem rises below and feeds a layer of hot plume material spreading like a pancake beneath the plate. In the shallow part of the pancake, the fast P -wave speed (V_p) directions, the long axes of the finite strain ellipsoids (FSE), and the mantle flow are all predicted to be parallel to each other and be directed radially away from the plume stem. In the deeper part of the pancake, however, the directions of fast V_p as well as the FSE are predicted to be orthogonal to the flow and directed circumferentially around the plume axis. This pattern is caused by the pancake material elongating circumferentially and contracting vertically as it expands. With a moving lithospheric plate, the fast V_p directions are circumferential in the deeper part of the pancake and then transition to having a strong, plate motion-parallel component in the shallower part.

Shear wave splitting and surface wave anisotropy measurements are computed for different situations. Cases with a plume that is centered on and thus interacting with a mid-ocean ridge predict fast split directions that angle toward but that do not parallel the ridge axis. Such predictions can explain the fast shear-wave split directions measured over eastern Iceland. For an intraplate plume, the shear wave splitting created within the plume pancake and below the lithosphere show fast directions that radiate outward on the upwind side of the plume but are at a large angle, often perpendicular, to the plume flow on the downwind side. This pattern is consistent with shear-wave splitting observations around the Eifel hotspot with a Eurasian plate that has a strong eastward—not westward—motion, which is consistent with global plate-motion models with small net westward plate motion. Shear wave splitting around the Hawaii hotspot appear to show strong influence by the fossil anisotropy in the oceanic lithosphere. Models that incorporate the combined effects of fossil lithosphere fabric in addition to anisotropy in the plume beneath the lithosphere can explain most of the split directions seen around Hawaii. Overall, our results show that for the strong spatially variable flow associated with plume-lithosphere interaction LPO that parallels mantle flow is the exception rather than the rule. Accurate interpretations of shear-wave splitting and surface wave anisotropy in terms of mantle flow require self-consistent calculations of mantle flow and the development of LPO.

The history of explosive volcanism in the Central Oregon Cascades: Insights from the Deschutes Basin.

Adam J. R. Kent, Daniel Eungard, Anita L. Grunder and Robert A. Duncan
College of Earth, Ocean, and Atmospheric Sciences (CEOAS)
Oregon State University, Corvallis, OR.

Although the Cascades are often viewed as an arc system with low explosive volcanic output, a number of large Plinian Quaternary eruptions have been documented. Before this time the published record is less clear, although such a long term record would provide key constraints on arc behavior and subduction processes. Herein we present initial results from a project designed to establish the temporal, volumetric, compositional and petrologic nature of the explosive silicic magmatic output of the central portion of the Cascade arc during Neogene times (~4-15 million years). The work is based on study of a remarkable section of volcanoclastic and pyroclastic deposits accumulated within the Deschutes Basin, located to the east of the modern arc in Central Oregon. Numerous volcanic units related to moderate and large size (VEI 3-5) explosive eruptions along the High Cascades between ~4-15 Ma are exposed within the basin.

Summaries of existing data show that pumice and ash shards have a range of compositions, with SiO₂ between 55-75 wt.%, and many individual eruptions show multiple pumice compositions consistent with magma mixing immediately prior to eruption. FeO-SiO₂ systematics suggest that Deschutes Formation volcanics have compositions that are intermediate between those found in the Quaternary High Cascades and the higher FeO compositions found in eruptives along the High Lava Plains trend.

Although our work is in an early stage we suggest that reconstruction of the Miocene and Pliocene explosive eruption record will improve our understanding of the Cascadia subduction system in a number of important ways: (1) documenting the record of explosive volcanism through time, and providing the means to relate this record to tectonic and other forcing factors; (2) providing a basis for studying the earliest phases of the High Cascades arc and the transition between Western Cascades volcanism to the High Cascades, (3) improved comparisons between the relatively well-studied Quaternary rocks of the Cascades and earlier episodes of arc volcanism, and (4) allowing for more complete comparisons between the Cascades and other subduction systems. Our work will also provide a stratigraphic and temporal framework for ongoing and future studies of basalt and sediment provenance and structural evolution within the Deschutes Basin and surrounding regions.

Mapping fluids in the Cascadia subduction zone using marine electromagnetics

Kerry Key

Scripps Institution of Oceanography, UCSD

kkey@ucsd.edu

Fluids play an important role in the processes occurring at subduction zones since the release of water from the down going slab impacts seismicity and enhances arc volcanism. Despite this importance, crucial details of the fluid flux remain poorly constrained by geophysical observations. A major uncertainty offshore Cascadia concerns the volume and distribution of fluids in the crust and mantle of the incoming oceanic plate, and how these fluids are released in the down going slab. Since bulk electrical conductivity is highly dependent on the presence of pore fluids such as water and melts, electromagnetic (EM) induction methods provide one of the only non-invasive techniques for constraining the distribution of fluids over broad spatial and depth scales. The marine controlled source electromagnetic (CSEM) method uses a deep-towed source to transmit energy through the lithosphere to an array of seafloor EM receivers, providing constraints on fluids in the crust and shallow uppermost mantle. The magnetotelluric (MT) method use seafloor EM receivers to measure naturally occurring low-frequency EM induction, providing broader-scale sensitivity to fluids in the crust and upper mantle. This poster reviews recent constraints on fluid fluxes obtained from marine EM surveys offshore Central America (Figure 1) and Hydrate Ridge, Oregon, and discusses how future marine EM surveys can address some of the outstanding fluid questions listed in the GeoPRISMS Draft Implementation Plan.

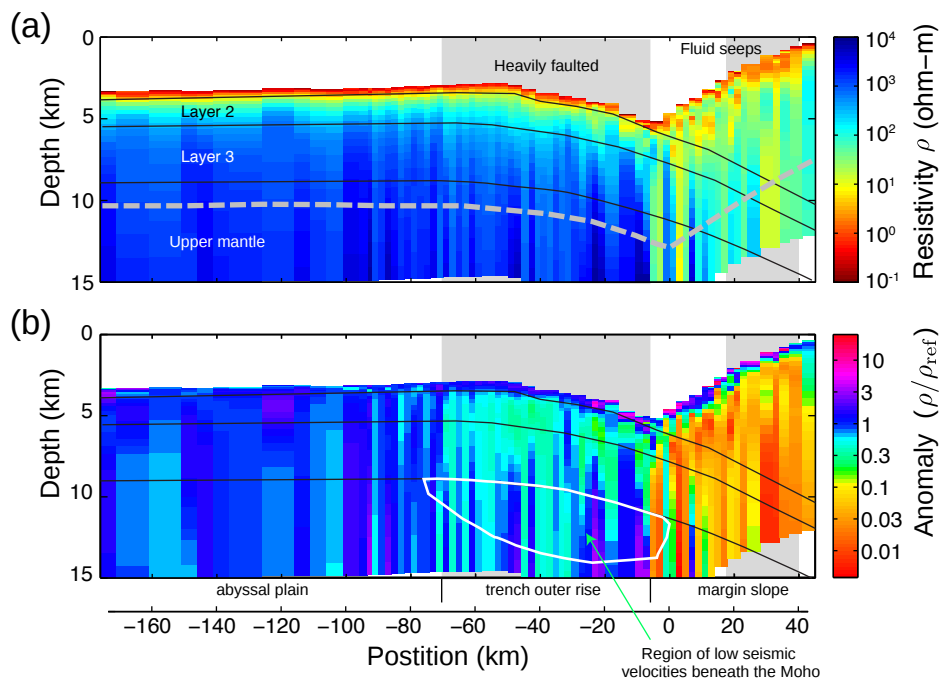


Figure 1: Controlled-source EM detection of fluids in porous trench outer rise faults from the SERPENT project in the subduction zone offshore Nicaragua (Key et al., submitted). (a) Resistivity section obtained from 1D inversion of each receiver's data. The dashed grey line indicates the maximum depth of resolution. (c) Anomalous resistivity (the values in A normalized by an average 1D profile) shows a factor of 3 decrease in crustal resistivity beneath the heavily faulted trench, indicating the presence of conductive fluids in the faults. Shallow low resistivity on the margin occurs near a band of fluid seeps 20-40 km inland of the trench axis that is thought to be associated with fluid expulsion from subducting sediments.

<http://marineemlab.ucsd.edu/projects/SERPENT/>

Ambient Noise Non-Linear Time Correction for Ocean Bottom Seismometers

King, C. and Shen, Y.

Ambient noise analysis of Ocean Bottom Seismometers (OBS) has lead to realization that clock times may vary non-linearly with deployment. Modern methods include linear interpolation between deployment and recovery of the OBS. Linear interpolation thus leaves significant error that affects all time based seismic analysis and tomography. We use 24 OBS stations from the PLUME 2005 deployment and 12 land stations from the Global Seismograph Network and GEOFON network to complete this study. We preformed Earthquake response removal, frequency filtering and resampling to 10 samples per second on daily seismic traces. Between station pairs, we calculate the Empirical Green's Function (EGF), stacking daily EGFs into 2-month stacks and cross correlating these stacks with a reference EGF. Least squares optimization of our data shows that the mean absolute clock drift is 0.1s with a maximum time drift of 1.2s. Variance in the residuals, the difference between the data and calculated clock drift, constrains our uncertainty.

Magma mixing and potential magmatic sources below Mount Hood, Oregon

Alison M. Koleszar, Adam J. R. Kent
Oregon State University

Mount Hood, the northern-most Cascades volcano in Oregon, erupts compositionally homogeneous intermediate lavas that are produced by magma mixing between silicic and mafic endmembers. The long-term compositional homogeneity of lavas produced at Mount Hood shows that the composition of the parent magmas and their mixing proportions have remained remarkably constant for the 500,000 year lifetime of the edifice, suggesting long-term stability of both the source magmas and the plumbing system that controls the process of mixing. We combine several types of geochemical data to examine mixed lavas that erupt from Mount Hood, with the goal of characterizing the parental endmembers and identifying their sources.

Virtually all of the lavas erupted from Mount Hood are produced by magma mixing; the endmember magmas do not erupt and therefore cannot be directly sampled. Kent et al. (2010) used the limited range in whole rock compositions and the presence of two plagioclase populations to estimate the potential parent magmas at Mount Hood by linear regression. These calculations suggest that the parents are likely a basalt/basaltic andesite and a rhyodacite/rhyolite. These previous results, based on whole rock compositions, can be combined with phenocryst and melt inclusion data to more thoroughly describe the parental magmas that participate in mixing at Mount Hood.

We identify two populations of calcic amphibole in lavas erupted from Hood, indicative of crystallization from two different parent magmas. Compositional differences between these two amphibole groups, including Al/Si and Fe/Mg ratios, Eu-anomalies, and other trace elements indicate parental magma compositions similar to those calculated by Kent et al. (2010). The use of appropriate trace element partition coefficients allows us to estimate trace element contents of these parent magmas, necessary to characterize the source regions for the magmas involved in mixing at Mount Hood.

The silicic endmember calculated from whole rock data and indicated by the compositions of magnesiohornblende in lavas erupted at Mount Hood is broadly consistent with the composition of high-SiO₂ melt inclusions hosted in plagioclase, pyroxene, and amphibole. Likewise, the calculated mafic endmember is broadly in agreement with the magma composition suggested by tschermakitic pargasite. The mafic endmember at Mount Hood has a trace element signature consistent with typical Cascades calc-alkaline basalt (CAB), including Nb-Ta troughs and enrichment in large ion lithophile elements (LILE) relative to high-field strength elements (HFSE), reflecting slab input into the subduction zone. The sources of parent magmas are often obscured by the process of magma mixing, but can be deconvolved by examining crystal cargo and melt inclusions derived from separate parental magmas.

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Long-term strain accumulation in the Cascadian slow slip zone constrained by leveling and tide gauge data

Randy D. Krogstad, David A. Schmidt, Ray J. Weldon II, Reed J. Burgette
Department of Geological Sciences, University of Oregon

Analyzing leveling lines in western Oregon, Burgette et al. [2009] identified a pervasive 0.4 ± 0.3 mm/yr uplift signature that tracks along the eastern edge of the coast range, which does not seem to correlate with elevated topography. The uplift signature cannot readily be resolved with locked zone models that prescribe a slip rate deficit that decreases monotonically with depth, as is typically done. We explore the hypothesis that strain is being accumulated in the episodic tremor and slip (ETS) zone and is not completely released during slow slip events.

A backslip methodology is used to input a down-dip locking profile and relative slip deficit rates along the fault interface from which resultant uplift patterns are calculated. The slip deficit within the locked zone is assumed to equal the full convergence rate, while exponentially decaying to zero along the transition zone. Free parameters related to the locked zone are the down-dip extent of the locked zone and the down-dip extent of the transition zone. Parameters related to the slow slip zone are varied while being constrained using tremor locations and GPS derived inversion results of multiple slow slip events. The parameters of primary focus are the slip deficit and location of strain accumulation along the slow slip zone. Modeled results are then compared to the long-term leveling and tide gauge data to check for misfit and residual patterns.

Historical leveling and tide gauges provide precise uplift measurements over an interval of several decades with typical uncertainties lower than vertical GPS measurements. Also, the density of east-west data points along a leveling line provides an excellent source for determining uplift gradients. Analysis of the leveling data in Oregon shows that the data require a second zone of locking slightly updip of tremor locations in the slow slip zone. Assuming the locking profile follows the shape of a Gaussian, the optimal distribution has a 1-sigma down-dip width of 2 km and a peak strain accumulation rate that is $\sim 10\%$ of the plate convergence rate. If isolated from the dynamics of the up-dip locked zone, the strain accumulation in the slow slip zone would also cause an area of subsidence directly west of the slow slip zone. To account for the observed uplift in this area, the locked zone must be extended slightly down-dip than previously recognized. Recent long-term leveling data in Washington and northern California are also presented and reveal a similar, although less distinct, uplift signature above the slow slip zone. The significance of strain being accumulated in the slow slip zone is two fold: 1) shear resistance in the ETS zone is non-zero and 2) accumulated strain at ~ 35 km depth may be released during the next megathrust event, extending the fault rupture further inland toward large metropolitan areas.

The upland response to great subduction earthquakes in Cascadia-- potential signals from sedimentary archives

Elana Leithold and Karl Wegmann, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695

Over the past several decades, the occurrence of great ($M_w \geq 8$) earthquakes at the Cascadia subduction zone at 300-500 year frequencies has been established based on studies of subsided coastal lowland soils, low-lying coastal lakes and lagoons, fjords, and deep sea turbidites. Little is known, however, about the terrestrial upland response to great subduction or other large earthquakes in Cascadia. Based on research in other areas of the world with large topographic relief, earthquake-triggered landslides are likely to be a significant hazard to life and infrastructure faced during and in the immediate aftermath of future events. Furthermore, the Earth surface response will have decadal-scale impacts on sediment supply to fluvial networks and coastal margins, with implications for both fresh and salt water ecosystems. Over millennial time scales, moreover, mass wasting associated with large earthquakes has likely played a fundamental role in modulating the flux of terrigenous sediments to the marine environment and in the evolution of topography above Cascadia and other subduction margins.

In this poster we explore the potential for a lacustrine sedimentary record of co-seismic landsliding in the Cascadia uplands, with particular reference to Lake Quinault, a deep, glacial moraine-dammed lake on the Olympic Peninsula, Washington. We hypothesize that following a great subduction zone earthquake, the production of sediment by deep-seated bedrock landslides will overwhelm erosion via nearer-surface mechanisms on a decadal time scale. Because of their hypothesized greater depth of origin from beneath the surface, we predict that compared to other strata, the organic matter and sediments accumulating in Lake Quinault immediately after a large earthquake and continuing for several years will have distinctive geochemical signatures. We outline the potential for using stratigraphic geochemical signals to document and compare the basin-averaged impacts of mass wasting during repeated large earthquakes spaced over several millennia.

The Seismic Structure of the Mantle Wedge under Cascade Volcanoes

Alan Levander, Kaijian Liu, Robert Porritt, Richard Allen

For subduction corner flow models to be correct, the mantle wedge of a subduction zone must have an unusual lithosphere-asthenosphere boundary, as the reduced viscosities from slab dewatering, melting, and relatively hot return flow must move the lithosphere-asthenosphere boundary close to the base of the crust of the overriding plate. This should be detectable with several different seismic probes. Under a number of the volcanoes of the Cascadia arc we have identified a characteristic seismic signature in individual station Ps receiver functions and in Ps CCP image volumes made from USArray Transportable Array and Flexible Array stations. In the mantle wedge, the CCP images and the RFs show a strong negative event just below the Moho, paired with a weak to moderate positive event between 50-70 km, and a strong slab event. At most of these volcanoes, a strong negative signal also appears between 15 and 25 km depth in the crust. The signature is particularly clear under Mt. Lassen and to a lesser degree under Mt. Shasta in data from FAME (Flexible Array Mendocino Experiment), where instruments were close to the volcanic centers. Random averages using all stations throughout the western U.S., and only stations in the Cascadia backarc region show that this signature is not common to the western U.S. as a whole, nor to the backarc region in particular.

Joint inversion of the Ps receiver functions and ambient noise and ballistic Rayleigh wave phase velocities (Porritt et al., 2011; Liu et al., 2012) for those volcanoes with the paired events provides 1D shear velocity profiles having common characteristics. A strong sub-Moho low velocity zone from 5 to 15 km thick gives rise to the paired negative-positive signals in the receiver functions. These mantle wedge low velocity zones, with velocities of $3.7 < V_s < 4.0$ km/s, are evident in 30 of the 39 stations we examined, with velocity minima occurring at ~50-70 km depth. We speculate that this low velocity region is at the center or top of the corner flow beneath each volcano. The LAB is then either at or near the base of the crust, or below a thin lid. Directly beneath Mt. Lassen and Mt. Shasta, in the heavily instrumented Mendocino region, is a large, connected low velocity zone, that extends between the two volcanoes along strike. We interpret this as the locus of corner flow at the southernmost edge of Cascadia.

Cascadia stations not exhibiting this seismic signature have a different characteristic seismic structure: There is no abrupt velocity increase at Moho depths, instead V_s increases gradually from the lower crust to as deep as ~70 km, forming a thick, relatively high velocity layer ($4.0 < V_s < 4.5$ km/s), with a correspondingly deeper LAB. This is predominantly seen in stations toward the back arc.

This project was initiated as part of the CIDER 2011 summer program.

Trace metal behavior recorded in phenocrysts from 1980 eruptions of Mount St. Helens

Matthew W. Loewen and Adam J.R. Kent

Arc magmas associated with subduction zones such as Cascadia are often linked to the formation of magmatic ore deposits. Observing the processes associated with metal mobility and enrichment in active arc volcanoes can elucidate the controls that lead to the formation of such ore deposits. In addition, volatile element mobility in a volcanic system may be related to the timing and style of volcanic eruptions (e.g., Berlo *et al.*, 2004; Kent *et al.*, 2007; Rowe *et al.*, 2008). At Oregon State University we have developed and tested a protocol for trace metal analysis by laser ablation-ICP-MS that allows for accurate quantification of trace metal abundances at 30-50 μm scales. With this tool, we will measure a suite of trace metals including Li, Cu, Zn, Pb, Sn, and Mo in phenocryst phases from the 1980 eruptions of Mt. St. Helens to constrain the timing and depth of trace metal mobility in an arc volcanic system.

The conditions leading to the May 18, June 12, July 20, and August 8, 1980 Plinian eruptions of Mt. St. Helens are well understood with both extensive geophysical models of the magma chamber geometry and densities/textures of the pumice from each eruptive phase (Scandone and Malone, 1985; Cashman *et al.*, 2005). Hornblende is an especially attractive phase to examine as it can provide additional constraints on the temperature and depth of formation (Holland and Blundy, 1994; Rudolfi *et al.*, 2010) and the rate of ascent (Rutherford and Hill, 1993). Concurrent studies are expanding on trace metal behavior recorded in hornblende from the 2004 eruption of Mt. St. Helens (Hampel *et al.*, 2011). This study will focus on the 1980 eruptions expanding resolution of Li and Cu change and adding other potentially volatile metals (e.g., Zn, Pb, Sn, Mo). This work will develop an understanding of mobile element behavior both (1) at different depths in a volcanic system by comparing cryptodome and subsequent pumice hornblende from May 18, 1980 and (2) as a volcanic plumbing system changes with time by following amphibole chemistry over three Plinian eruptions in summer 1980 as the system moved towards more dominant dome growth.

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The Nicaragua/Costa Rica segment of the Middle America subduction zone exhibits seismogenic zone characteristics that are strongly dependent on plate structure, temperature, and fluid-related processes. Local earthquake tomography-derived velocity models aimed at characterizing lateral and downdip variability along the megathrust of this erosive margin have been limited to individual onshore/offshore experiments. This study utilizes data from a quality-controlled integration of amphibious datasets (Moore-Driskell *et al.*, in review) from the Osa and Nicoya networks collected as part of CRSEIZE (PIs. S. Schwartz/L. Dorman) and the Jaco/Quepos, Nicaragua, and Nicaragua outer-rise networks collected as part of the SFB 574 program (PIs. E. Flueh/W. Rabbel). The individual studies previously completed use different local earthquake relocation and tomography approaches that have led to variable resolution and velocity models that reflect the parameterization used for that particular inversion. We use the double difference local earthquake tomography approach, utilizing catalog derived absolute and differential times and waveform cross-correlation derived differential times. With the use of an automatic pick verification method, we limit our data to only the highest confidence arrival picks. Results using this data show improved hypocentral locations of seismogenic zone earthquakes and compressional and shear velocity structure of the seismogenic zone extending approximately 400 km along strike from Nicaragua through central Costa Rica. The coarse grid (20 x 20 km) compressional velocity images are used to develop a higher resolution model using 10 x 10 km and 5 x 5 km inversion grids. Highest resolution occurs within the shallow seismogenic zone, but we also image the nose of the forearc mantle wedge. We find that the updip limit of seismogenic zone microseismicity is variable and may be located closer to trench in Nicaragua. The interplate interseismic microseismicity occurs near the expected continental Moho intersection with the subducting plate interface, and comparison with recent subduction tremor, which occurs downdip of microseismicity, suggests that the tremor may be a better proxy for the downdip limit of rupture during major earthquakes. Results provide insight into the role of fluids within the seismogenic zone and shallow forearc mantle.

Evidence of Cascadia Earthquakes in Lacustrine Sediments

Ann E. Morey, Chris Goldfinger and Amy M. Garrett

Lacustrine sediments have been used successfully over the past few decades to develop earthquake chronologies and rupture assessments in a variety of locations and settings around the world, yet few sedimentary archives from inland lakes in the Pacific Northwest have been explored for evidence of Cascadia great earthquakes. We have recently investigated lacustrine sediments recovered from four lakes; three from the Klamath Mountains at the Oregon-California border, and one from the central Oregon Coast Range, for evidence of earthquakes. Sediment cores from these sites contain inorganic minerogenic layers with distinctive features in their physical properties that correlate between lakes and to seismogenic offshore turbidites, with supporting age control. Detailed analyses of disturbance event properties, and the great distance and multiple depositional environments over which these events correlate, suggests that Cascadia lakes contain seismogenic deposits, and supports the hypothesis that gravity-driven seismogenic sediment deposits may record a crude primary signal of shaking which we call a “paleoseismogram.”

High precision Sr-Nd-Hf-Pb isotopic data on northern Cascade arc basalts reveal spatial gradients in mantle source compositions and subducting sediment input

Emily K. Mullen*, Dominique Weis and Marion Carpentier

Pacific Centre for Isotopic and Geochemical Research, University of British Columbia, Earth and Ocean Sciences, Vancouver, B.C. Canada V6T1Z4

*emullen@eos.ubc.ca

The northernmost segment of the Cascade Arc, from Glacier Peak northward, is known as the Garibaldi Volcanic Belt (GVB) and is separated from the remainder of the arc by an abrupt bend in the orientation of the arc axis. In the Cascade Arc, primitive magmas are predominantly calc-alkaline. In the GVB, however, basalts display a progressive northerly shift from calc-alkaline to alkalic compositions, with hawaiite and alkali olivine basalt at the northernmost vents, Mt. Meager, Salal Glacier and Bridge River cones [1,2]. The gradient in alkalinity is accompanied by a northerly reduction in “arc signature” and increases in P and T of basalt generation [2,3]. These trends may be related to the age of the subducting plate at the trench, which decreases ~4 Myr northward [4], potentially leading to reduced slab inputs and consequently smaller melt fractions formed at greater depths [2]. New high-precision whole-rock Sr-Nd-Pb-Hf isotope and trace element data have been obtained on GVB basalts to characterize the mantle beneath each volcanic center and determine whether the geochemical gradients displayed by the basalts can be explained solely by changes in slab input or require multiple mantle components.

Relative to other primitive Cascade arc basalts, GVB basalts have higher ϵ_{Nd} at a given $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{208}\text{Pb}/^{204}\text{Pb}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$. The Pb isotopic ratios of the GVB alkalic basalts are among the most primitive yet identified in the Cascade Arc. In Pb isotopic space, the GVB defines a linear array extending from Juan de Fuca MORB to subducting sediment in the northern Cascadia basin, interpreted as a mixing line indicating variable sediment input to the mantle. Sediment input is negligible in the alkalic basalts, consistent with the absence of HFSE anomalies and low La/Nb, and generally increases progressively to the south (with the exception of a high alumina olivine tholeiite from Glacier Peak that records minimal sediment input). However, Hf-Nd isotopic data require two distinct depleted mantle components, one dominating in the northern GVB and the other, variably modified by slab input, in the south. Inverse correlation of ϵ_{Nd} and ϵ_{Hf} is consistent with arc-parallel mantle mixing.

Trace element modeling, phase equilibria and thermobarometry indicate that the GVB alkalic basalts segregated from the mantle at high pressures and MORB-like temperatures (up to ~2.7 GPa, 1475°C) and have garnet lherzolite residues. The mantle source is not modified by a subduction component and is isotopically depleted. Unless the alkalic basalts represent extremely low melt fractions, the mantle source is enriched in incompatible elements, indicating a recent metasomatic enrichment event superimposed on long-term mantle source depletion. In contrast, calc-alkaline basalts of the southern GVB were generated near the base of the crust from depleted lherzolite or harzburgite modified by sediment melt or fluid [3].

Because the GVB alkalic basalts lack an arc signature, have a hot and possibly recently-enriched mantle source, and are located at the termination of the currently subducting slab, a “slab edge effect” may be responsible for their generation. In this scenario, decompression melting is triggered by upwelling of asthenospheric mantle through a window between the active Juan de Fuca plate and near-stagnant Explorer plate [5,6], along the subducted trace of the Nootka fault.

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Leland O'Driscoll

Imaging of the southern Juan de Fuca slab: improving upper mantle seismic structure through the inclusion of 3D raypaths in P-wave delay time inversion

We focus on the slab structure beneath the recently conducted Mendocino FlexArray experiment in the greater northern California region. Previous imaging of the Juan de Fuca plate exhibits an increase in the fastness of seismic velocity perturbation within the Gorda segment in comparison to the plate segment beneath Oregon and southern Washington. We incorporate data primarily from the TA, the Mendocino FlexArray and the short-period NCEDC stations. Following the methodology of *Schmandt and Humphreys* (2010), we use finite-frequency sensitivity kernels, high-resolution crustal velocity models for travel time corrections, and apply careful scrutiny of input data. Here, we improve on the inversion methodology by inclusion of 3D raypaths, where we trace through a starting 3D velocity model and update raypaths (and travel times, when applicable) through successive iterations. Compared to previously published images of velocity perturbation structure, we find the Gorda segment of the Juan de Fuca slab to (1) penetrate to a shallower depth, (2) display a thinner lithospheric thickness, and (3) have a tight curvature at its southern terminus.

We also test the hypothesis that the slab (or subslab) and/or adjacent asthenosphere have an anisotropic fabric by defining a priori velocity constraint during the ray tracing procedure. If time allows, we will present preliminary results from the analysis of anisotropy within the slab region as well as an extension of the 3D ray tracing results from the entire Juan de Fuca plate.

What the mismatch between current geodetic data and paleoseismic data in southern Cascadia can tell us about the earthquake cycle

Patton, Et Alia

Interseismic vertical deformation in northern California is collocated with paleoseismic evidence of coseismic vertical deformation, but they are not opposite in sense of motion as expected with the classic subduction zone model as evidenced from Plafker's work on the 1960 Chile and 1964 Alaska subduction zone earthquakes.

GPS and tide-gage data are compared with paleoseismic data in the form of sediment cores in the region of Humboldt Bay and Crescent City, northern California. In Humboldt Bay, North Spit (NOAA) and Mad River slough (campaign) tide gage data show rates of subsidence of ~3 and ~2 mm/yr respectively, while the Crescent City tide gage (NOAA) shows ~3mm/yr of emergence. GPS vertical motion rates show a similar gradient of subsidence and uplift in this region, consistent with the tide gage data. Paleoecologic estimates of the magnitude of coseismic subsidence in Mad River slough are ~0.5 m.

Mechanisms likely responsible for this mismatch include (1) upper plate fault rupture (e.g. Patton Bay fault in 1964 Alaska)(2) varying land-level / sea-level relations during coseismic periods, (3)spatial variation in slip patches along the megathrust for different earthquakes, (4) and deep locking and deep slip on the megathrust (similar to 2011 Tohoku-Oki). Tide gage deployments in the next year and updates to level surveys around Humboldt Bay will help reveal more details about the spatial variation in fault coupling. Resampling buried soils for new AMS radiocarbon ages will also provide more details that might further reveal age discordance in regions affected by different upper plate faults of the accretionary prism in northern California.

Modeling Rupture in the 1700 Great Cascadia Earthquake Based on High-Quality Paleoseismic Observations

Pei-Ling Wang^{1,2}, Kelin Wang², Andrea D. Hawkes³, Benjamin P. Horton⁴, Simon E. Engelhart⁴, Alan R Nelson⁵, Robert Witter⁶, Yuki Sawai⁷

1. Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada.
2. Pacific Geoscience Centre, Geological Survey of Canada, Sidney, BC, Canada.
3. Geology & Geophysics, M22, Woods Hole Oceanographic Institution, Woods Hole, MA, United States.
4. Earth and Environmental Science, University of Pennsylvania, Philadelphia, PA, United States.
5. Geologic Hazards Science Center, United States Geological Survey, Golden, CO, United States.
6. Newport Coastal Field Office, Oregon Dept of Geology, Newport, OR, United States.
7. Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki, Japan.

Paleoseismic evidence such as buried soils and overlying mud and associated tsunamis deposits have indicated abrupt coastal subsidence during the great AD 1700 Cascadia earthquake. These records have been modeled using a rather uniform rupture model, a mirror image of the uniform interseismic fault locking based on modern GPS observations. However, no megathrust earthquakes, such as Sumatra, Chile, and Alaska, have uniform slip; the rupture must have had multiple patches of concentrated slip. Variable moment release is also seen in the 2011 Tohoku-Oki earthquake in Japan, although there is only one patch. The use of a uniform rupture scenario for Cascadia is due mainly due to the poor resolving power of the previous paleoseismic data. In this work, we invoke recently obtained more precise data from detailed microfossil studies and data from statistical transfer functions (TF) to better constrain the slip distribution. Our 3-D elastic dislocation model allows the fault slip to vary along strike. Along any profile in the dip direction, we assume a bell-shaped slip distribution with the peak value scaling with local rupture width, consistent with rupture mechanics. We found that the coseismic slip is large in southern Cascadia, and areas of high moment release are separated by areas of low moment release. The amount of slip in northern and southern Cascadia is poorly constrained due to the paucity of paleoseismic observations. Although data uncertainties are large, the coastal variable subsidence can be explained with multiple slip patches. For example, in accordance with the minimum coseismic subsidence estimated by the microfossil data, there is an area near Alsea Bay, Oregon (about 44.5°N) that had very little slip in the 1700 event. This area approximately coincides with a segment boundary previously defined on the basis of gravity anomalies. There is also reported evidence for the presence of a subducting seamount in this area, and the seamount might be responsible for impeding rupture during large earthquakes. The nature of this rupture barrier and whether it is a persistent feature are important topics of future research. Our results indicate that there is not always a one-to-one correlation between areas of more complete interseismic locking and larger coseismic slip. In addition, critical data are still missing. Future work is needed to improve the spatial coverage as well as resolution of paleoseismic observations.

Investigation of Cascadia Segmentation with Ambient Noise Tomography
R. Porritt

Along strike variation in the characteristics of subduction zone processes has been observed throughout the Cascadia Subduction Zone through analysis of arc magmas and the distribution of seismicity. We investigate links between these observations and subduction zone structure by imaging three-dimensional lithospheric scale shear velocity with ambient noise tomography (ANT). The crustal portion of the model is well resolved through typical ANT processing techniques. We expand the methodology to use longer period phase velocities in order to recover structure to ~120km depth. The resulting model, PNW10-S, represents structural information in terms of relative shear velocity in the crust and uppermost mantle. Crustal structure mirrors surface geology to ~10 km depth and then transitions to a structure that is dominated by the subducting slab. The subducting slab and overriding crust appear segmented into three parts with boundaries near 43°N and 46°N. This three-way structural segmentation is aligned with the variation in recurrence of episodic tremor and slip along the subduction zone (Brudzinski and Allen, 2007). Upper to middle crustal boundaries between the Klamath Mountains and Siletzia Terrane (43N) and between the Crescent Formation and Olympic Peninsula (47N) are also coincident with locations of increased occurrence of tremors raising the question of whether there is a link between the intensity of tremor activity and shallow (less than 10km) crustal structure. The slab-segment boundary at 43N is a stronger feature than the northern segment boundary at 46N and appears to be the continuation of the Blanco Fracture Zone separating the Gorda segment of the plate from the rest of the Juan de Fuca plate. The southern half of the arc system, south of 45N, shows lower velocities from the surface to ~80 km depth relative to the northern portion of the arc. We propose this is due to clockwise plate rotation, which causes extension in the south, and results in increased melting. Along the arc, four broad low-velocity features are also imaged just below the Moho and centered at 42N, 44N, 47N, and 49N. We interpret these as ponding of melt just below the crust where differentiation can occur before further ascent through the crust.

E. Roeloffs

Observing Details of Cascadia Transient Aseismic Slip with Borehole Strainmeters

The 75 Plate Boundary Observatory (PBO) borehole strainmeters (BSM's) constitute the world's most ambitious BSM deployment to date. They are recording a wealth of data revealing aseismic crustal deformation around faults in California, within the Cascadia subduction zone, and in the Mount St. Helens and Yellowstone magmatic centers. The PBO BSM's have recorded transient strain in all these regions, though only in Cascadia has the deformation been large enough to be confirmed with continuous GPS.

The PBO BSM data set is maturing. Four to seven years after installation, many of the strainmeters are providing better data as formation rocks continue to compress the instruments, improving their coupling to the surrounding crust. These longer data records open new data analysis options. With higher quality data and better analysis techniques, more information is emerging from the PBO BSM data.

The Cascadia "slow slip events" (SSE's) provide the most dramatic example of a phenomenon that can be observed in detail with BSM's. Since 2007, five SSE's have been recorded by up to six PBO BSM's, producing strain excursions typically 50-100 nanostrain that last 2-3 weeks. Revealing these signals requires removing long-term strains caused by borehole relaxation (10's of microstrain/year) without distorting the transient tectonic strains, which can be achieved by fitting an appropriate analytic function. BSM's also record strains imposed by surface-water loads and groundwater-pressure variations, typically at least as large as the SSE signals. Each PBO BSM has four independent horizontal gauges, and for many of the BSM's, these seasonal strains are similar on all gauges, a feature that facilitates their separation from tectonic shear strains. Applying these techniques to time series of daily average data from the four gauges of PBO BSM B004 in northern Washington state shows that Cascadia SSE's in 2007, 2008, 2009, 2010, and 2011 are very well modeled as oblique-thrust slip fronts propagating along strike on the inferred surface of the subducting Juan de Fuca oceanic plate. Moreover, the latter four events produced remarkably similar shear strain time histories, differing only in propagation speed and along-strike extent. In contrast, the 2007 event produced smaller and briefer strain excursions. These conclusions do not depend on calibration of the strainmeter.

Detailed comparison of the B004 BSM data with model-calculated strains can be accomplished with minimal assumptions about the calibration by working with time histories of maximum shear strain amplitude and direction rather than the shear strains themselves. Using this approach, and assuming slip is on the plate interface, constrains the up-dip limit of slip for the 2008 through 2011 SSE's to between depths of 25 and 28 km as the events propagate NW along southern Vancouver Island. Moreover, matching the maximum-shear strain time histories shows that slip is oblique, having left-lateral to dip-slip ratios of 0.2-0.3.

Finally, the amount of slip can be determined by adjusting the model to match the sizes of offsets recorded by continuous GPS. For the 2008 SSE, models with spatially uniform slip of 1.5 to 2 cm are consistent with the up-dip GPS offsets, as well as with expected strainmeter calibration coefficients.

As further innovative data analysis methods are developed, the PBO BSM's have potential to bring our pictures of aseismic crustal deformation into much sharper focus.

Trace metals as potential indicators for volatile exsolution beneath Mount St Helens, WA

Rowe, M.C.¹, Hampel, T.¹, Kent, A.J.R.², Thornber, C.T.³, Webster, J.D.⁴

¹School of the Environment, Washington State University, Pullman WA 99163.

²Department of Geosciences, Oregon State University, Corvallis, OR 97331

³Cascade Volcano Observatory, Vancouver, WA 98683

⁴American Museum of Natural History, New York, NY

The exsolution and movement of volatiles controls eruption conditions of intermediate and silicic magmas. Constraining the location, rate, and timing of volatile migration therefore is a long-standing goal of volcanological studies. Emitted gas compositions and concentrations can be monitored either through direct measurement or remotely for active volcanic systems, however this does not help us understand volatile movements in inactive or older systems. Silicate melt and fluid inclusions are often used to constrain volatile abundances, however these are often highly dependent on the nature of the crystalline phases they are trapped within. In the absence of suitable melt inclusions, this work focuses on using trace elements and ore elements within phenocryst phases, in particular amphibole, plagioclase, and pyroxene, to track volatile behavior and fluid migration in intermediate and silicic arc magmas.

This study focuses on analysis of mineral phases from the 2004-2008 eruption of Mount St. Helens. Several samples of 1980-1986 Mount St. Helens erupted dacite are included for comparison, primarily focusing on Li and Cu. Major elements were measured by electron microprobe analysis at Washington State University and the trace elements (Li, Sc, Co, Cu, Zn, Sr, Y, Zr, Mo, Ag, Sn, Sb, Ba, Ce, W, and Pb) were analyzed by laser ablation inductively coupled plasma (LA-ICP-MS) at Oregon State University. Crystallization temperatures are calculated from major element analyses after Blundy and Holland (1990), Holland and Blundy (1994), and Ridolfi et al. (2010). With the exception of Li and Cu, which vary by up to two orders of magnitude, we see little systematic variation over the course of the eruption. Within individual samples however, we see significant variation in trace metals. In addition we observe correlations between trace and ore metal (particularly, Zn, Sn, Li, and Ag) and Cl concentrations in several of the samples, suggesting variation in trace elements may relate to changes in halogen content of the melt at the time of crystallization. Cl concentrations are also well correlated to crystallization temperature and may therefore provide us with a means of tracking exsolution of volatiles during cooling and crystallization of the dacitic magma.

Interesting, Li and Cu variations are significantly different in the 1980-96 Mount St. Helens mineral phases. While Cu and Li are correlated in amphibole, concentrations are generally significantly lower than in 2004-2008 material. Similarly, there are no significant differences in Li content between mineral phases, contrary to what is observed for the 2004 eruption. The distinct differences in Li and Cu concentrations between the two Mount St Helens eruptions may imply a very different volatile exsolution history and may provide additional insight into the relationship between volatile exsolution and migration and eruption dynamics.

The Role of Mafic Recharge in Silicic Magma Systems

Philipp Ruprecht^a, George W. Bergantz^b, Kari M. Cooper^c, Olivier Bachmann^b

^a Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964 (ruprecht@ldeo.columbia.edu)

^b Dept. of Earth and Space Sciences, University of Washington, Seattle, WA 98195

^c Geology Department, University of California, Davis, CA 95616

Introduction

Silicic volcanism is dominated by piecemeal addition of mafic magmas to and fractional crystallization within the crustal magma system. Numerous studies have discussed the role of mafic recharge and mixing with silicic magma with their implications for eruptive behavior and compositional evolution [1,2] as well as extent, timing, and physical mechanisms of mixing [e.g., 3-6]. However, most volcanic systems show diverse textural and geochemical features that are the testimony to many episodes of recharge and mixing with compositionally diverse end-members. Thus, extracting the effect of a single episode of mafic recharge on a silicic shallow crustal magma reservoir is rarely possible. Even less common is the ability to compare and contrast the effects of magma mixing with a similar magma batch that had limited interaction with mafic recharge. The effusive recharge magma-rich (approx. 1 km³) 1846-47 eruption and the homogenous Plinian 1932 eruption (i.e., mafic recharge volumetrically minor) of Quizapu volcano, Chile, are unique in having produced compositionally almost identical silicic end-member magma, yet differ in their eruptive style and their volumetric contribution from mafic magma just prior to eruption [7,8]. The two large eruptions (~ 5 km³ each) provide insight into the dynamics of a single recharge episode and in particular into the effect of magma recharge on the eruptive behavior and the timing of recharge, mixing, and eruption. Furthermore, the historic eruption age enables the use of short-lived uranium-series studies (i.e., ²³⁰Th-²²⁶Ra) to address the effect of recharge on the recorded crystal residence timescales.

The Quizapu magma system

On the basis of mineral compositions, textures, and geothermobarometry we derive an architecture of the Quizapu plumbing system [8] consisting of a dacite magma (overwhelmingly dominated by An₂₅₋₄₀ plagioclase and magnesiohornblende) overlying an andesitic mush (< An₆₀) of intermediate temperature that feeds the eruptible dacite lense on top by crystal-melt separation. The hot recharge magmas usually feed the andesitic mush, driving the step-wise fractionation from andesite to dacite [9]. Only in rare occasions does andesite directly interact with the shallow dacite magma and leads to silicic eruptions. High Mg concentrations in almost all calcic plagioclase require recent mafic addition and Mg in plagioclase diffusion calculations for hybridized andesites suggest magma recharge and mixing within weeks of the 1846-47 eruption [10]. We consider the thermal effects on the mixing and eruption dynamics associated with hot mafic recharge and find that overall mixing efficiency for the erupted volume is set early during the recharge event -limiting the amount of hybridization [8]- and that short-term reheating leads to significant viscosity reduction in the resident dacite magma. We argue that late-stage reheating in the 1846-47 Quizapu eruption and in similar eruptions may have reduced the potential for a Plinian eruption as the water-saturated dacite is more efficiently degassed upon ascent [11]. Finally, reheating also shows to have a significant role on the recorded crystal residence ages. ²³⁰Th-²²⁶Ra plagioclase separate ages are more than 1.4 kyr older than average plagioclase model ages [10], suggesting that recorded model ages are significantly altered during short-term reheating events.

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DEGASSING PATTERNS AND ERUPTION PROCESSES OF CINDER CONES IN CENTRAL OREGON: A MELT INCLUSION PERSPECTIVE

Dan Ruscitto, Daniele McKay, Paul Wallace, Kathy Cashman

Cinder cone eruptions are the dominant form of Holocene volcanism in the Central Oregon segment of the High Cascades. We examine eruption products from three young (< 2300 yr b.p.) monogenetic vents (Collier, Four-in-One, and Sand Mountain) in Central Oregon and find significant compositional similarities to eruptions characterized as violent strombolian (e.g. Paricutin). Each eruption produced at least one scoria cone (≤ 185 m high), blocky lava flows (< 0.2 km³) and a tephra blanket extending up to several km away from the vent. Bulk tephra samples from Collier Cone and Four-in-One Cone exhibit narrow ranges in composition (56-57 and 53-55 wt% SiO₂, respectively). Additionally, bulk lavas are more silicic than associated tephra (55-65 and 55-57 wt% SiO₂, respectively) and show compositional trends extending towards rhyolite xenoliths incorporated into erupted lavas. Pre-eruptive volatile contents in olivine-hosted (% Fo host: 77-85) melt inclusions from tephra associated with each eruption are high (≤ 4 wt% H₂O, ≤ 1200 ppm CO₂). Compositions from Sand Mountain show limited variability and do not trend towards more silicic contaminants.

Degassing patterns and inferred melt inclusion formation pressures from Sand Mountain are consistent with either closed system degassing model or a gas-fluxing model, where a shallow magma system was flushed by a CO₂-rich vapor derived from deeper in the system. Collier and Four-in-One inclusions, however, reflect limited amounts of degassing and suggest formation in isolated middle to upper crustal magma chambers/sills prior to eruption. Differences in magma migration and storage patterns between Collier and Four-in-One versus Sand Mountain and the Mexican cones may be related to magma volumes and eruption durations or proximity to a larger, well-established volcanic edifice. Despite the major differences in magma migration and storage processes, tephra deposits suggest phases of Violent Strombolian activity in the Central Oregon Cascades. Additionally, high pre-eruptive volatile contents and extensive crustal assimilation recorded in lavas suggest that monogenetic eruptions in Central Oregon may be comparable to Paricutin, Mexico: a 9-yr long eruption (1943-1952) characterized by intermittent, ash-rich eruption columns (≤ 8 km high) and extensive lava and tephra production. The presence of H₂O-rich basaltic andesite magmas (and Paricutin-like eruptive activity) in Central Oregon is unexpected. Magmas in the Cascades arc (north of Mt. Shasta) have been considered H₂O-poor, a consequence of the elevated temperature and resulting shallow dehydration of the young, subducting slab. Our work shows that this view is erroneous and mafic eruptions in this region have the potential to be more explosive than previously realized.

Mantle wedge processes in the northern Cascade arc from olivine-hosted melt inclusions

Steven Shaw¹, Susan M DeBari¹, Paul J Wallace², Thomas W Sisson³, Michael Rowe⁴

¹Geology Dept., Western Washington University, Bellingham, WA, United States

²Dept. of Geological Sciences, University of Oregon, Eugene, OR, United States

³Volcano Hazards, U.S. Geological Survey, Menlo Park, CA, United States

⁴Dept. of Geoscience, University of Iowa, Iowa City, IA, United States

The subducting Juan de Fuca plate is the hot endmember of slabs worldwide, and its unique thermal character prompts debate about the role of fluid-flux melting versus decompression melting in the Cascade arc. While slow subduction of this hot slab is expected to result in strong dehydration prior to reaching sub-arc depths, there is no consensus on whether the slab is entirely dehydrated at this point, and whether volcanism is the result of water-poor, decompression melting, or fluid-flux melting. We provide the first measurements of pre-eruptive volatile contents in olivine-hosted melt inclusions from primitive magmas in the northern region of the arc, at Mount Baker and Glacier Peak. These volatile contents and melt inclusion compositions are used to model mantle melting processes.

Low-K olivine tholeiite (LKT) and calc-alkaline basalt (CAB) melt inclusions at Glacier Peak have minimum H₂O concentrations of 2.0 and 2.2 wt.% and fO₂ of Δ QFM +1.1 and +1.5, respectively. The evolved compositions of these melt inclusions in both lava types (host olivine: Fo₈₅₋₈₉) are corrected to mantle values by addition of ≤ 15 wt. % olivine, and the results suggest that the minimum water contents in the parental magma are 1.7 wt.% and 2.0 wt.%. Measured values themselves may be low due to degassing at crustal depths. The Mount Baker Schreier's Meadow cinder cone (CAB) has minimum H₂O concentrations of 2.3 wt.%, though these cannot be adequately disentangled from potential crustal involvement and/or magma mixing/mingling to be corrected to mantle values.

Results of modeling indicate that both LKT and CAB at Glacier Peak are the result of 13-15% fluid-fluxed melting of a compositionally heterogeneous mantle source, last equilibrated at the base of the crust. Source regions are interpreted to contain both an ocean island basalt (OIB)-like component and a mid-ocean ridge basalt (MORB)-like component. Minimum H₂O contents suggested in the source region are between 0.21 and 0.28 wt.%. This is in contrast to southern regions of the Cascade arc, where LKT magmas are considered to be the result of dry decompression melting of a MORB-like source.

Utility of OBS/DPG Arrays for Physical Oceanography: Tsunami waveforms, Infragravity wave interferometry, and seafloor pressure anomalies

Anne Sheehan¹, Zhaohui Yang¹, Josh Stachnik², Oleg Godin³, Nick Zabolotin³, John Collins⁴, Justin Ball¹

¹University of Colorado, ²University of Alaska Fairbanks, ³CIRES/NOAA, ⁴Woods Hole Oceanographic Institution

Arrays of ocean bottom seismometers and seafloor pressure gauges provide unique datasets that are of great utility beyond traditional seismological studies of earthquake source and Earth structure. Here we present a summary of ongoing analysis of data from the 2009-10 New Zealand MOANA OBS/DPG experiment applied to tsunami, infragravity wave, and seafloor pressure anomaly studies. Similar studies could be envisioned with data soon to be available from the OBS data from the Cascadia Initiative. For the MOANA experiment thirty broadband ocean-bottom seismometers (Trillium 240) with differential pressures gauges (Cox-Webb DPGs) from the SIO OBSIP pool were deployed for one year off both coasts of the South Island of New Zealand, at station spacing of approximately 100 km, and water depths from 550-4700 m. We observe clear tsunami signals generated by the July 15, 2009 magnitude 7.8 Dusky Sound (Fiordland) New Zealand earthquake on the seafloor differential pressure gauges (DPGs). Large, dense spatial arrays of seafloor pressure gauges at a variety of water depths, such as with MOANA or the Cascadia Initiative, can fill a major gap in tsunami wave field sampling between well separated Deep-ocean Assessment and Reporting of Tsunamis (DART) bottom pressure recorders in the deep ocean and tide gauges along coastal areas. These data sets can also provide detailed data on the temporal variability, directionality, and spectra of infragravity waves. The year-long, continuous records of pressure from the MOANA experiment are used to study infragravity waves in the 0.5-30 mHz frequency range via ambient noise cross correlation. A compressed cross correlation function, which compensates for wave dispersion, reduces the signal averaging times necessary of accurate passive measurements of infragravity wave travel times and directivity. The directionality of infragravity waves can be used to help determine their source, such as from coastal swell forcing or from deep water tidal resonance. In many instances extreme but slow variations in pressure, with corresponding signals on the horizontal and vertical component seismometers, are observed, the origin of these signals are still being investigated.

SEISMIC STRONG MOTION ARRAY PROJECT (SSMAP) TO RECORD FUTURE LARGE EARTHQUAKES IN THE NICOYA PENINSULA AREA, COSTA RICA

The seismic strong motion array project (SSMAP) for the Nicoya Peninsula in northwestern Costa Rica is composed of 10 sites with Geotech A900/A800 accelerographs (three-component) and GPS timing. Since 2006, the main objectives of the array are to: 1) record and locate strong subduction zone mainshocks [and foreshocks, “early aftershocks”, and preshocks] in Nicoya Peninsula, at the entrance of the Nicoya Gulf, and in the Papagayo Gulf regions of Costa Rica, and 2) record and locate any moderate to strong upper plate earthquakes triggered by a large subduction zone earthquake in the above regions. Our digital accelerograph array has been deployed as part of our ongoing research on large earthquakes in conjunction with the Earthquake and Volcano Observatory (OVSICORI) at the Universidad Nacional in Costa Rica. The country wide seismographic network has been operating continuously since the 1980’s, and has been upgrade with broad-band seismometers and Episensors. The recording of seismicity and strong motion data for large earthquakes along the Middle America Trench (MAT) has been a major research project priority over these years, and this network spans nearly half the time of a “repeat cycle” (~ 50 years) for large ($M_s \sim 7.5-7\frac{3}{4}$) earthquakes beneath the Nicoya Peninsula, with the last event in 1950. The major goal of our project is to contribute unique scientific information pertaining to a large subduction zone earthquake and its related seismic activity in Nicoya. We are now collecting a database of strong motion records for moderate sized events ($M=4.0-4.9$) to document this last stage prior to the next large earthquake. Recent $M=5.1$ events have occurred in the Gulf of Nicoya rupture area of the 1990 $M_w=7.0$ which was associated with the subduction of a seamount. In addition, we have recorded $M=5.0$ events in the Central Valley region and the northern volcanic chain. Relocation solutions in the Nicoya region define the subducting Cocos plate.

Aseismic Slip in a 1-D Model of a Subduction Channel Shear Zone

Robert M. Skarbak, Alan W. Rempel, David A. Schmidt

University of Oregon, Department of Geological Sciences

Evidence exists for a mixture of brittle and ductile behavior in subduction zone settings under conditions similar to those that prevail where slow slip occurs (e.g. laboratory deformation experiments, seismic data, and field observations of material exhumed from slow slip depths). In this view, slow slip is hosted not on a discrete planar surface, but within a heterogeneous shear zone consisting of a mixture of competent and incompetent material. Thus, we present a numerical model for quasi-dynamic rupture on a one-dimensional, elastic fault composed of a mixture of velocity-weakening and velocity-strengthening material. We do not explicitly include mechanisms for viscous-ductile deformation, but make a simple analogy between velocity-weakening (velocity-strengthening) material and brittle (ductile) material.

We use a modified version of the model presented by *Rubin* (2008), wherein a subduction zone plate boundary fault is modeled as a linear interface embedded within an elastic full-space. The governing equations are solved on a one-dimensional fault that is locked at the up-dip edge (corresponding to a seismogenic zone that is locked on the timescale of slow slip events) and made to slip at the plate convergence velocity at the down-dip edge (corresponding to depths well below those of tremor activity and slow slip events). To mimic a subduction channel shear zone, we introduce some percentage η of slightly velocity-strengthening material as regularly spaced segments within the fault. Thus, η is restricted to the range $0 < \eta < 1$; where for example $\eta = 1$ corresponds to no velocity-strengthening material within the fault, and $\eta = 0.5$ corresponds to equal amounts of velocity-weakening and -strengthening material, etc. Our results show that the ratio of velocity-weakening to velocity-strengthening material in the model fault controls the style of slip (i.e. stable, slow, or dynamic sliding) and support the notion that the deformational behavior of subduction zone interfaces is governed by the interplay of brittle and ductile rheologies within a finite-width shear zone.

The Depth Dependence of Earthquake T-phases at an Ocean Acoustic Observatory

Ralph A. Stephen
S. Thompson Bolmer
Woods Hole Oceanographic Institution, Woods Hole, MA 02543-1542.

Peter F. Worcester
Matthew A. Dzieciuch
Scripps Institution of Oceanography, La Jolla, CA 92093-0225

James A. Mercer
University of Washington, Seattle, WA 98105-6698

Bruce M. Howe
University of Hawaii at Manoa, Honolulu, HI 96822

Earthquake locations and source mechanisms play a key role in studying plate tectonics and seafloor spreading processes. T-phases are earthquake signals that have propagated, at least partially, in the ocean sound channel. T-phase hydrophone networks detect much smaller earthquakes over basin scales than land-based networks and they detect many more earthquakes than comparable regional scale seismic land networks. Furthermore since T-phases travel at lower velocities than seismic phases, they result in much more precise locations of events given the same timing accuracy. T-phases are typically spread over 10's of seconds and a common problem is precisely identifying the arrival time of an event. T-phase stations usually consist of single hydrophones moored near the sound channel axis and the depth dependence within the water column of the T-phase envelope and frequency content is rarely studied. In the North Pacific Ocean, from 2004 to 2005, ambient noise and earthquakes were observed at an ocean acoustic observatory, in 5,000m water depth, consisting of a vertical hydrophone array (from about 750m above the seafloor to 375m from the surface) and three co-located ocean bottom seismometers. This data set provides a unique opportunity to observe earthquake signals and their characteristics throughout the water column and on the seafloor. In at least one case, a T-phase from a distant earthquake was readily observed even at the seafloor, well below the conjugate depth.

Constructing a comprehensive low-frequency earthquake catalog from a dense temporary deployment of seismometers along the Parkfield-Cholame segment of the San Andreas fault

by D.F. Sumy¹, E.S. Cochran¹, R.M. Harrington²

¹U.S. Geological Survey, Pasadena, CA, USA

²Karlsruhe Institute of Technology, Germany

The Parkfield Experiment to Record Microseismicity and Tremor (PERMIT) is a thirteen-station broadband array installed between May 2010 and July 2011 near Cholame, California, to improve seismic network coverage south of the High Resolution Seismic Network (HRSN). The array is located along a portion of the San Andreas fault that transitions from locked to creeping northward along fault strike. The overarching goal of the project is to explore the spatiotemporal relationships between low-frequency earthquakes (LFEs) and local earthquake activity reported in the Northern California Seismic Network (NCSN) catalog and identified in the temporary array data. We identify LFEs from a catalog of tremor episodes automatically detected using a neural network approach. We apply cross-correlation techniques to isolate template events from eight strong tremor episodes that occurred during the first three weeks of the temporary deployment. The templates are then used to detect and locate LFEs during the entire thirteen-month deployment. Previous studies have shown that tremor activity increased along this section of the San Andreas before and after the 2004 Parkfield earthquake, suggesting that stress interactions exist between earthquakes in the shallow, seismogenic zone and the deeper transition zone. Understanding the range of fault slip behaviors, including how tremor and earthquakes interact, will provide critical information for assessing seismic hazard.

Low-Frequency Earthquakes on the Cascadia Subduction Interface

Justin R Sweet and Kenneth C Creager
University of Washington, Seattle, WA

Low-frequency earthquakes (LFEs) are a recently identified class of earthquakes that occur coincidentally with tectonic tremor in time and space. LFEs comprise much of the tectonic tremor in Japan, and LFE locations have been used to pin down the location of tremor bursts within subduction zones around the world (Brown et al., 2009, GRL), as well as on deep segments of the San Andreas Fault (Shelly et al., 2009, GRL). While prior LFE studies have allowed us to see where and when various fault patches are radiating seismic energy with unprecedented detail, the time history of repeating LFEs has received less attention. Using well-recorded LFEs as templates, we employ a cross-correlation filter to find matching events. We have identified several locations in the northern Cascadia subduction zone which produce LFEs that repeated several hundred times during the past five years. These LFEs are active during multiple Episodic Tremor and Slip (ETS) events. In each case, the matching events first appear rather suddenly and at a feverish pace. Following this initial burst of several hours, the events exhibit a much more discrete pattern of recurrence that starts out as frequent pops that become less and less frequent over a period of several days. We suggest that the initial burst is associated with the passage of a slip front on the fault surface at the location of the template event. Later pops may be attributed to resurgent slow slip that briefly generates seismic energy during the days following the passage of the initial slip front. One LFE template was also active during an inter-ETS event. Its time history was similar to the initial bursts during the ETS events, but it was not followed by the later pops—perhaps due to the absence of resurgent slow slip during the small inter-ETS event. We have identified several LFE templates beneath the Olympic Peninsula of Washington State that fall roughly between the 35 to 45km depth contours of the plate interface. We find a systematic change in repeat times for LFEs as you move from updip LFEs in the ETS zone, to LFEs farther downdip. Updip LFEs tend to be active only during ETS events (with accompanying tremor), while LFEs farther down dip appear to repeat nearly continuously in smaller bursts (without detected tremor). Using these LFE templates, we intend to extend the search for repeating events to the 5-year continuous recording period of the CAFE experiment. By analyzing the time history of individual LFEs and comparing LFEs from nearby locations, we are likely to be able to better unravel the relation between tremor generation and slow slip.

Imaging the Middle America subduction zone with body waves extracted from ambient noise by seismic interferometry

Wanda Vargas, Larry Douglas Brown, Anastasia Cabolova, Diego Quiros, Chen Chen
Cornell University, Department of Earth and Atmospheric Sciences, Ithaca, New York

Subduction zones have long been a prime target for seismic imaging with a variety of active and passive methodologies. Here we report an attempt to use seismic interferometry to extract body waves (P and S) from ambient noise recorded during a broadband experiment in southwestern Mexico for reflection imaging of the crust and subducting Cocos plate. The Middle America Subduction Experiment (MASE; Kim et al., 2010) included a quasi linear array of 100 broadband seismic instruments deployed at a nominal spacing of 6 km which continuously recorded for up to 30 months. Our focus was on using cross-correlation of ambient noise along this array to 1) determine if useful body waves could be extracted, 2) assess which conditions were most favorable for such extraction, and 3) evaluate whether these waves could be used to image deep lithospheric structure, with particular interest in the seismogenic zone. While surface wave tomography using cross-correlation techniques have found widespread success in mapping crustal structure, examples of body wave imaging of crustal targets using this approach are still very few. In our analysis, we have found it necessary to suppress the surface wave energy to enhance body waves from virtual sources. Our pre-processing sequence includes bias removal, bandpass filtering, deconvolution (spectral whitening), and sign- bit conversion. The resulting data windows are cross-correlated and stacked until useful signals are apparent. The virtual shot gathers thus far produced show clear Rayleigh and Pg waves, with weaker but distinct Sg phases. We have also found arrivals with hyperbolic travel times that match those expected for deep reflections. Crustal imaging is limited by the large station spacing, which results in relatively few stations at sub-critical offsets. However several apparent reflections from sub-Moho depths suggest that key elements of the subduction process can be imaged using reflections derived from ambient noise. We further suggest that such interferometry may provide a cost-effective approach to monitoring temporal changes in the seismogenic zone at depth.

Understanding magma formation and mantle conditions in the Lassen segment of the Cascade Arc: Insights from volatile contents of olivine-hosted melt inclusions

Kristina J. Walowski and Paul J. Wallace

University of Oregon, Department of Geological Sciences, 1272 University of Oregon, Eugene, OR 97403

Volcanism in the Cascade Arc results from subduction of the Explorer, Juan de Fuca, and Gorda microplates, which contain some of the youngest and consequently warmest oceanic crust on Earth, beneath the North American plate. The resulting volcanic arc is clearly segmented by style and volume of magmatism and geochemistry of the erupted products. In the southernmost portion of the Cascade Arc, from Mt. Shasta to Lassen Peak, volcanism is the result of the oblique subduction of the atypically deformed Gorda plate, and the magmas produced are some of the most compositionally diverse of all the arc. This compositional variability and an abundance of primitive mafic magmatism make it an ideal location to further inspect the influences of a young subducting slab and mantle heterogeneities on arc volcanism. Cinder cones, which typically erupt relatively undifferentiated magmas, have been sampled with varying distance from the trench, spanning ~80 km from Black Butte in the west to Round Valley Butte in the east, from which melt inclusions will be analyzed for volatile, major and trace elements. Analyses of melt inclusions from Cinder Cone, the youngest of the primitive magmas sampled (9.3 wt% MgO; olivine hosts Fo₈₉₋₉₀) (erupted in ~1666), indicate that magmatic volatile contents generally overlap with other arcs, such as the Marianas, but the Cinder Cone melts have lower maximum volatile concentrations than measured in other arcs. These volatile contents (1.7 - 3.4 wt% H₂O and ≤1500 wt% CO₂) are similar to the volatile contents of primitive melt inclusions from central Oregon (Ruscitto et al., 2010, EPSL). The incompatible element concentrations of the Cinder Cone melts are also similar to the concentrations in central Oregon melts. Elements such as TiO₂ (~0.9 wt%) are higher in the Cinder Cone melts compared to the melts from nearby Mt. Shasta, suggesting that the Cinder Cone magmas originated from a more enriched mantle source. These results agree with the initial hypothesis that the Mt. Shasta region appears anomalous in the Cascades with respect to mantle source and degree of melting, and that the mantle source(s) for the Lassen segment appears to be more similar to that of central Oregon. Continued work inspecting across-arc geochemical variations in volatiles and fluid-mobile trace elements (H₂O, CO₂, Li, and B) will aid in evaluating the influence of subduction of warm oceanic lithosphere on dehydration reactions in the slab and melt production in the mantle wedge.

Effects of subducted seamounts on megathrust earthquakes and rupture propagation
H. Yang

Abstract. A key question of seamount subduction is under what conditions a seamount will generate or stop megathrust earthquakes. Here we show results from numerical experiments in the framework of rate-and state-dependent friction law in which seamount is characterized as a patch of elevated effective normal stress. We find that seamounts sitting up-dip to the nucleation zone act as rupture barriers except when they are located at shallow depth near the trench. More importantly, we observe that seamount-induced barriers could turn into asperities that initiate new megathrust earthquakes rupturing the whole seismogenic zone. Such result is contrary to the traditional view that large earthquakes do not nucleate at shallow depth. We find that whether subducted seamounts generate or impede large megathrust earthquakes depends critically on their relative locations to the earthquake nucleation zone. These results suggest that a strong barrier patch on a heterogeneous fault may not necessarily reduce the maximum size of earthquakes. Instead, the barrier could turn into a patch of large coseismic slip when it is ruptured.

Determining Mantle Anisotropy at a Transform Plate Boundary via Ocean Bottom Seismometers: South Island, New Zealand

Daniel W. Zietlow¹, Anne F. Sheehan¹, Zhaohui Yang¹, Joshua C. Stachnik^{1,4}, John Collins², and Martha K. Savage³

¹ CIRES and Department of Geological Sciences, University of Colorado, Boulder, CO 80309, USA

² Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

³ Institute of Geophysics, Victoria University of Wellington, Wellington 6012, New Zealand

⁴ now at Geophysical Institute, University of Alaska, Fairbanks, AK 99775, USA

We examine mantle anisotropy offshore New Zealand using shear wave splitting measurements from the Marine Observations of Anisotropy Near Aotearoa (MOANA) ocean bottom seismic experiment. The Alpine Fault on the South Island of New Zealand marks the transform plate boundary between the Australian and Pacific plates. Previous land-based seismic experiments have yielded teleseismic shear-wave splitting directions nearly parallel to the Alpine Fault; however, conflicting interpretations of these measurements exist due to the limited array aperture. Specifically, these splitting measurements were considered to either represent lithospheric shearing or asthenospheric flow. In order to test whether anisotropy is due to either of the above mechanisms, ocean bottom seismometers were deployed to examine variations in shear wave splitting as a function of distance from both sides of the Alpine Fault. This areal array of 30 OBS had approximately 100 km spacing and allows us to study the extent of anisotropy across a distance approximately five times greater than the width of the South Island. In the case of lithospheric shearing, we expect the strength of the splitting to be strongest close to the fault and then gradually decrease with distance from the fault. In the case of asthenospheric flow, we expect to see an asymmetry in the splitting measurements on both sides of the fault. Before splitting measurements could be made, however, orientation of the OBS horizontal components was necessary. The horizontal components were oriented using a novel surface wave technique and confirmed with traditional body wave methods (Stachnik et al., 2012). Though inherent noise in OBS data makes splitting measurements challenging, several teleseismic events of magnitude 6.0 or greater recorded on the MOANA array provided usable measurements demonstrating lateral variations in anisotropy. Splitting measurements of SKS and SKKS phases yield fast orientations off the east coast nearly perpendicular to the Alpine Fault, whereas the west coast exhibits fast orientations more parallel to the fault. Stations off the continental shelf exhibit NNE fast directions. These results suggest that asthenospheric flow cannot account for the observed mantle anisotropy under the South Island. Instead, west coast fast directions seem associated with fault deformation, with other observed anisotropy possibly due to fossil lithospheric anisotropy. Splitting measurements on S-phases are underway and will better elucidate mantle anisotropy in the region.