ESS 502: The Solid Earth: Cascadia Subduction and Hazards 2018

1. The set of geophysical tools (same as first half)
   a. Seismology
   b. Geodesy
   c. Heat Flow
   d. Gravity (acceleration/potential field)
   e. Magnetics
   f. (plus a little basic geochemistry)

2. Fundamental observables and inferred models

Observe	**Infer**
Seismic travel times	earthquake locations
Seismic travel times	3-D P and S velocity models
Seismic amplitudes	Anelastic attenuation (Q)
Electric and Magnetic Fields	3-D electric conductivity models
Areomagnetics	location of major earthquake faults
Areogravity	location of major earthquake faults
Lidar	location of major earthquake faults
GPS	crustal block rotations/deformation
Seismic tremor	ETS (episodic tremor and slip)
GPS/strain/tilt	silent earthquakes/episodic slip
Gravity	3-D density model
Heatflow	3-D temperature structure

See Web page for Schedule: subject to change

Reading List for Cascadia Subduction and Hazards

Overview of Cascadia tectonic setting.
Read the paper Wells et al., 1998 and answer these questions (turn in your answers):
1) Summarize the main points of the tectonic model that they propose.
2) What are the key observations?
3) What do you not understand?
We will discuss this paper as a class. Be prepared to come up to the board and explain the key points.

Wells, R. E., Weaver, C. S., and Blakely, R. J., 1998, Fore arc migration in Cascadia and its neotectonic significance; Geology, v. 26, p. 759-762.

Model for Intermediate depth intraslab earthquakes:
Read one of the following three papers and identify 1) the most important point(s), 2) the key observations that back this up, 3) whether you believe these results and 4) why they are important. Before class you should meet with the other people in your group to discuss these four issues. In class you will explain your answers to these 4 questions to

other members of your class, and learn about the other 2 papers from other members of the class as described in the "Active Learning Model" on the web page.

Peacock and Wang, Seismic consequences of warm versus cold subduction metamorphism: Examples from southwest and northeast Japan, Science, 286, 937-939, 1999.

Preston, L.A., K.C. Creager, R.S. Crosson, T.M. Brocher, and A.M. Tréhu, Intraslab earthquakes: Dehydration of the Cascadia slab, Science, 302, 1197-1200, 2003.

Hacker, B.R., S.M. Peacock, G.A. Abers, and S.D. Holloway, Subduction factory 2. Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration reactions?, J. Geophys. Res, 108, doi:10.1029/2001JB001129, 1-16, 2003.

Serpentine Mantle Wedge:

The three papers by Bostock, 2002; Blakely, 2005 and Audet, 2009 should be read in groups and presented to each other in class, following the same procedure and answering the same questions as for the intermediate-focus earthquakes.

This is the first paper to present compelling evidence for the existence of a strongly serpentinized mantle wedge.
Bostock, M.G., R.D. Hyndman, S. Rondenay, and S.M. Peacock, An inverted continental Moho and serpentinization of the forearc mantle, Nature, 417, 536-538, 2002.

This paper discusses magnetic and gravity anomalies to infer the geographic location of the serpentinized mantle wedge and its implications.
Blakely, R.J., T.M. Brocher, and R.E. Wells, Subduction-zone magnetic anomalies and implications for hydrated forearc mantle, Geology, 33, 445-448, 2005.

This paper discusses evidence for a serpentinized mantle wedge with a sharp boundary directly under Mount St Helens and its implications.
Hansen, S.M., B. Schmandt, A. Levander, E. Kiser, J. E. Vidale, G.A. Abers, K. C. Creager, Seismic evidence for a cold serpentinized mantle wedge beneath Mount St Helens, 2016, *Nat. Commun., 7, 13242 doi:, 2016, 10.1038/ncomms13242*.

This paper reports seismic evidence for water at high pore pressure in the upper crust of the subducting Juan de Fuca Plate.
Audet, P. M. G. Bostock, N. I. Christensen, and S. M. Peacock, Seismic evidence for overpressured subducted oceanic crust and megathrust fault sealing, Nature, 457| 1 January 2009| doi:10.1038/nature07650, 2009.

Episodic Tremor and Slip:

You should all read the first paper (only 2 pages) and one of the following 3 papers for discussion in class**:**

Rogers, G., and H. Dragert, Episodic tremor and slip on the Cascadia subduction zone: The chatter of silent slip, Science, 300, 1942-1943, 2003.

You can choose which of these three papers you want to read for discussion in small groups.

This is an excellent paper that discusses the scaling laws of earthquakes. In a nutshell, for normal earthquakes the seismic moment scales as a characteristic duration cubed. This is because earthquakes generally propagate at near the shear wave speed, so the fault length is proportional to the duration, fault area is the square of the length (for an equidimensional fault) and empirically, the amount of slip is roughly proportional to the fault length (strain scales as slip/fault length, stress drop, which is proportional to strain, is observed to be roughly independent of earthquake size). So, the seismic moment (shear modulus * fault area * amount of slip) is proportional to duration cubed. Slow slip/ETS/Low-Frequency Earthquakes, Very Low-Frequency Earthquakes, etc all have duration approximately proportional to seismic moment.
Ide, S., et al. (2007), A scaling law for slow earthquakes, *Nature, 447, doi:10.1038/nature05780,* 76-79.

Paper on how slip transitions with depth from stable sliding at depth to episodic slip characterized by frequent small events to infrequent large slip events and ultimately to stick-slip megathrust earthquakes at shallow depths.
Wech, A. G. and K. C. Creager, 2011, A continuum of stress, strength and slip in the Cascadia subduction zone, *Nature GeoSci.,4, doi:10.1038/ngeo121*.

Paper on sensitivity of tremor to tides and implications for fault friction:
Houston, H., Low friction and fault weakening revealed by rising sensitivity of tremor to tidal stress, *Nature GeoSci, 2015, doi: 10.1038/NGEO2419, 1-8.*

Excellent review paper:
Peng, Z. and J. Gomberg, (2010) An integrated perspective of the continuum between earthquakes and slow-slip phenomena, Nature GeoSci., 3, doi: 10.1038/ngeo940.

More ETS papers…
The focus of this paper is on a comparison of the spatial distribution of tremor and of geodetic inferred slip for four Episodic Tremor and slip events in Cascadia.
Wech, A. G., K. C. Creager and T. I. Melbourne (2009), Seismic and geodetic constraints on Cascadia slow slip, *J. Geophys. Res., 34, doi:10.1029/2008JB006090,* 1-9.

This paper uses low-frequency earthquakes to get S-P times to get the source depth of tremor and demonstrates that tremor is on the plate interface, lies above the intraplate earthquakes and that the curst has especially high Vp/Vs ratios consistent with the presence of fluids.

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

This paper presents evidence for a strong correlation between tides and the strength of tremor during ETS events. This implies that tremor is sensitive to stresses that are 10^5 times smaller than lithostatic stress.

Rubinstein, J. L., et al. (2008), Tidal modulation of nonvolcanic tremor, *Science, 319,* 186-189.

Some Review Papers:

Peng, Z. and J. Gomberg, (2010) An integrated perspective of the continuum between earthquakes and slow-slip phenomena, Nature GeoSci., 3, doi: 10.1038/ngeo940.

Rubinstein, J. L., D. R. Shelly, and W. L. Ellsworth, Non-volcanic Tremor: A window into the roots of fault zones, S. Cloetingh, J. Negendank (eds.), New Frontiers in Integrated Solid Earth Sciences, International Year of Planet Earth, DOI 10.1007/978-90-481-2737-5_8, 2010.

Gomberg, J. and the Cascadia 2007 and Beyond Working Group, 2010, Slow-slip phenomena in Cascadia from 2007 and beyond: A review, *GSA Bulletin, 122 p. 963–978; doi: 10.1130/B30287.1*.

Schwartz, S.Y. and J.M. Rokosky, Slow slip events and seismic tremor at circum-pacific subduction zones, *Rev. Geophys. 45, RG3004, doi:10.1029/2006RG000208*, 2007.

Mostly Tremor papers:

Abers, G. A., L. S. MacKenzie, S. Rondenay, Z. Zhang, A. G. Wech, and K. C. Creager, 2009, Imaging the source region of Cascadia tremor and intermediate-depth earthquakes, *Geology, 37, doi: 10.1130/G30143A.1,* 1119-1122.

Ghosh, A., J. E. Vidale, J. R. Sweet, K. C. Creager, and A. G. Wech, 2009, Tremor patches in Cascadia revealed by seismic array analysis, *Geophys. Res. Lett., 36, L17316, doi:10.1029/2009GL039080,* 1-5.

Ghosh, A., J. E. Vidale, J. R. Sweet, K. C. Creager, A. G. Wech, and H. Houston, 2010, Tremor bands sweep Cascadia, *Geophys. Res. Lett., 37, L08301, doi:10.1029/2009GL042301,* 1-5.

Ghosh, A, J. E. Vidale, J. R. Sweet, K. C. Creager, A. G. Wech, H. Houston, and E. E. Brodsky, 2010, Rapid, continuous streaking of tremor in Cascadia, Geochem., Geophys., Geosyst., 11, Q12010, doi:10.1029/2010GC00330.

Colella, H. V., J. H. Dieterich, K. Richards-Dinger, A. M. Rubin, (2012) Complex characteristics of slow slip events in subduction zones reproduced in multi-cycle simulations, Geophys. Res. Lett., 39, doi:10.1029/2012GL053276, 2012.

Gomberg, J., et al. (2008), Widespread triggering of nonvolcanic tremor in California, *Science, 319*, 173.

Houston, H., B. G. Delbridge, A. G. Wech, K. C. Creager, Rapid Tremor Reversals in Cascadia generated by a weakened plate interface, *Nature Geoscience, v. 4, no. 6, 404-409, doi:10.1038/ngeo1157, 2011*.
Houston, H., Low friction and fault weakening revealed by rising sensitivity of tremor to tidal stress, *Nature GeoSci, 2015, doi: 10.1038/NGEO2419, 1-8.*
Ide, S., et al. (2007b), Mechanism of deep low frequency earthquakes: further evidence that deep non-volcanic tremor is generated by shear slip on the plate interface, Geophys. Res. Lett., 34, L03308, doi:1029/2006GL028890, 1-5.
Ide, S., (2012), Variety and spatial heterogeneity of tectonic tremor worldwide, J. Geophys. Res., 117, doi:10.1029/2011JB008840, 1-18.
Ide, S., and S. Yabe, Universality of slow earthquakes in the very low frequency band. *Geophys. Res. Lett.*, 41(8), 2014, 2786-2793.
Ito, Y., K. Obara, K. Shiomi, S. Sekine, H,. Hirose, Slow earthquakes coincident with episodic tremors and slow slip events, *Science, 315*, 503-506, 2007.
Ito, Y., et al. (2007), Slow Earthquakes Coincident with Episodic Tremors and Slow Slip Events, Science, 315, 503-506.
Kao, H., S.-J. Shan, H. Dragert, G.C. Rogers, J.F. Cassidy, and K. Ramachandran A wide depth distribution of seismic tremors along the northern Cascadia margin, *Nature, 436, 841-844,* 2005.
Obara, K., Nonvolcanic deep tremor associated with subduction in southwest Japan, Science, 296, 1679-1681, 2002.
Royer, A. A., A. M. Thomas, M. G. Bostock, Tidal modulation and triggering of low-frequency earthquakes in northern Cascadia, *J. Geophys. Res., Solid Earth, 120, 384–405, doi:10.1002/2014JB011430, 2015.*
Rubin, A. M., and J.G. Armbruster. Imaging slow slip fronts in Cascadia with high precision cross-station tremor locations. *Geochem., Geophys., Geosyst., 14.12 (2013): 5371-5392*.
Rubinstein, J. L., et al. (2007), Non-volcanic tremor driven by large transient shear stresses, Nature, 448, doi:10.1038/nature06017, 579-582.
Shelly, D. R., et al., Non-volcanic tremor and low-frequency earthquake swarms, *Nature, 446, 305-307*, 2007.
Sweet, J. R., K. C. Creager and H. Houston, A family of repeating low-frequency earthquakes at the downdip edge of tremor and slip, 2014, *Geochem., Geophys., Geosyst., 15, doi* 10.1002/2014GC005449, 3713-3721.
Wech, A. G., and K. C. Creager (2007), Cascadia tremor polarization evidence for plate interface slip, Geophys. Res. Lett., 34, doi:10.1029/2007GL031167, 1-6.
Wech, A. G., K. C. Creager and T. I. Melbourne (2009), Seismic and geodetic constraints on Cascadia slow slip, J. Geophys. Res., 34, doi:10.1029/2008JB006090, 1-9.
Wech, A. G., K. C. Creager, H. Houston, and J. E. Vidale, An earthquake-like magnitude-frequency distribution of slow slip in northern Cascadia, 2010, *Geophys. Res. Lett., doi:10.1029/2010GL044881, 1-5*.
Wech, A. G. and K. C. Creager, 2011, A continuum of stress, strength and slip in the Cascadia subduction zone, *Nature GeoSci.,4, doi:10.1038/ngeo121*.

Other recommended reading:

Crustal Structure of Puget Lowlands:

Van Wagoner, T.M., R.S. Crosson, K.C. Creager, G.F. Medema, L.A. Preston, N.P. Symons, and T.M. Brocher, Crustal structure and relocated earthquakes in the Puget Lowland, Washington from high resolution seismic tomography, J. Geophys. Res, 107, doi:10.1029/2001JB000710, 1-23, 2002.

Blakely, R.J., R.E. Wells, C.S. Weaver, and S.Y. Johnson, Location, structure, and seismicity of the Seattle Fault zone, Washington: Evidence from aeromagnetic anomalies, geologic mapping, and seismic-reflection data, GSAB, 114, 169-177, 2002.

These are back ground reading if you are interested in pursuing ETS further:

Dragert, H., K. Wang, and T.S. James, A silent slip event on the deeper Cascadia subduction subduction zone, Science, 292, 1525-1528, 2001.

La Rocca, M., W. McCausland, D. Galluzzo, S.D. Malone, G. Saccorotti, and E. Del Pezzo, Array measurements of deep tremor signals in the Cascadia subduction zone, GRL, 32, L21319, doi:10.1029/2005GL023974, 2005.

Liu, Y.J., and J.R. Rice, Aseismic slip transients emerge spontaneously in three-dimensional rate and state modeling of subduction earthquake sequences, JGR, 110, doi:10.1029/2004JB003424, 2005.

McCausland, W., S.D. Malone, and D.J. Johnson, Temporal and spatial occurrence of deep non-volcanic tremor: From Washington to northern California, GRL, 32, L24311, doi:10.1029/2005GL024349, 2005.

McCrory, P. A., R. D. Hyndman, and J. L. Blair. Relationship between the Cascadia fore-arc mantle wedge, nonvolcanic tremor, and the downdip limit of seismogenic rupture, *Geochem., Geophys., Geosyst., 15, no. 4 (2014): 1071-1095*.

Miller, M., D.J. Johnson, C.M. Rubin, H. Dragert, K. Wang, A. Qamar, and C. Goldfinger, GPS-determination of along-strike variation in Cascadia margin kinematics: Implications for relative plate motion, subduction zone coupling, and permanent deformation, Tectonics, 20, 161-176, 2001.

Miller, M., T. Melbourne, D.J. Johnson, and W.Q. Sumner, Periodic slow earthquakes form the Cascadia subduction zone, Science, 295, 2423, 2002.

Obara, K. and H. Hirose, Non-volcanic deep low-frequency tremors accompanying slow slips in the southwest Japan subduction zone, *Tectonophysics, 417*, 33-51, 2006.

Expanding on Wells et al. 1998

Wells, R. E., and Simpson, R. W., 2001, Microplate motion of the Cascadia forearc and implications for subduction deformation; Earth Planets Space, v. 53, p. 275-283.

Stress-Strain Paradox: Why do crustal earthquakes show north-south compressions and strain measurements show east-west compression west of the Cascades?

Wang, K., Stress-strain paradox, plate coupling, and forearc seismicity at the Cascadia and Nankai subduction zones, Tectonophysics, 319, 321-338, 2000.

Update on crustal deformation in Washington and Oregon

McCaffrey, R., M. D. Long, C. Goldfinger, P. C. Zwick, J. L. Nabelek, C. K. Johnson, and C. Smith, Rotation and plate locking along the southern Cascadia subduction zone Geophys. Res. Lett., 27, 3117-3120, 2000.

McCaffrey, R., R. W. King., S. J. Payne and M. Lancaster, Active tectonics of northwestern US inferred from GPS-derived surface velocities. *J. Geophys. Res., 118(2), 2013, 709-723*.

Schmalzle, G., R. McCaffrey, K. C. Creager, Central Cascadia Subduction Zone Creep, 2014, *Geochem., Geophys., Geosyst., 15, doi:10.1002/2013GC005172,* 1515-1532.

Papers on seismic imaging of low-velocity wave-guides at the tops of slabs interpreted as basalt and gabro (7 km/s) surrounded by mantle peridotite (8 km/s).

Abers, G.A., Seismic low-velocity layer at the top of subducting slabs: observations , predictions and systematics, Phys. Earth Planet. Int., 149, 7-29, 2005.

Abers, G. A., Hydrated crust at 100-250 km depth, Earth and Planet. Sci. Lett., 176, 323-330, 2000.

Glacio-seismology

Wiens, D., Simultaneous teleseismic and geodetic observations of the stick-slip motion of an Antarctic ice stream, Nature, Vol. 453, Iss. 7196, 2008.

Okal, E, and D. MacAyeal, Seismic and hydroacoustic tremor generated by colliding icebergs, J. Geophys Res, 113, 2008.

Kawakatsu, H., and S. Watada, Seismic evidence for deep-water transportation in the mantle, Science, 316, 1468-1571, 2007.

Northwest Structure studies

Bostock, M. G., the Moho in subduction zones, *Tectonophysics, 609, doi: 10.1016/j.tecto.2012.07.007, 547-557,* 2013.

ten Brink, U.S., P.C. Molzer, M.A. Fisher, R.J. Blakely, R.C. Bucknam, T. Parsons, R.S. Crosson, and K.C. Creager, Subsurface geometry and evolution of the Seattle Fault Zone and the Seattle Basin, Washington, BSSA, 92, 1737-1753, 2002.

Wagner, L. S., M. J. Fouch, D. E. James and S. Hanson-Hedgecock, Crust and upper mantle structure beneath the Pacific Northwest from joint inversions of ambient noise and earthquake data, Geochem, Geophys, Geosys, 13, doi:10.1029/2012GC004353, 1-21, 2012.

McGary, R. S., Evans, R. L., Wannamaker, P. E., Elsenbeck, J., and Rondenay, S. , Pathway from subducting slab to surface for melt and fluids beneath Mount Rainier. Nature, 511(7509), 2014, 338-340.

West, J. D. , M. J. Fouch,, J. B. Roth, L. T. Elkins-Tanton, Vertical mantle flow associated with a lithospheric drip beneath the Great Basin, *Nature GeoSci, doi: 10.1038/NGEO526, 1-6, 2009.*

Li, C., R. D. van der Hilst, E. R. Engdahl, and S. Burdick. A new global model for P wave speed variations in Earth's mantle. *Geochem., Geophys., Geosyst., 9, no. 5 (2008).*

Schmandt, B., and Lin, F. C., P and S wave tomography of the mantle beneath the United States, *Geophys. Res. Lett., 41(18), (2014), 6342-6349.*

Schmandt, B. and E. Humphreys, Seismically imaged relict slab from the 55 Ma Siletzia accretion to the northwest United States, 2011, *Geology, doi: 10.1130/G31558.1*, 175-178.

Kiser, E., I Palomeras, A. Levander, C. Zelt, S. Harder, B. Schmandt, S. Hansen, K. C. Creager, C. Ulberg, Magma reservoirs from the upper crust to the Moho inferred from high-resolution Vp and Vs models beneath Mount St. Helens, Washington State, USA, 2016, *Geology,* 44, doi: 10.1130/G37591.1, 411-414.