Metamorphic Processes Implementation Strategy - GeoPRISMS SCD

S. Penniston-Dorland (U. Maryland, sarahpd@umd.edu), G. Bebout (Lehigh U., geb0@lehigh.edu), B. Hacker (U.C. Santa Barbara, hacker@geol.ucsb.edu), H. Marschall (U. Bristol, Horst.Marschall@bristol.ac.uk), M. Feineman (Penn State, mdf12@psu.edu), T. John (U. Münster, timm.john@uni.muenster.de), P. Agard (UPMC Paris VI, philippe.agard@upmc.fr), P. van Keken (U. Michigan, keken@umich.edu), G. Abers (Lamont, abers@ldeo.columbia.edu), J. Filiberto (Rice Univ., Justin.Filiberto@rice.edu), T. Zack (U. Mainz, zack@uni-mainz.de), J. Gross (LPI, Gross@lpi.usra.edu), J. Ague (Yale, jay.ague@yale.edu), E. Baxter (Boston U., efb@bu.edu), J. Alt (U. Michigan, jalt@umich.edu), M. Cloos (U. Texas, cloos@mail.utexas.edu)

We propose an implementation strategy with a **Metamorphic Processes** theme for inclusion in the GeoPRISMS SCD initiative. This theme will include studies of metamorphic processes that address SCD key questions involving the role of volatiles, fluids and melts, geochemical cycling, and the end-products of metamorphic processes within subduction zones. Investigation of exposed high-pressure terrains will allow us to disentangle processes of mixing and material transport occurring within the subducting slab. Interpretation of isotopic and chemical signals in arc volcanic rocks and of geophysical data relies ultimately on understanding **processes** of release and transport occuring within and above the subducting slab. This theme will directly address the program's intent to expand the dimensions of the original program by including "consideration of ancient and exhumed margins." Field-based studies of fossil subduction-zone metamorphic rocks, allied experimental work, and modeling of thermal evolution and related dehydration histories will all be included within this theme. We propose to emphasize coordinated, interdisciplinary approaches, in which a variety of scientists, including metamorphic petrologists, geochemists, and geophysicists will use field, analytical, modeling and experimental approaches, and work together to understand transport and redistribution processes occurring at high P and T within the dynamic subduction zone environment.

Why choose a thematic approach? A thematic approach has a number of benefits. First, it will allow room for global comparisons among fossil subduction zones and comparison of fossil subduction zones with modern convergent margins. Second, it will allow for optimal combinations of field sites to maximize the diversity in P-T history, lithology, exhumation-related overprinting, and subduction environment. Finally, it will maximize the input from experimental and theoretical studies.

SCD Questions to be addressed by contributions from the Metamorphic Processes theme:

- How are volatiles, fluids, and melts stored, transferred, and released through the subduction system?

Research that currently addresses this question includes modeling subduction-zone thermal evolution [e.g., 1, 2] and related dehydration histories [3-6] with the goal of quantifying fluid fluxes. These models can be tested by constraints from subduction-related metamorphic rocks [7-10]. The models can be refined by better constraints on model inputs. Theoretical models mostly consider slab dehydration; greater focus on CO_2 and on halogens, S, and N, will place important constraints on full volatile budgets in subduction zones. Element mobility and processes of mass transfer are other topics addressed by studies of metamorphic rocks. Investigation of features such as veins and metasomatized rocks, including hybridized rocks in mélanges, provides insight into mechanisms of fluid transport, fluid-flow paths, mobility of elements, and mixing processes within subduction zones [8, 11-15]. Examination of serpentinites from mélange complexes and the eruptive deposits of serpentine mud volcanoes constrains the mobility of elements at low P-T conditions during subduction [16-18]. Mineral solubility experiments have demonstrated large solubility increases with increasing pressure whereas phase equilibria and *in situ* experiments are beginning to demonstrate the importance of silica and alumina polymerization in fluids under sub-arc conditions [19]. The role of polymers in controlling the composition of subduction-zone fluids and the effects of chlorine and other ligands need to be investigated. Geochronology has the potential to constrain devolatilization timescales and fluxes [20] and provide an upper bound on timescales of fluid flow events of thousands to hundreds of thousands of years [21-22]. Speedometry based on diffusion modeling of fast-diffusing elements is another tool that can allow determination of timescales of such brief events [23-27]. From this temporal information we can start to understand metamorphic porosities and permeabilities in order to integrate fluid release and element transport into our models.

- What are the geochemical products of subduction zones, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust?

Subduction zone metamorphic processes are a primary means of mass fractionation between crust and mantle. The residua of metamorphic processes in the slab may contribute to regions of anomalous isotopic composition in the deep mantle [28-30] and may play a role as a source for ocean island basalts [31-32]. Metamorphic processes such as dehydration, fluid flow, and metasomatism are involved in the concentration and transport of elements creating ore deposits associated with arc magmatism.

Overarching scientific topics in the GeoPRISMS Draft Science Plan addressed by the Metamorphic Processes theme (question numbers are linked to the following figure)**:**

1) **Fluids, Magmas and Their Interactions**: Metamorphic processes generate fluids and magmas involved in subduction-zone processes, and fossil subduction zones preserve records of these processes.

1a) What volatile and non-volatile elements are released by the metamorphic reactions occuring in the downgoing slab and mantle wedge?

1b) What are rates, timescales and lengthscales of devolatilization and hydration reactions, and how do these rates affect rock rheology? What is the role of reaction kinetics during fluid flow?

1c) What are the compositions and physical characteristics of fluids within subduction zones and how do they evolve? How do fluid compositions affect element mobility in fluids? What are the fluid fluxes during metamorphic processes? What are the fluid-flow paths (fractures, channels, grain scale 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? What are the durations of fluid flow events?

1d) What special metamorphic processes occur along interfaces between different rock types (e.g., along the slab sediment–mantle wedge interface) and what signature do they impart to fluids and magmas?

1e) Does the formation of hybrid rocks (such as in mélange zones) result in transient sinks for volatiles and trace elements, with unique physical properties and *P*-*T* stabilities?

2) **Geochemical cycles**: Metamorphic processes play a key role in the cycling of various elements through subduction zones.

2a) What is the effect of fluid composition on trace element partitioning and isotope fractionation in subduction zones? How do elements partition among minerals and fluids and where do they reside in minerals? How do isotopes fractionate and how do fractionation factors evolve with changing *P* and *T*?

2b) How do processes in the forearc affect the overall budget of elements in the subduction zone?

2c) What is the role of slab-sourced diapirs in mass transport in subduction zones?

2d) Where in the subduction system does the material removed by subduction erosion go? What role does subduction erosion play in fluid and magma generation and in the evolution of continental crust?

2e) What happens to subducted continental margins? How long do they remain in the mantle and what role do they play in fluid and magma generation and in the evolution of the continental crust?

2f) What is the alteration state of a slab as it enters a subduction zone? How much pore water goes down within the subducting sediment and what happens to the associated chlorine?

2g) What is the ultimate fate of subducted slab components as they are recycled into the deep mantle?

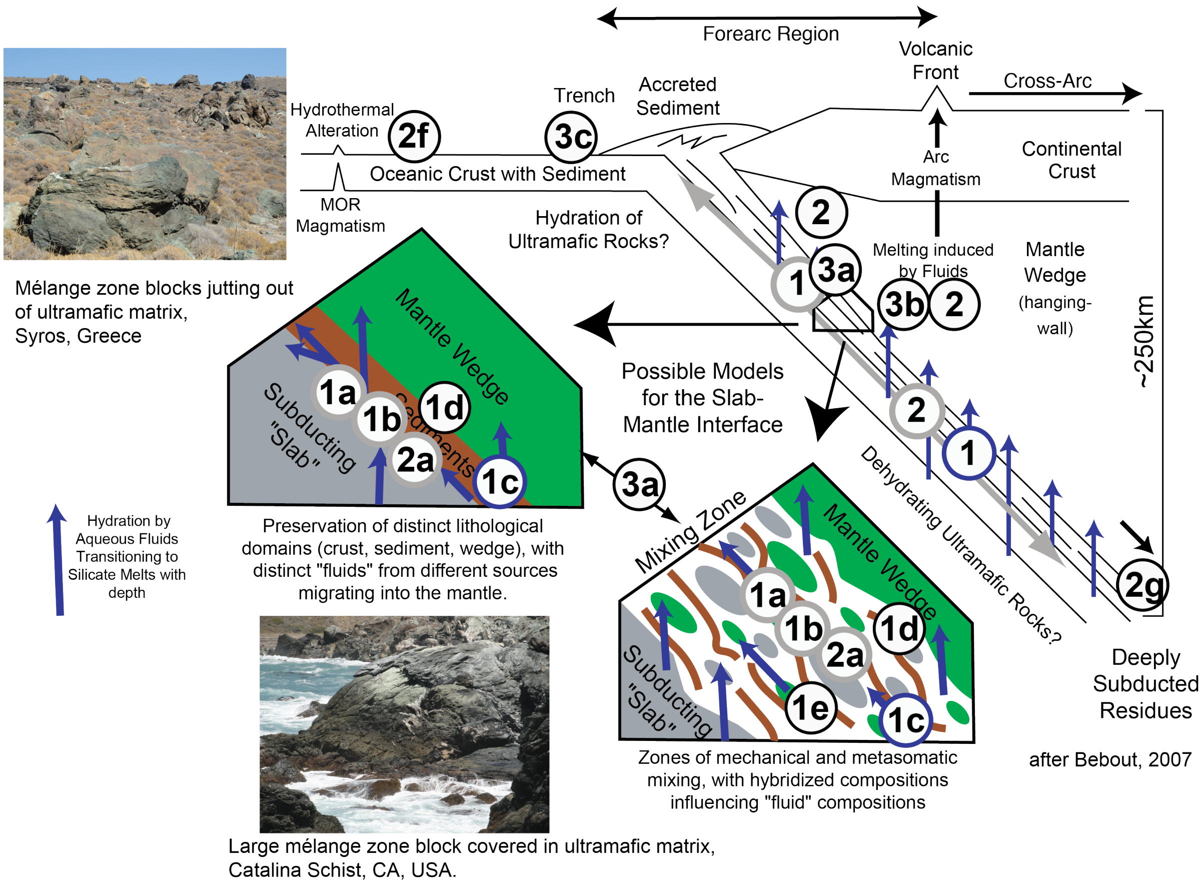
2h) Can global-scale mass balances be verified by exhumed subduction-related metamorphic rocks?

3) **Plate Boundary Deformation and Geodynamics**: Fossil subduction zones record deformation histories and provide information about physical properties of rocks found within active systems

3a) What is the nature of the slab–mantle wedge interface and how does it change with depth and 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 (i.e., in the "subduction channel") and its physical, chemical, and seismic properties [e.g., 33]?

3b) How do metamorphic processes affect the seismic velocity structure of the slab and wedge? What does seismology tell us about metamorphic processes in the slab and wedge?

3c) What are the implications of serpentinization of the subducting slab in the outer rise [e.g., 34] and deeper? What are the implications of serpentinization in the forearc mantle wedge?



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

References 1. I. Wada, I., K. Wang, *Geochem. Geophys. Geosyst.* 10, Q10009 (2009). 2. E.M. Syracuse, P.E. van Keken, G.A. Abers, *Phys. Earth Planet. Inter.* in press. 3. M.W. Schmidt, S. Poli, *Earth and Planet. Sci. Lett.* 163, 361 (1998). 4. M.W. Schmidt, S. Poli, *Treatise on Geochemistry*, 3, The Crust, Rudnick, R., ed. 567 (2003). 5. B.R. Hacker, *Geochem. Geophys. Geosyst.* 9, Q03001 (2008). 6. P.E. van Keken, B.R. Hacker, E.M. Syracuse, G.A. Abers, *J. Geophys. Res.* in press. 7. G.E. Bebout, *Chem. Geol.* 126, 121 (1995). *8.* G.E. Bebout, *Earth Planet. Sci. Lett.* 260, 373 (2007). 9. C.M. Breeding, J.J. Ague, *Geology* 30, 499 (2002). 10. T. Zack, T. John, *Chem. Geol.* 239, 199 (2007). 11. G.E. Bebout, M.D. Barton, *Chem. Geol.* 187, 79 (2002). 12. J.J. Ague, *Chem. Geol.* 239, 217 (2007). 13. R. King, G.E. Bebout, M. Grove, T. Moriguti, E. Nakamura, *Chem Geol.* 239, 305 (2007). 14. T. John, R. Klemd, J. Gao, C.-D. Garbe-Schonberg, *Lithos* 103, 1 (2008). 15. D.P. Miller, H.R. Marschall, J.C. Schumacher, *Lithos* 107, 53 (2009). 16. M.J. Mottl, C.G. Wheat, P. Fryer, J. Gharib, J.B. Martin, *Geochim. Cosmochim. Acta* 68, 4915 (2004). 17. I.P. Savov, J.G. Ryan, M. D'Antonio, P. Fryer, *Jour. Geophys. Res*. 112, B09205 (2007). 18. K.H. Hattori, S. Guillot, *Geochem. Geophys. Geosyst.* 8, Q09010 (2007). 19. C.E. Manning, *Earth and Planet. Sci. Lett.* 223, 1 (2004). 20. B. Dragovic, L.Y. Mehl, E.F. Baxter, J. Selverstone, *Geochim. Cosmochim. Acta* 74, A246 (2010). 21. A. Camacho, J.K.W. Lee, B.J. Hensen, J. Braun, *Nature* 435, 1191 (2005). 22. A.D. Pollington, E.F. Baxter, *Earth and Planet. Sci. Lett.* 293, 63 (2010). 23. J.J. Ague, E.F. Baxter, *Earth and Planet. Sci. Lett.* 261, 500 (2007). 24. E.B. Watson, E.F. Baxter, *Earth and Planet. Sci. Lett.* 253, 307 (2007). 25. F.-Z. Teng, W.F. McDonough, R.L. Rudnick, R.J. Walker, *Earth and Planet. Sci. Lett.* 243, 701 (2006). 26. S. Chakraborty, *Ann. Rev. Earth Planet. Sci*. 36, 153 (2008). 27. S.C. Penniston-Dorland, S.S. Sorensen, R.D. Ash, S.V. Khadke, *Earth and Planet. Sci. Lett.* 292, 181 (2010). 28. A. Stracke, A.W. Hofmann, S.R. Hart, *Geochem. Geophys. Geosyst.* 6, Q05007 (2005). 29. A. Zindler, S. Hart, *Ann. Rev. Earth and Planet. Sci.* 14, 493 (1986). 30. A.W. Hofmann, W.M. White, *Earth and Planet. Sci. Lett.* 57, 421 (1982). 31. A.V. Sobolev, A.W. Hofmann, S.V. Sobolev, I.K. Nikogosian, *Nature* 434, 590 (2005). 32. T. Kogiso, M.M. Hirschmann, *Earth and Planet. Sci. Lett.* 249, 188 (2006). 33. P. Agard, P. Yamato, L. Jolivet, E. Burov, *Earth Sci. Rev*. 92, 53 (2009). 34. C.R. Ranero, A. Villasenor, J. Phipps Morgan, W. Weinrebe, *Geochem. Geophys. Geosyst.* 6, Q12002 (2005).