

**ESS 502: The Solid Earth: Cascadia Subduction and Hazards 2009**

1. The set of geophysical tools (same as first half)
  - a. Seismology
  - b. Geodesy
  - c. Heat Flow
  - d. Gravity (acceleration/potential field)
  - e. Magnetism
  - f. (plus a little basic geochemistry)
  
2. Fundamental observables and inferred models

<b>Observe</b>	<b>Infer</b>
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
Areomagnetism	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

**Tentative Schedule:**

- 2/17) Lecture on deep earthquakes and summarize Cascadia Tectonics
- 2/19) Read Wells et al., 1998; brief small group discussion followed by students at the board and then overall discussion/summary
- 2/24) Student Presentations on layered vs whole mantle convection
- 3/26) Read 3 papers on Intermediate-focus earthquakes, students discuss outside class, then break into alternate groups to discuss in class
- 3/3) Go to ETS workshop on Monday or Tuesday: no class Tuesday; schedule is here:  
<http://earthweb.ess.washington.edu/~gomberg/Cascadia2007&Beyond.html>
- 3/5) Read 3 papers on serpentine, students discuss outside class, then break into alternate groups to discuss in class
- 3/10) Read ETS summary papers and discuss in class
- 3/12) Read 3 more ETS papers, students discuss outside class, then break into alternate groups to discuss in class
- 3/17) Final Presentations (need to confirm this date)

# Reading List for Cascadia Subduction and Hazards

## Overview of Cascadia tectonic setting.

**Feb 19:** Read the paper Wells et al., 1998 and answer these questions (you should turn in your answers at the end of class):

- 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:

**Feb 26:** 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 and Seattle Fault,

**Feb 28:** The three papers by Bostock, 2002; Blakely, 2005 and Kawakatsu, 2007 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 reports seismic evidence for serpentine just above the subducting slab at depths of 50-150 km beneath northern Honshu, Japan. The very old, cold Pacific plate is subducting beneath Honshu.

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

**Episodic Tremor and Slip: There are several new papers that I will add to this list!**

You should all read the first paper (only 2 pages) and one of the following 3 papers for discussion in class on Tuesday, March 6.

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 on Friday.

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. 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. (2007a), A scaling law for slow earthquakes, *Nature*, 447, doi:10.1038/nature05780, 76-79.

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 crust has especially high  $V_p/V_s$  ratios consistent with the presence of fluids.

Shelly, D. R., G. C. Beroza, S. Ide, and S Nakamura, 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.

Shelly, D. R., et al. (2007), Non-volcanic tremor and low-frequency earthquake swarms, *Nature*, 446, 305-307.

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.

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.

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

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:10.1029/2006GL028890, 1-5.

Ito, Y., et al. (2007), Slow Earthquakes Coincident with Episodic Tremors and Slow Slip Events, *Science*, 315, 503-506.

Rubinstein, J. L., et al. (2007), Non-volcanic tremor driven by large transient shear stresses, *Nature*, 448, doi:10.1038/nature06017, 579-582.

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.

**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 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.

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

Obara, K., Nonvolcanic deep tremor associated with subduction in southwest Japan, *Science*, 296, 1679-1681, 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.

*Papers on seismic imaging of low-velocity wave-guides at the tops of slabs interpreted as basalt and gabbro (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.

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.

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.