Pacific Northwest Earthquake Science Workshop, November 5, 2019

Notes courtesy of Harvey Kelsey, Morgan Moschetti, Jakir Hossen and Evelyn Roeloffs

Controls on seismogenesis in Cascadia (Michael Bostock)

This presentation on seismogenesis in Cascadia focused on crustal and slab earthquakes, and tremor. Tremor occurs in a margin-parallel, 40-80 km wide band, with variable intensity. Crustal seismicity has a more diffuse concentration, with notable landward concentrations in WA and northern CA. Where tremor occurs there tends to be little crustal seismicity. Intraslab seismicity is most sparsely distributed, and concentrated at the plate edges. These patterns are not random: for instance, tremor is anticorrelated with crustal seismicity.

In the shallow parts of Cascadia, focal mechanism (Wada and Wang 2002) patterns are dominated by (or, influenced by) plate edge effects, whereas deeper, down-dip tension and slab normal compression (i.e. slab pull) have greater influence on patterns of seismicity. A gap in the slab is apparent at depths >100 km in Oregon, possibly caused by thermal erosion from passage of Yellowstone hot spot.

Slab strain arises because of the concave seaward curvature of the downgoing plate, which causes a room problem and consequent slab folding. A minimum curvature model of the interface surface shows strong curvature at southern end and at northern end of CSZ, strong bending in Puget Sound and northern CA, and more constant slab dip in Vancouver Island and central OR.

The three main concentrations in slab seismicity are associated with plate bends at depths of 40 km or more. Slab curvature also correlates with crustal seismicity.

A variety of evidence suggests the hypothesis that slab fluids released downdip of the tremor zone are influencing crustal seismicity. This is consistent with the seismicity pattern and increased He3/He4 in springs landward of tremor.

In conclusion, seismicity concentrates near plate edges, tremor is a useful guide to slab morphology and proxy for where slab contains fluids under high pressure, crustal seismicity is marked by presence of slab fluids, the down-dip limit of tremor and the volcanic arc are informing us of deeper strain, and understanding the role of the movement of fluids a promising avenue for research (e.g., are fluids from the slab making their way up to shallow depths?).

Recurrence and fault slip (Rob Witter)

Rob focused on recurrence and slip modes. Constraints on recurrence come from coastal subsidence, tsunami deposits, and shaking impacts, which suggest that recurrence intervals vary along strike. The offshore turbidite record varies systematically, with more frequent thinner mud turbidites suggesting that recurrence intervals may get shorter going to the south. A turbidite model of segment rupture is based on 19, 22 and 40 turbidites in the north, center, and south of Cascadia. The Bradley Lake record is consistent with the offshore record and inference that recurrence intervals are shorter in the south. 9 tsunami deposits in a 2500 year record at Discovery Bay (work of Carrie Garrison-Laney), dated using precise ages measured using Oxcal models with multiple samples above and below the tsunami deposits indicate "Bed 2" may have been a Cascadia event, on a shorter segment rupture that generated a tsunami and shaking but was insufficient to subside the outer coast.

The orphan tsunami story (Satake, 2003) favors one of three rupture models for the 1700 earthquake. These are a long narrow rupture slip patch of 1100x48 km2 with 19 m slip (preferred), a full-slip zone and landward partial-slip zone of 1100x100 km2 (predicts uplift where there was subsidence) and a short northern rupture of 670x56 km2 with 39 m slip (too much subsidence). Slip models for CSZ megathrust ruptures more generally include heterogeneity, with slip 'patches' (Wang et al.) or subevents, which all influence coastal subsidence (Wirth and Frankel 2019; Melgar et al 2016).

To test inferences that recurrence intervals vary along strike and may be shorter in the south, will require use of observations on the coast to verify/calibrate the modelling approaches, more precise dates, modeling of slip constrained by both subsidence and tsunami observations, and by estimates of shaking from landside and liquefaction data. Outstanding questions to explore consider the mechanisms by which recurrence intervals are affected by plate curvature and the width of seismogenic zone along the margin.

Slow slip (Noel Bartlow)

'Slow slip' refers to fault slip that happens too slowly to emit seismic waves. It is found in subduction zones as well as on strike slip faults, and sometimes precedes large earthquakes. It also is often accompanied by tremor. Tremor releases less than 5% of energy released in slow slip, but is easier to analyze then the aseismic slip, and tremor episodes migrate along the plate interface.

Cascadia Episodic Tremor and Slip (ETS) recurs at intervals of 14, 20, 7-10 months from north to south, with smaller events happen between large events. Slow slip tends to nucleate at the downdip end of the ETS zone. Tremor migrates at about 10km per day along strike, and can travel in the dip direction several orders of magnitude faster. At the north and south ends of CSZ the slip is equal to or more than plate convergence rate. The closest analog to Cascadia is Nankai.

Tremor shows variation in space and time, and appears in the same place over and over again, suggesting that there is a structural control on tremor. Tremor migration at various speeds and sometimes in the direction opposite to plate convergent, along the down dip edge it is more episodic than up dip, where it is more continuous. Generally tremor first migrates up dip and then migrates along strike, and can stop at any point in this process. Tremor has been inferred to occurs along a 1) discrete slip surface on discrete velocity-weakening asperities on a planar surface (see Hayman et al. 2014 Geology), 2) a shear zone with discrete width (i.e., brittle failure in a ductile matrix) with failure along foliations (consistent with focal mechanisms; what is seen in fault rocks, see Fagereng et al 2014 GRL).

Implications of ETS for earthquakes include the potential for it to causes stress increases that could trigger earthquakes, and delineation of coupling changes on plate interface. A gap between down-dip edge of locking and the ETS zone (Wang and Trehu, 2016, J Geodynamics), which may indicate velocity strengthening behavior the gaps and therefore, a transition from velocity weakening behavior to velocity-strengthening behavior, and a role for high pore fluid pressures. The models of Bruhat and Segall show a gap between ETS and locked zone is necessary to fit the long term GPS data.

Ground Motions and Seismic Hazard in the PNW (Erin Wirth)

The lack of Cascadia earthquakes makes predicting ground motions challenging, so inferences are made from global earthquake. The 2011 Tohoku earthquake reveals high energy radiation from discrete patches in the down-dip portion of rupture, which generates strong ground shaking that may impact built structures. It remains unknown if high energy subevent patches will occur in Cascadia.

Understanding has been gained from studies of PNW magnitude 3's and 4's. These show how shaking would vary in deep basins (revealed by gravity lows), with basin amplification being highly dependent on the earthquake source. For shallow earthquakes at Seattle basin edge, amplification is much greater within the basin as compared to south of the Seattle fault.

Earthquake simulations for Cascadia, particularly for M9 events, have advanced and are being used to explore how basins amplify shaking. They show that amplification is higher than what is seen for crustal earthquakes in northern CA, by as much as 2-5 times. Simulations also provide insights about interactions between wavefield and subducting slab impact ground motions. Dynamic rupture simulations also are providing new insights.

Future directions should continue to use global earthquakes to study the rupture processes, offshore geophysical instrumentation is critical, deploy broadband seismometers in sedimentary basins, improve the 3D velocity model, develop increasingly realistic 3-D kinematic and dynamic simulations.

Lightning Talks

*Prehistoric, headwater-basin-encompassing debris-avalanche landslides, Northern California (Harvey Kelsey)*

[*The seismic expression of hydration in the crust and mantle of the Cascadia margin*](https://seismo.ess.washington.edu/gomberg/PNWEqNovemberEvents/Presentations/LightningTalks/2_Delph_LightningTalk)*(Jonathan Delph)*

Seismic imaging reveals a correlation between slow crustal velocities and tremor rates.

[*Utility of Using Gravity Data to Map Active Faults in Washington*](https://seismo.ess.washington.edu/gomberg/PNWEqNovemberEvents/Presentations/LightningTalks/3_Anderson_PNW_EQ_Sci_Gravity_Fault)*(Megan Anderson)*

Gravity data collected over 12 years have proven useful for mapping the Seattle basin and faults.

[*Fragile features as megathrust ground motion intensity constraints*](https://seismo.ess.washington.edu/gomberg/PNWEqNovemberEvents/Presentations/LightningTalks/4_McPhillips2019_PNWLightningTalk.pptx)*(Devin Phillips)*

[*Pleistocene terraces above the Cascadia Subducton Zone*](https://seismo.ess.washington.edu/gomberg/PNWEqNovemberEvents/Presentations/LightningTalks/5_Stanton_NWEq_lightningtalk_stanton.pptx)*(Kelsay Stanton)*

[*Historic southern Cascadia quakes and sedimentological evidence of NSAF triggering*](https://seismo.ess.washington.edu/gomberg/PNWEqNovemberEvents/Presentations/LightningTalks/6_Goldfinger-2019ed.pptx)*(Chris Goldfinger)*

[*A 5-year CMHRP project focused on subduction zone marine geohazards*](https://seismo.ess.washington.edu/gomberg/PNWEqNovemberEvents/Presentations/LightningTalks/7_Watt_lightning)*(Janet Watt)*

Lots of new offshore data have been collected to assess the upper plate deformation and its relationship to the megathrust.

[*Sedimentary Processes of Astoria Canyon*](https://seismo.ess.washington.edu/gomberg/PNWEqNovemberEvents/Presentations/LightningTalks/8_Hill_PNW_EQ_workshop_2019.pptx)*(Jenna Hill)*

[*Astoria Canyon: Modern sediment flux*](https://seismo.ess.washington.edu/gomberg/PNWEqNovemberEvents/Presentations/LightningTalks/9_Ogston_eElightning_PNWE_compress.pptx)*(Andrea Ogston)*

A study to understand sediment influxes is underway, including deployment of a shallow water, tripod to measure suspended sediment characteristics.

[*A Database and Working Group for Cascadia Earthquake Research*](https://seismo.ess.washington.edu/gomberg/PNWEqNovemberEvents/Presentations/LightningTalks/10_Walton_2019_Powell_db_lightning.pptx)*(Maureen Walton)*

[*Applications of Borehole Strain data to Pacific Northwest Earthquake Research*](https://seismo.ess.washington.edu/gomberg/PNWEqNovemberEvents/Presentations/LightningTalks/11_roeloffs_PNW_5Nov19.pptx)*(Evelyn Roeloffs)*

*Enigmata (Paul Bodin)*

Unusual features of Cascadia include its lack of interface seismicity, and its lack of intraplate aftershocks (in contrast to Mexico and Anchorage events with thousands of aftershocks), the quietness of central Cascadia, events as deep as 30 km in the Puget Sound region, and ambiguous relation between the Seattle fault and earthquakes, abundance of swarms.

Questions exist about the role of fluids, coupling/locking, interactions between crustal faults and the plate interface, the state of stress throughout the SZ, the role of geology, lithology, physical conditions, and the possibility of tsunami earthquakes in Cascadia?

*Visualization of aftershock forecasts (Max Schneider)*

Aftershocks really affect seismic risk. Getting aftershock forecasts would be useful to emergency managers for prioritizing and scheduling recovering. Gerstenberger et al. provide an example for New Zealand. Max is building visualization tools for the NW that include uncertainties. He notes that a 'one-size fits all' does not apply to visualization. Tools address two main communication goals: where are aftershocks likely, and where are they not likely?

Max has interviewed emergency managers, and is doing an online study of users on the west coast to try several versions of visualization showing uncertainty. Trial users have to read visualization maps, consider two places, answer aftershocks are likely in a week.

*Regional ground motion amplification (Morgan Moschetti)*

Amplification depends on source and path. Shaking depends on source depth, the types of phases, and 3D structures. Spatial patterns following the Anchorage earthquake are affected by sediment thickness and reveal locations that on average experience higher or lower ground motions, which could reflect the effect of subduction zone guided waves. An analysis of clusters shows relative amplification at the SW end of Cook inlet, also identified in other studies.

Simulations are important for Cascadia, and a preliminary map for the PNW has been completed.

*Effects of topography on site response (Ian Stone)*

Topographic effects typically are not usually considered in ground motion simulations because they depend on source location and wave frequency, but now is possible with high performance computing. Modeling with Specfem 3D is underway to examine topographic amplification in Seattle, using 30-m gridded topography for frequencies up to 3 Hz from M4 events on the Seattle fault. Simulated PGV measures derived with and without topography are compared, and show that amplification occurs at the top of hills on cliffs, usually of ~30%. S waves and surface waves are amplified, not P waves. M6.5-7.0 events and finite fault sources will be studied next.

*Site amplification basin effects and source parameters in Portland Oregon (Art Frankel)*

The USGS has been operating 12 accelerometer arrays operating since 2005, in the Portland Hills and basin and the Tualatin basin. An inversion to get amplification relative to rock site RBOK and source parameters for 10 M3-4 events shows fill or alluvium have amplify at about 1 Hz, Portland Hills soil over basalt has 4-6 Hz amplification and stiff soils in the Portland basin have little amplification. Stiff soil sites in Tualitan basin have a bit of amplification. The Tualatin basin has a bigger gravity signature and is much deeper than the Portland basin, explaining why it has more amplification. Stress drops average about 50 bars, and are independent of seismic moment.

*Planning the modeling collaboratory for subduction zone science (MCS) (Gabe Lotto)*

This collaboratory was recommended in the SZ4D plan, with the goal of not just building better models, but also integrating work of observationalists and modelers. A 5-10 year goal is to develop better physics-based earthquake and volcano forecasts, which will require figuring out how to scale fundamental physics models into regional models. Another goal is to build connections with agencies, US and international.

Access to HPC resources is essential.

Currently the collaboratory is in a 3-4 year exploratory period. There have been 2 workshops, in Minneapolis in May-June 2019 and Eugene in Oct 2019, and another is planned for mid-2020 (location TBD) on volcano modeling. "Fireside chats between observationalists and modelers" also are being planned.

*CSZ has introduced new ballgame for EQ Hazards in PNW (James Bela)*

Jim suggests that seismic hazard conveyed using PSHA approaches may be misleading. He recommends an idea presented at http://www.xeris.it/Hazard/index.html.

*Anisotropy (Fred Pollitz)*

Seismic surface wave anisotropy improves depth resolution for tomographic models. Yuan and Romanowicz (2010 EPSL) used such measurements to show that the fast direction was parallel to tectonic motions. USArray data from 171 vertical component seismometers and 399 sources showed that in the central and eastern US there is not such dramatic variation in anisotropy, relative to that found in the western US. In PNW segmentation may be inferred in the anisotropy, perhaps related to the style of slab rollback.

Tsunami generation, propagation, and impacts (Bre MacInnes)

Since this was a meeting about earthquakes, this presentation focused on the generation of tsunamis, particularly the social motivation for such understanding, how big and strong a tsunami may be, and the impacts of earthquake rupture complexity, surface versus buried ruptures, and rupture heterogeneity.

Melgar et al.'s 2019 study compared uniform slip model predictions with those including stochastic slip and found for Mw8s, uniform slip models produced similar patterns but heterogeneous models generated wave heights that were greater by a ~meter, with similar results for Mw9s except wave heights were greater by up to 18 m. Simple concentrated slip also gave better fits to observations than a wide simple model.

 Tung and Masterlark (2018) showed that surface ruptures produce larger waves than buried ones.

Models with a weaker crust near the trench (with variable Young's modulus and Poison's ratio) made up to a 20% difference in wave height. The horizontal component of seafloor deformation also may be important in determining wave heights. Some studies indicate that having all the slip occur instantly overestimates the tsunami, though a new study by Williamson et al. 2019 did not find this to be true.

Current Cascadia rupture models being used in tsunami studies by the WA Geological Survey include the 'L1 source' with northern extension and the U of Oregon uses complex ruptures and a of different earthquake sizes. There is a really wide variation of possible wave heights from these simulations, suggesting that a probability standpoint may be more useful than a worst-case scenario. Currently CWU is continuously inverting GPS for seafloor deformation and Tsunami Warning Centers have access to these but are not using them yet.

Bre suggests that forecasts should be focused on observations of the tsunami itself, rather than try to use the earthquake to predict the tsunami.

A participant asked if anyone is modeling the influence of seaward dipping thrusts on tsunami sources outside of Oregon, and another participant answers that this is being done and Kelin Wang notes that some results show that the wavelength of their impact is small.

Cascadian ground failure (Alex Grant)

A recent landslide map of OR and WA is incomplete but still reveals an overwhelming number of landslides and lots of reminders of damaging landslides (e.g., Oso, Perkins Lane, and bluff failures in Seattle).

Coseismic ground failure in Washington has been reported as observations of landslides, ground cracking and liquefaction from the 1949, 1965 and 2001 intraplate earthquakes. (Note that ground failure is catchall term, referring to processes during or after shaking, such as landslides, rockfall, flow slides, liquefaction, and lateral spreads (the latter two not addressed in this talk).

There are not very many landslide inventories because of the high cost of building them, and few from a megathrust earthquakes. in the global ground failure inventory one is from the 2011 Tohoku earthquake.

General trends show that larger earthquakes produce more landslides, though this was not true for the 2011 Tohoku, 2010 Maule, and 1964 Alaska events. The numbers of landslides also do not correlate with strength of shaking. These observations indicate there is a dominance of geological control.

For Cascadia there is a Cowichan history of a landslide destroying a village near Nanaimo that likely was the 1700 event. Recent efforts have applied direct physical models of landscape evolution to Seattle, including a suite of failure modes with different likelihoods and for summer and winter ground water levels.

Current a slope stability analysis of large rockslides in central Oregon is using dendrochronology and14C ages to calibrate an age-roughness correlation for lidar-mapped landslides in the Tyee formation of Oregon. This correlation is then used to estimate landslide density variations with time, and thus far doesn't find a clear signal associated with the 1700 earthquake.

Many opportunities to map landslides exist in Cascadia, on and offshore, and for other earthquake inventories.

A participant asks if human alteration of the landscape matters, such as cutting into banks, and Alex notes that a paper in press about the Tohoku earthquake landsliding implies that this does increase the hazard, but is not factored into forward predictions. It can be addressed statistically, for example by looking at which slides are close to roads.

Lessons from recent earthquakes elsewhere (Yajing Liu)

Topics covered include discoveries about earthquake source processes, inferred slow slip and repeating earthquakes before large earthquakes, the relationship between interseismic locking and coseismic slip, the role of dynamic weakening, and reactivation of hidden or inactive faults.

Work by Kato and Obara looking at repeating earthquakes before the 2011 Tohoku earthquakes show how the evolved in time and space over the months before and used their seismic moment to estimate equivalent moment of aseismic slip. There is some ocean-bottom pressure gauge data that is consistent with their findings. Prior to the 2014 Iquique earthquake there were swarms and repeating earthquakes, suggesting bilateral along-strike and down-dip migration at 1-10 km/day and a total equivalent slip of ~10 cm. GPS velocities also changed and the observed foreshocks could not account for these. Bouchon et al. (2013) found that 70% of large interplate earthquakes are preceded by foreshock sequences mediated by slow slip.

Oceanic transform faults also exhibit seismic swarms and possible slow slip. Persistent M6 ruptures on the Gofar Transform are separated by barriers, hosting intensive swarms. Perhaps

swarm migration is driven by aseismic slip, as a result of strong dilatancy effects, and deep seismic swarms may be driven by slow slip in mantle.

Models of slow slip behavior prior to a large earthquake require transitional frictional stability. Simulations show that intervals of slow slip events and amplitudes change prior to earthquakes, with a consistent decrease of the recurrence interval and decreasing magnitudes. If low permeability or diffusivity prevails, thermal pressurization will increase pore pressure and weaken the fault.

For slow slip events to be useful, we need to make use of long and short term deformation data.

The Kaikoura earthquake showed that not much slip had accumulation in areas that slipped several meters, in the Ridgecrest earthquake many faults were activated.

Earthquake Early Warning Science (Jeff McGuire)

Topics currently being investigated for EEW include the current and needed speed of warnings, social science issues, offshore capabilities, high MMI threshold users, source depth estimates, and use of GNSS data.

Running data from the 2003 M8.3 Tokachi-oki earthquake through ShakeAlert yielded a M7.1 estimate after 20s, and a zone 50-100 km the P wave arrives before the alert. This is an optimistic case. A similar analysis for the M7.1 Anchorage earthquake showed damaging shaking arrived within 10-15 s of P wave and at 12 s everyone would have received an alert; i.e., it will be a 'mixed bag' result. For a repeat of the 2001 Nisqually earthquake, warnings would likely arrive after shaking is felt within 50+ km.

A key need in Cascadia is the ability to track rupture as it grows from 6 to7.0. Example of an event that starts in Newport, OR shows that once it reaches M7 everyone from Vancouver Island to the Mendocino Triple Junction will have been alerted. If the magnitude is wrong, way too many people would be alerted, so a key problem to understand is how often this can happen without consequences and social science proposals have been solicited to address this.

Also need to think about warning people along the coast.

For the Tokachi-oki example the coastal warning times limited by the time it takes for the signal to reach the stations on the coast. There are cabled seismometers offshore OR and WA and we need to start using them. NOAA telemetered buoys may be another way to get the data from the seafloor to the airwaves.

The current Shakealert system does not estimate depth, although a change from 5 km deep to 50 km deep translates to factor of 2 in the alert radius.

The Ridgecrest earthquake proved how much geodesy is needed, although it probably is not useful for M<7 events.

A participant asked what the data rate of NOAA buoys is and Jeff replied that he thought the current sample interval of 15 minutes could be increased. Another participant asked how fast a finite fault inversion can be done. A group currently is working on this.

Actual and aspirational geodesy (and seismology) (William Wilcock)

The Cascadia Initiative deployed many OBSs, but the instruments were fairly far apart and only portions of the region were monitored for just 18 months. Stone et al. 2018 showed that not a lot of earthquakes occurred during those 18 months.

Schmalzle et al., 2006 showed that we cannot constrain locking near the deformation front with land-based instruments. Detecting small slow slip events requires a significant number of sensors.

One of the two most advanced seafloor geodetic techniques is GPS-A, which is now much more economical due to use of wave glider. In 1994-1996 the first measurements were made offshore, and in the US there are now 4 sites, and data were collected this summer. Dave Chadwell initially proposed 12 offshore geodetic sites in 2012, and USGS has now funded some additional sites, but they are expensive. The Canadians now have 5 GPS-A sites with possibly 3 more to come. The other technique uses seafloor pressure sensors. Both techniques require correcting for oceanographic effects.

We should be using the cabled observatories for lots of types of geodesy. A newly proposed cabled borehole observatory in Cascadia around 44.5 N would utilize the OOI cabled array (Trehu 2018). We should really use the OOI nodes, which are currently used mostly for oceanographic purposes. A white paper about tsunami and earthquake early warning offshore is available now at www.cascadiaoffshore.org (led by David Schmidt).

Another measurement approach uses fiber optical strain (developed by M. Zumberge), on scale of 200 m horizontally, but this is power hungry (but getting better). Acoustic ranging is another approach, but only works across a few km. Borehole tilt, CORKS and other borehole instruments, and fluid flow meters also would be useful.

Differential bathymetry was very successfully used to measure deformation after the Tohoku earthquake but requires a pre-earthquake baseline.

Seattle basin and FZ via ambient noise (Natasha Toghramadjian)

That basins amplify due to soft deposits and basin edges focus traps seismic energy and causes constructive interference was first noticed for 1995 Kobe earthquake. Seattle sits on a sedimentary basin bounded to south by active Seattle fault zone. Nelson et al 2014 highlighted a diversity of subsurface interpretations of the Seattle fault zone structures. This motivated a multi-phase study now underway. The phase 1 data collection involved deployment of 10 broadbands across the Seattle basin at schools, churches, nonprofit, etc. Phase 2 included deployment of a dense nodal array across the Seattle fault zone. Surveys sent across several social media outlets, an ad on the PNSN website, and 150 letters yielded 200 volunteers. Nodals were retrieved last month. Phase 3 involved deployment of bedrock broadbands, to operate for 4-5 months.

The main tool to analyze the nodal data is cross correlation of ambient seismic noise. In this, one

windows the seismic noise at two stations, and cross correlates the noise windows between the stations. Examples for frequencies up to 10 Hz show that from sources south of the Seattle fault, the amplification is not right next to the station, but further north in the basin.

A participant asked if difference based on saturation of the soil were observed in the nodal data, but insufficient analyses have been done thus far to answer this.

2020 RV Langseth MCS Survey and piggy back deployments (Pablo Canales)

A multi-institutional experiment, 'Illuminating the Cascadia Plate Boundary Zone' has been funded by the NSF (S. Carbotte from LDEO is the lead PI). This will occur in June-July 2020 an involve ultra-long offset, 15 km, MCS data along the entire accretionary wedge. For permitting reasons, lines cannot go south of Oregon border. It was motivated by the ridge-to-trench experiment (Han et al., 2017), and questions about variations in sediments offshore OR vs WA and different fault vergences, and desire to map reflectivity going downdip and along strike (controlling the locked or slow-slipping behavior) hope mapping reflectivity. All resulting controlled source seismic data set will be open access. The lines have been designed to overlap with existing high-resolution surveys and old wells.

Another concurrent experiment involves 4 legs, on the R/V Oceanus and Langseth. A third proposal to the NSF, 'Cascadia 2020 Investigating Subduction Zone Segmentation with High-resolution VP model' (Trehu PI) is pending.

High-resolution dating of paleoseismic events (Jessie Pearl)

Paleoseismology asks same questions about past events as we want to know about future events.

Evidence addressing these exists in our natural world, in drowned forests, LIDAR that can see through vegetation, targeted trenching, and turbidite data.

Ghost forests exist across PNS landscapes, and in some cases still are in growth positions. Examples are found in Lake Sammamish (landslide drowned), Hood canal, and Bainbridge Island (fault scarp dammed). Trees are annually resolved proxies, and one can derive relationships with climate with resolution to the year and season. Tree-ring dating is an old technique, and cross-dating trees is like a barcode and can go back in time with trees that have overlapping growth periods. The oldest well-preserved trees found anywhere are 5000-6000 year old (not in Cascadia). Anoxic environments preserve trees very well.

Radiocarbon dating has uncertainties of 20-200 years. Each year a tree has a different radiocarbon intake, but we can also make use of cosmic rays that in some years created extra radiocarbon (e.g., in 993/994 CE and 774CE). There is a jump of 10-20 per mill in delta14C across these events, which allows floating chronologies to become absolute. This resolution allows us to distinguish much more uniquely between full or partial ruptures, estimate the return interval of megathrusts, gradual versus abrupt movement, etc. Our next step is to go out and get some of this wood and make measurements.

Closing discussion (moderators Kelin Wang and Danny Brothers)

What we should do as a community to have a local impact on hazards, and also a global impact on science (*Kelin Wang*)?

* It would be good to put together a group of experts to put together a tsunami earthquake source (*Rob Witter*).
* It would be wonderful to have a probabilistic tsunami hazard map that could be updated the way the seismic hazard maps are. This would be useful for planning vertical evacuation structures (*Scott Cameron*).
* It would be good to have a sense of when some research milestones that have been reached that constitute a new updated understanding that can be implemented (e.g., do we know more now about the recurrence intervals, or basin effects?; *Maximillian Dixon*).
* It would be good to have a group of experts who could put error bars or confidence limits to generate suites of realizations (of tsunamis) for Cascadia. There are experts who already know how to do this (*Frank Gonzalez*).
* Something easy that we are not doing a lot of is just mapping the inundation of existing tsunamis (*Chris Goldfinger*). One example of this is that the Salmon river estuary has been mapped, and the next step would be to develop models that are constrained by the tsunami deposit, not just coastal subsidence (*Rob Witter*).
* It is important to place Cascadia in the context of the global subduction science community. The SZ4D initiative grows out of the GeoPrisms and Margins programs. Cascadia is thought of as boring because of lack of seismicity and volcanic activity but we shouldn't let that happen (*Harold Tobin*).
* The consolidation process that takes place every 4 years program and all of the other collaborations that generate science for the USGS NSHM program are important. It is a real service in terms of credibility. The states want sources to be used when you generate a tsunami map that are at least consistent with the USGS sources, as this provides assurance to coastal residents, and also a target for those who want to push the research further (*Frank Gonzalez*).
* Does the Powell center project have tsunami scientists (Scott Cameron). There are two Powell Center projects, one is the Recurrence project and the other is the National Tsunami project. The latter has a lot of representation from USGS tsunami experts, from NOAA, and also from state tsunami program managers. It is important to note that the Powell Center projects are not large.

These last two comments are reminders of SCEC (*Danny Brothers*). That community extends beyond southern California because of their research on fundamental science. It's similar to this gathering here but far more evolved.

* We are not in the business of tsunami hazards (*Rob Witter*).
* Tsunamis fall between agencies (*Steve Hickman*). Truth is in the geology, which will tell us which models are correct. There is a lot of basic science in how ruptures propagate up to the seafloor. Tsunamis are a different problem, the science is global and appealing, and it is a ripe area for us as a community to get involved in. SZ4D and USGS SZ plan emphasize tsunamis and it is a great thing to have a SCEC-like effort on.

The interchange between the modelers and the observationalists was emphasized at the SZ4D Modelling Collaboratory workshop a few weeks ago (*Joan Gomberg*).