

GEOL599: Subduction

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Times Spring 2012; Class meets Thursdays 1:30-4:15pm, 3 units, Location: ZHS264

Objective Subduction of oceanic lithosphere plays an integral part in driving plate tectonics, continental formation and deformation, carbon and volatile cycles, and so controls the geological evolution of Earth.

The objective of this seminar is to take stock of what's been done in terms of geodynamic modeling and structural seismology, and, more importantly, identify a few new avenues how we can make progress on subduction science, both from a fundamental level, and in terms of understanding the dynamics of data-rich "natural laboratories" such as Japan (particularly after Tohoku), the United States (after and during EarthScope USArray), and the MARGINS/GeoPRISM sites.

After a series of introductory classes, we will focus on a subset of the wide field of subduction research, the topics of subduction initiation and the interactions of subduction with overriding plate deformation.

The class targets graduate students from all Earth science fields, applied math, and engineering and will include reading and in-class discussion of the recent literature and classic papers. We will have student presentations, and students are expected to work on a term paper. The latter can be a research project (preferred), or an in-depth review of a subject area.

Recommended preparation GEOL440, GEOL534.

Grading

- 40% student presentations
- 50% final project
- 10% class participation

Syllabus

Jan 19 Introduction. Student presentations on *Becker and Faccenna* (2009) and *Billen* (2008)

Additional reading: *Forsyth and Uyeda* (1975); *Uyeda and Kanamori* (1979)

Jan 26 Presentation by John Crowley on Plate force balance.

Feb 2 (DO lead) Kinematics and slab dip. Student presentations on *Heuret and Lallemand* (2005); *Heuret et al.* (2007); *Lallemand et al.* (2005)

Additional reading: *Tovish and Schubert* (1978); *Hager and O'Connell* (1978); *Jarrard* (1986); *King* (2001); *Heuret et al.* (2011)

Feb 9 (TWB lead) Rheology. Student presentations on *Billen and Hirth* (2005); *van Hunen and van den Berg* (2008)

Additional reading: *Christensen* (1984); *Hager* (1984); *Hirth and Kohlstedt* (2004)

Feb 16 Viscous bending. Student presentations on *Conrad and Hager* (1999); *Ribe* (2010)

Additional reading: *Bellahsen et al.* (2005); *Buffett and Rowley* (2006); *Buffett and Becker* (2012); *Capitanio et al.* (2011)

Feb 23 Initiation of subduction I. Discussion of *Gurnis et al.* (2000)

Additional reading: *Regenauer-Lieb et al.* (2001); *Kemp and Stevenson* (1996); *Toth and Gurnis* (1998); *Gerya* (2011)

Mar 1 Initiation of subduction II. Student presentation on *Nikolaeva et al.* (2010); *Leng and Gurnis* (2012)

Additional reading: *Lévy and Jaupart* (2012); *Nikolaeva et al.* (2011); *van Hunen and van den Berg* (2008)

Mar 8 (MSM lead) Convergence velocity and trench migration. Student presentations on *Schellart et al.* (2007); *Miller et al.* (2006)

Additional reading: *Stegman et al.* (2006); *Funiciello et al.* (2008); *Royden and Husson* (2006); *Bevis* (1986)

Mar 23 Slab overriding plate coupling: Student presentations on *Bostock et al.* (2002); *Royden and Papanikolaou* (2011)

Additional reading: *Rondenay et al.* (2001)

Mar 29 (DO lead) Slab overriding plate interactions. Presentation on *Wallace et al.* (2009).

Additional reading: *Faccenna et al.* (2006); *Capitanio et al.* (2011)

Apr 5 Flat slabs. Student presentations on *Anderson et al.* (2007); *Kim et al.* (2010).

Additional reading: *Skinner and Clayton* (2011)

Apr 12 (MSM lead) Flat slab dynamics. Student presentations on *van Hunen et al. (2002a,b)* and *Manea et al. (2012)*

Additional reading: *Olbertz et al. (1997)*; *Manea and Manea (2010)*

Apr 19 (TWB lead) Overriding plate deformation. Student presentations on *Whittaker et al. (2007)*; *Capitanio et al. (2010)*

Additional reading: *Davies and von Blanckenburg (1995)*; *Schellart (2008)*

May 10 Final project presentations.

Textbooks

No text book is required, but the first two strongly recommended.

- Turcotte, D. and Schubert, G. *Geodynamics*. Cambridge University Press, 2nd edition, 2001. (Update of a classic, standard text.)
- Ranalli, G. *Rheology of the Earth*. Chapman & Hall, 1995. (Somewhat out of date but highly useful, PDF may be available.)
- Schubert, G. Turcotte, D. and Olson, P.: *Mantle convection in the Earth and Planets*, Cambridge University Press, 2001. (More comprehensive treatment of convection with all the equations you'll ever need.)
- Davies, G. F., *Dynamic Earth: Plates, plumes, mantle convection*, Cambridge University Press, 1999. (Nice narrative of one of the traditional views on mantle dynamics.)
- Malvern, L. E., *Introduction to the mechanics of a continuous medium*, Prentice Hall, Inc., 1969. (Classic continuum mechanics text, very useful for more comprehensive background reading.)
- Karato, S.-i., *Deformation of Earth Materials*, Cambridge University Press, 2008. (Somewhat of an update of Ranalli with a slightly different angle.)

Statement for Students with Disabilities

Any student requesting academic accommodations based on a disability is required to register with Disability Services and Programs (DSP) each semester. A letter of verification for approved accommodations can be obtained from DSP. Please be sure the letter is delivered to me (or to TA) as early in the semester as possible. DSP is located in STU 301 and is open 8:30 a.m.5:00 p.m., Monday through Friday. The phone number for DSP is (213) 740-0776.

Statement on Academic Integrity

USC seeks to maintain an optimal learning environment. General principles of academic honesty include the concept of respect for the intellectual property of others, the expectation that individual work will be submitted unless otherwise allowed by an instructor, and the obligations both to protect one's own academic work from misuse by others as well as to avoid using another's work as one's own. All students are expected to understand and abide by these principles. Scampus, the Student Guidebook, contains the Student Conduct Code in Section 11.00, while the recommended sanctions are located in Appendix A: <http://www.usc.edu/dept/publications/SCAMPUS/gov/>. Students will be referred to the Office of Student Judicial Affairs and Community Standards for further review, should there be any suspicion of academic dishonesty. The Review process can be found at: <http://www.usc.edu/student-affairs/SJACS/>.

References

- Anderson, M., P. Alvarado, G. Zandt, and S. Beck (2007), Geometry and brittle deformation of the subducting Nazca Plate, Central Chile and Argentina, *Geophys. J. Int.*, *171*, 419–434.
- Becker, T. W., and C. Faccenna (2009), A review of the role of subduction dynamics for regional and global plate motions, in *Subduction Zone Geodynamics*, edited by F. Funiciello and S. Lallemand, *Int. J. Earth Sci.*, pp. 3–34, Springer.
- Bellahsen, N., C. Faccenna, and F. Funiciello (2005), Dynamics of subduction and plate motion in laboratory experiments: insights into the plate tectonics behavior of the Earth, *J. Geophys. Res.*, *110*, doi:10.1029/2004JB002999.
- Bevis, M. (1986), The curvature of Wadati-Benioff zones and the torsional rigidity of subducting plates, *Nature*, *323*, 52–53.
- Billen, M. I. (2008), Modeling the dynamics of subducting slabs, *Ann. Rev. Earth Planet. Sci.*, *36*, 325–356.
- Billen, M. I., and G. Hirth (2005), Newtonian versus non-Newtonian upper mantle viscosity: Implications for subduction initiation, *Geophys. Res. Lett.*, *32*, doi:10.1029/2005GL023457.
- Bostock, M. G., R. D. Hyndman, S. Rondenay, and S. M. Peacock (2002), An inverted continental Moho and serpentization of the forearc mantle, *Nature*, *417*, 536–538.
- Buffett, B., and T. W. Becker (2012), Bending stress and dissipation in subducted lithosphere, *J. Geophys. Res.*, *submitted*, available online at <http://geodynamics.usc.edu/~becker/preprints/bb11b.pdf>, accessed 01/2012.
- Buffett, B. A., and D. B. Rowley (2006), Plate bending at subduction zones: Consequences for the direction of plate motions, *Earth Planet. Sci. Lett.*, *245*, 359–364.

- Capitanio, F. A., D. R. Stegman, L. Moresi, and W. Sharples (2010), Upper plate controls on deep subduction, trench migrations and deformations at convergent margins, *Tectonophys.*, *483*, 80–92.
- Capitanio, F. A., C. Faccenna, S. Zlotnik, and D. R. Stegman (2011), Subduction dynamics and the origin of Andean orogeny and the Bolivian orocline, *Nature*, *480*, 83–86.
- Christensen, U. R. (1984), Convection with pressure- and temperature-dependent non-Newtonian rheology, *Geophys. J. R. Astr. Soc.*, *77*, 343–384.
- Conrad, C. P., and B. H. Hager (1999), The effects of plate bending and fault strength at subduction zones on plate dynamics, *J. Geophys. Res.*, *104*, 17,551–17,571.
- Davies, J. H., and F. von Blanckenburg (1995), Slab breakoff: a model of lithospheric detachment and its test in the magmatism and deformation of collisional orogens, *Earth Planet. Sci. Lett.*, *129*, 85–102.
- Faccenna, C., O. Bellier, J. Martinod, C. Piromallo, and V. Regard (2006), Slab detachment beneath eastern Anatolia: A possible cause for the formation of the North Anatolian fault, *Earth Planet. Sci. Lett.*, *242*, 85–97.
- Forsyth, D. W., and S. Uyeda (1975), On the relative importance of the driving forces of plate motion, *Geophys. J. R. Astr. Soc.*, *43*, 163–200.
- Funiciello, F., C. Faccenna, A. Heuret, E. Di Giuseppe, S. Lallemand, and T. W. Becker (2008), Trench migration, net rotation and slab-mantle coupling, *Earth Planet. Sci. Lett.*, *271*, 233–240.
- Gerya, T. (2011), Future directions in subduction modeling, *J. Geodyn.*, doi:10.1016/j.jog.2011.06.005.
- Gurnis, M., S. Zhong, and J. Toth (2000), On the competing roles of fault reactivation and brittle failure in generating plate tectonics from mantle convection, in *The History and Dynamics of Global Plate Motions*, *Geophysical Monograph*, vol. 121, edited by M. A. Richards, R. G. Gordon, and R. D. van der Hilst, pp. 73–94, AGU, Washington DC.
- Hager, B. H. (1984), Subducted slabs and the geoid: constraints on mantle rheology and flow, *J. Geophys. Res.*, *89*, 6003–6015.
- Hager, B. H., and R. J. O’Connell (1978), Subduction zone dip angles and flow derived by plate motion, *Tectonophys.*, *50*, 111–133.
- Heuret, A., and S. Lallemand (2005), Slab dynamics and back-arc deformation, *Phys. Earth Planet. Inter.*, *149*, 31–51.
- Heuret, A., F. Funiciello, C. Faccenna, and S. Lallemand (2007), Plate kinematics, slab shape and back-arc stress: A comparison between laboratory models and current subduction zones, *Earth Planet. Sci. Lett.*, *256*, 473–483.

- Heuret, A., S. Lallemand, F. Funiciello, C. Piromallo, and C. Faccenna (2011), Physical characteristics of subduction interface type seismogenic zones revisited, *Geochem., Geophys., Geosys.*, 12(Q01004), doi:10.1029/2010GC003230.
- Hirth, G., and D. L. Kohlstedt (2004), Rheology of the upper mantle and the mantle wedge: A view from the experimentalists, in *Inside the Subduction Factory*, *Geophys. Monograph*, vol. 138, edited by J. Eiler, pp. 83–105, American Geophysical Union, Washington DC.
- Jarrard, R. D. (1986), Relations among subduction parameters, *Rev. Geophys.*, 24, 217–284.
- Kemp, D. V., and D. J. Stevenson (1996), A tensile, flexural model for the initiation of subduction, *Geophys. J. Int.*, 125, 73–94.
- Kim, Y., R. W. Clayton, and J. M. Jackson (2010), Geometry and seismic properties of the subducting Cocos plate in central Mexico, *J. Geophys. Res.*, 115(B06310), doi:10.1029/2009JB006942.
- King, S. D. (2001), Subduction: Observations and geodynamic models, *Phys. Earth Planet. Inter.*, 127, 9–24.
- Lallemand, S., A. Heuret, and D. Boutelier (2005), On the relationships between slab dip, back-arc stress, upper plate absolute motion, and crustal nature in subduction zones, *Geochem., Geophys., Geosys.*, 6, doi:10.1029/2005GC000917.
- Leng, W., and M. Gurnis (2012), Dynamics of subduction initiation with different evolutionary pathways, *Geochem., Geophys., Geosys.*, 12(Q12018), doi:10.1029/2011GC003877.
- Lévy, F., and C. Jaupart (2012), The initiation of subduction by crustal extension at a continental margin, *Geophys. J. Int.*, 188, 779–797.
- Manea, V. C., and M. Manea (2010), Flat-slab thermal structure and evolution beneath Central Mexico, *Pure Appl. Geophys.*, 168, 1475–1487.
- Manea, V. C., M. Pérez-Gussinyé, and M. Manea (2012), Chilean flat slab subduction controlled by overriding plate thickness and trench rollback, *Geology*, 40, 35–38.
- Miller, M. S., A. Gorbatov, and B. L. N. Kennett (2006), Three-dimensional visualization of a near-vertical slab tear beneath the southern mariana arc, *Geochem., Geophys., Geosys.*, 7, Q06,012, doi:10.1029/2005GC001110.
- Nikolaeva, K., T. V. Gerya, and F. O. Marques (2010), Subduction initiation at passive margins: Numerical modeling, *J. Geophys. Res.*, 115(B03406), doi:10.1029/2009JB006549.
- Nikolaeva, K., T. V. Gerya, and F. O. Marques (2011), Numerical analysis of subduction initiation risk along the Atlantic American passive margins, *Geology*, 39, 463–466.
- Olbertz, D., M. J. R. Wortel, and U. Hansen (1997), Trench migration and subduction zone geometry, *Geophys. Res. Lett.*, 24, 221–224.

- Regenauer-Lieb, K., D. A. Yuen, and J. Branlund (2001), The initiation of subduction; criticality by addition of water?, *Science*, *294*, 578–580.
- Ribe, N. M. (2010), Bending mechanics and mode selection in free subduction: a thin-sheet analysis, *Geophys. J. Int.*, *180*, 559–576.
- Rondenay, S., M. G. Bostock, and J. Shragge (2001), Multiparameter two-dimensional inversion of scattered teleseismic body waves 3. Application to the Cascadia 1993 data set, *J. Geophys. Res.*, *106*, 30,795–30,807.
- Royden, L. H., and L. Husson (2006), Trench motion, slab geometry and viscous stresses in subduction systems, *Geophys. J. Int.*, *167*, 881–905.
- Royden, L. R., and D. J. Papanikolaou (2011), Slab segmentation and late Cenozoic disruption of the Hellenic arc, *Geochem., Geophys., Geosys.*, *12*(Q03010), doi:10.1029/2010GC003280.
- Schellart, W. P. (2008), Overriding plate shortening and extension above subduction zones: A parametric study to explain formation of the Andes Mountains, *Geol. Soc. Amer. Bull.*, *120*, 1441–1454.
- Schellart, W. P., J. Freeman, D. R. Stegman, and L. N. Moresi (2007), Evolution and diversity of subduction zones controlled by slab width, *Nature*, *446*, 308–311.
- Skinner, S. M., and R. W. Clayton (2011), An evaluation of proposed mechanisms of slab flattening in Central Mexico, *Pure Appl. Geophys.*, *168*, 1461–1474.
- Stegman, D. R., J. Freeman, W. P. Schellart, L. Moresi, and D. May (2006), Influence of trench width on subduction hinge retreat rates in 3-D models of slab rollback, *Geochem., Geophys., Geosys.*, *7*, doi:10.1029/2005GC001056.
- Toth, J., and M. Gurnis (1998), Dynamics of subduction initiation at pre-existing fault zones, *J. Geophys. Res.*, *103*, 18,053–18,067.
- Tovish, A., and G. Schubert (1978), Island arc curvature, velocity of continents and angle of subduction, *Geophys. Res. Lett.*, *5*, 329–332.
- Uyeda, S., and H. J. Kanamori (1979), Back-arc opening and the mode of subduction, *J. Geophys. Res.*, *84*, 1049–1061.
- van Hunen, J., and A. P. van den Berg (2008), Plate tectonics on the early Earth: limitations imposed by strength and buoyancy of subducted lithosphere, *Lithos*, *103*, 217–235.
- van Hunen, J., A. P. van den Berg, and N. J. Vlaar (2002a), On the role of subducting oceanic plateaus in the development of shallow flat subduction, *Tectonophys.*, *352*, 317–333.
- van Hunen, J., A. P. van den Berg, and N. J. Vlaar (2002b), The impact of the South-American plate motion and the Nazca Ridge subduction on the flat subduction below South Peru, *Geophys. Res. Lett.*, *29*(1690), doi:10.1029/2001GL014004.

Wallace, L. M., et al. (2009), Characterizing the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand, *Geochem., Geophys., Geosys.*, 10(Q10006), doi:10.1029/2009GC002610.

Whittaker, J. M., R. D. Müller, M. Sdrolias, and C. Heine (2007), Sunda-Java trench kinematics, slab window formation and overriding plate deformation since the Cretaceous, *Earth Planet. Sci. Lett.*, 255, 445–457.