

Metamorphic processes in the subducting slab and overlying mantle wedge

Jay Ague (Yale University, jay.ague@yale.edu)

Gray Bebout (Lehigh University, geb0@lehigh.edu)

Justin Filiberto (Rice University, Justin.Filiberto@rice.edu)

Juliane Gross (Lunar and Planetary Institute, Gross@lpi.usra.edu)

Brad Hacker (University of California Santa Barbara, hacker@geol.ucsb.edu)

George Harlow (American Museum of Natural History, gharlow@amnh.org)

Craig Manning (University of California Los Angeles, manning@ess.ucla.edu)

Sarah Penniston-Dorland (University of Maryland, sarahpd@geol.umd.edu)*

Jeff Ryan (University of South Florida, ryan@shell.cas.usf.edu)

Kyla Simons (University of Miami, kkate89@gmail.com)

Thomas Zack (University of Mainz, zack@uni-mainz.de)

Topics: subduction zones, fluids and magmas

keywords: metamorphism

*corresponding author

The MARGINS Subduction Factory initiative to date has focused on probing the depths of *active* subduction zones. Much progress has been made towards addressing the three fundamental science themes proposed by the science plan: (1) How do forcing functions such as convergence rate and upper plate thickness regulate production of magma and fluid from the Subduction Factory? (2) How does the volatile cycle (H₂O and CO₂) impact biological, physical and chemical processes from trench to deep mantle? (3) What is the mass balance of chemical species and material across the Subduction Factory, and how does this balance affect continental growth and evolution? Clearer understanding of processes occurring deep in active subduction zones requires further investigation of *fossil* subduction zones: including the metamorphic rocks that were once parts of the subducting slab or overlying mantle that directly experienced those processes. Field-based studies of subduction-zone metamorphism, and allied experimental work, can address key questions raised by the Subduction Factory community and these types of studies should figure more prominently in future MARGINS initiatives.

Research that addresses MARGINS science themes includes modeling of subduction-zone thermal evolution (e.g. van Keken et al., 2002) and related dehydration histories (e.g. Schmidt and Poli, 1998, 2003; Hacker, 2008) with the goal of providing estimates of fluid fluxes within subduction zones. These models can be tested by petrologic and geochemical constraints from subduction-related metamorphic rocks (e.g. Bebout, 1995, 2007; Breeding and Ague, 2002). The models can be refined by better constraints on model inputs, such as the degree of hydration of oceanic lithosphere and by inclusion of (de)hydration of overlying mantle wedge. Recent studies of arc volcanic degassing have begun to incorporate insights gained through study of metamorphic suites (Elkins et al., 2006; Mitchell et al., in press) and studies of geochemical trends in forearc serpentinite seamounts (and associated peridotites) and in arc volcanic rocks incorporate and complement information gained through study of forearc metamorphic suites (Morris and Ryan, 2003; Mottl et al., 2004; Savov et al., 2005; 2007). Theoretical models for devolatilization thus far mostly consider dehydration; greater focus on CO₂, especially in mixed carbonate-silicate sediments, and on halogens, S, and N, will place important additional constraints on volatile budgets in subduction zones. Studies of metamorphic rocks are just beginning to scratch the surface in the understanding of how components other than H₂O behave during devolatilization reactions.

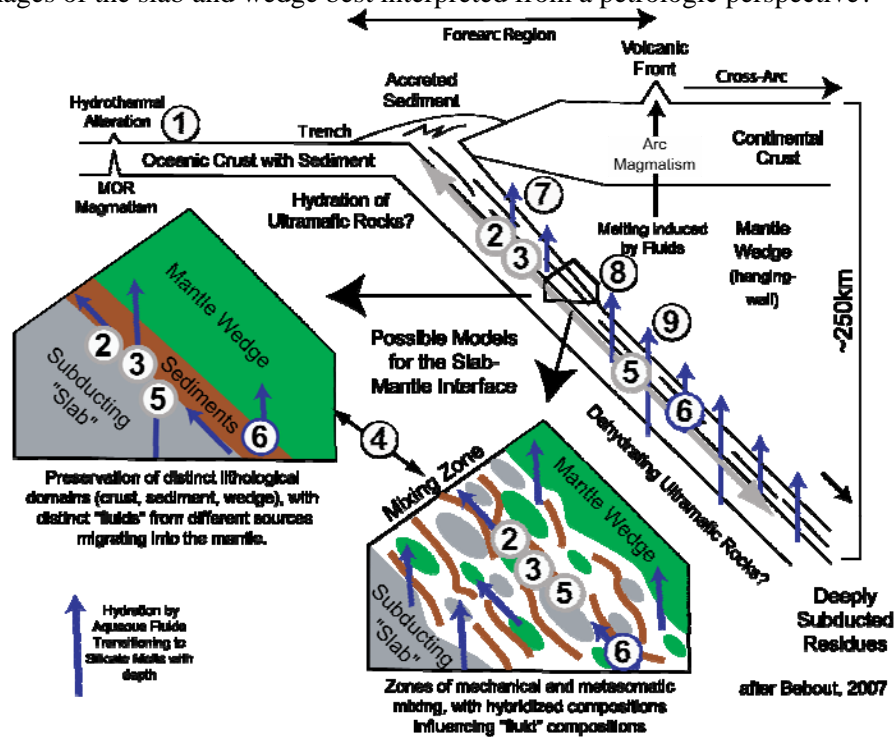
Element mobility and processes of mass transfer are other topics that have begun to be addressed by studies of metamorphic rocks. Investigation of features such as veins and metasomatized rocks, including hybridized rocks found in mélangé zones, provides insight into mechanisms of fluid transport, fluid flow pathways, mobility of elements, and mixing processes within subduction zones (e.g. Bebout and Barton, 2002; Ague, 2007; Bebout, 2007; King et al., 2007; John et al., 2008; Miller et al., 2009). Examination of serpentinites from mélangé complexes and from the eruptive deposits of serpentine mud volcanoes of the Mariana subduction system constrains both the mobility of elements at low P-T conditions during subduction and the material transport requirements of arc systems (Mottl et al., 2004; Savov et al., 2007; Hattori and Guillot, 2007). Mineral solubility experiments have demonstrated large solubility increases with increasing pressure while phase equilibria and *in situ* experiments are beginning to demonstrate the importance of silica and alumina polymerization under sub-arc conditions (see summary in Manning, 2004). The role of polymers in controlling the composition of subduction zone fluids and also the effects of chlorine and other ligands need to be investigated.

The physical properties of subduction-zone rocks are also understudied. Particularly critical is improving our ability to use geophysical observables, like seismic wave speeds and attenuation, to inform our understanding of compositional and structural variation within subduction zones (and vice versa) (e.g., Abers et al., 2003; Hacker et al., 2003). Of critical importance is the measurement or calculation of shear moduli—and their variation with pressure and temperature—in crustal minerals.

Studies of metamorphic rocks that reached various depths in ancient subduction zones are critical to understanding processes at modern convergent plate boundaries. It is important to combine efforts from experiments, geochemical observations, petrologic observations, modeling, and field investigations to ground truth ideas of what happens in the subducting slab and overlying mantle wedge during subduction.

We have identified the following key issues to address:

- 1) What is the alteration state of a slab as it enters a subduction zone?
- 2) What metamorphic reactions occur in the downgoing slab and mantle wedge and what metamorphic assemblages form? What volatile and non-volatile elements are released by those reactions?
- 3) What are the rates and timescales of devolatilization reactions during subduction and how do these rates affect rock rheology? What is the role of reaction kinetics during fluid release? Do reactions occur at near-equilibrium or are reactions significantly "overstepped"?
- 4) What is the nature of the slab-mantle wedge interface and how does it change with depth? over time? How much fluid is channelized upward along the décollement? What can we learn from exposed metamorphic rocks about the processes that occur at the interface and its physical, chemical, and seismic properties?
- 5) How do major and trace elements partition among minerals and between minerals and fluid in subduction zones and where do these elements reside in minerals? Similarly, how do isotopes fractionate and how do these fractionations evolve with changing pressure and temperature?
- 6) What are the compositions and physical characteristics of fluids (e.g. aqueous COHSN fluids, hydrous silicate melts) within subduction zones and how do they evolve? How do fluid compositions affect element mobility in fluids? What are the fluid fluxes, including fluxes of CO₂, during metamorphic processes? What are the fluid-flow pathways (fractures, porous flow) and dominant mechanisms (advection, diffusion) within the subducting slab and overlying mantle wedge? What physical and chemical properties of rocks affect their transport properties?
- 7) How do processes in the forearc affect the overall budget of elements in the subduction zone? To what extent does recycling of elements at shallow levels affect the overall budget within subduction zones? What contributions do forearcs make to arc magma source regions?
- 8) What are the implications (both physical and for volatile cycling) of serpentinization in the outer rise of the subducting slab (e.g. Ranero et al., 2005) and in the forearc mantle wedge?
- 9) What velocity structure is expected for the slab and wedge based on metamorphic processes? How are seismic images of the slab and wedge best interpreted from a petrologic perspective?



Sketch of a subduction zone showing locations corresponding to key questions identified above.

References

- Abers, G.A., Plank, T., and Hacker, B.R., 2003. The wet Nicaraguan slab. *GRL*, 30, 1098, doi:10.1029/2002GL015649.
- Ague, J.J., 2007, Models of permeability contrasts in subduction zone mélanges: Implications for gradients in fluid fluxes, Syros and Tinos Islands, Greece, *Chem. Geol.*, 239, 217-227.
- Bebout, G.E., 1995, The impact of subduction-zone metamorphism on mantle-ocean chemical cycling, *Chem. Geol.*, 126, 121-218.
- Bebout, G.E., 2007, Metamorphic chemical geodynamics of subduction zones, *EPSL*, 260, 373-393.
- Bebout, G.E., and Barton, M.D., 2002, Tectonic and metasomatic mixing in a high-T, subduction zone mélanges – insights into the geochemical evolution of the slab-mantle interface, *Chem. Geol.*, 187, 79-106.
- Breeding, C.M., and Ague, J.J., 2002, Slab-derived fluids and quartz-vein formation in an accretionary prism, Otago Schist, New Zealand, *Geology*, 30, 499-502.
- Elkins, L.J., Fischer, T.P., Hilton, D.R., Sharp, Z.D., McKnight, S., and Walker, J., 2006, Tracing nitrogen in volcanic and geothermal volatiles from the Nicaraguan volcanic front, *GCA*, 70, 5215–5235.
- Hacker, B.R., 2008, H₂O subduction beyond arcs, *G³*, 9, Q03001, doi:10.1029/2007GC001707.
- Hacker, B.R., Abers, G.A., and Peacock, S.M., 2003. Subduction Factory 1. Theoretical mineralogy, densities, seismic wave speeds, and H₂O contents, *JGR*, v. 108, 10.1029/2001JB001127.
- Hattori, K. H., and Guillot, S., 2007, Geochemical character of serpentinites associated with high- to ultrahigh-pressure metamorphic rocks in the Alps, Cuba, and the Himalayas: Recycling of elements in subduction zones, *G³*, vol. 8, Q09010, doi:10.1029/2007GC001594, 27 p.
- John, T., Klemd, R., Gao, J., and Garbe-Schonberg, C.-D., 2008, Trace-element mobilization in slabs due to non steady-state fluid-rock interaction: Constraints from an eclogite-facies transport vein in blueschist (Tianshan, China), *Lithos*, 103, 1-24.
- King, R., Bebout, G.E., Grove, M., Moriguti, T., Nakamura, E., 2007, Boron and lead isotope signatures of subduction-zone mélanges formation: hybridization and fractionation along the slab–mantle interface beneath volcanic fronts, *Chem Geol* , 239, 305-322.
- Manning, C.E., 2004, The chemistry of subduction-zone fluids, *EPSL*, 223, 1-16.
- Miller, D. P., Marschall, H.R., and Schumacher, J.C., 2009, Metasomatic formation and petrology of blueschist-facies hybrid rocks from Syros (Greece): Implications for reactions at the slab-mantle interface, *Lithos*, 107, 53-67.
- Mitchell, E.C., Fischer, T.P., Hilton, D.R., Hauri, E.H., Shaw, A.M., de Moor, J.M., Sharp, Z.D., and Kazahaya, K., in press, Nitrogen sources and recycling at subduction zones: Insights from the Izu-Bonin-Mariana arc, *G³*, doi:10.1029/2009GC002783.
- Morris, J.D., and Ryan, J.G., 2003, Subduction zone processes and implications for changing composition of the upper and lower mantle, in *Treatise on Geochemistry*, 2, The Mantle and Core, Carlson, R., ed., 451-470, Elsevier, New York.
- Mottl, M. J., Wheat, C. G., Fryer, P., Gharib, J., and Martin, J. B., 2004, Chemistry of springs across the Mariana forearc shows progressive devolatilization of the subducting slab. *GCA*, 68, 4915–4933.
- Ranero, C.R., Villasenor, A., Phipps Morgan, J., Weinrebe, W., 2005, Relationship between bend-faulting at trenches and intermediate depth seismicity, *G³*, 6, Q12002 doi:10.1029/2005GC000997.
- Savov, I.P., Ryan, J.G., D’Antonio, M., Kelley, K. and Mattie, P., 2005, Geochemistry of serpentinitized peridotites from the Mariana Forearc Conical Seamount, ODP Leg 125: Implications for the elemental recycling at subduction zones, *G³*, 6, doi:10.1029/2006JB004749.
- Savov, I.P., Ryan, J.G., D’Antonio, M. and Fryer, P., 2007, Petrology and geochemistry of serpentinitized peridotites from Mariana Forearc, South Chamorro Seamount, ODP Leg 195: Implications for the elemental recycling across and along the Mariana arc-basin system, *JGR*, 112, doi:10.1029/2004GC000777.
- Schmidt, M.W., and Poli, S., Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation, *EPSL*, 163, 361-379.
- Schmidt, M.W., and Poli, S., 2003, Generation of mobile components during subduction of oceanic crust, in *Treatise on Geochemistry*, 3, The Crust, Rudnick, R., ed., 567-591, Elsevier, New York.
- van Keken, P.E., Kiefer, B., and Peacock, S.M., 2002, High-resolution models of subduction zones: Implications for mineral dehydration reactions and the transport of water into the deep mantle, *G³*, 3, 10.