The leading edge of the mantle wedge:
Structural and metamorphic studies of peridotite thrust over metasediments & basalts

Peter Kelemen, Jamie Connolly, Brad Hacker, Greg Hirth and Craig Manning

We propose to study mantle peridotite thrust over metasediments and metabasalts, in order to provide direct observations of the leading edge of the mantle wedge in subduction zones. Taken together, exposures where the basal thrust of the Oman ophiolite brought peridotite over Cretaceous metasediments at (a) ~ 160°C and 3 kb (Kelemen & colleagues, unpublished data), (b) the basal thrust of the Trinity peridotite in California juxtaposed hanging wall peridotite with metasediments and metabasalts at ~ 500 to 650°C and 5 kb (Peacock & Norris, J. Met. Geol. 1989), and (c) peridotites within felsic gneisses in the ultra-high pressure metamorphic belt of western Norway at ~ 700°C and 30 kb (e.g., papers by Brad Hacker, Hannes Brueckner and their colleagues), provide a series of points along plausible subduction zone geotherms which will allow us to make specific observations that are potentially applicable to subduction zones worldwide. We will study localized deformation along thrust faults and lithological contacts, and constrain the relative importance of localized versus distributed deformation. We will determine the extent and nature of geochemical mass transfer from underlying metasediments and basalts into overlying mantle peridotites. And, we will delineate the combined physical and chemical processes arising from disequilibrium fluid transport combined with retrograde metamorphism in mantle peridotite.

A variety of recent studies have emphasized the importance of the “cold nose” overlying shallow subduction zones – the leading edge of the mantle wedge, where peridotite thrust over subducting sediments and oceanic crust. Properties of the “cold nose” are invoked to explain rheology, geodynamics, geochemical fluxes and fluid transport in the shallower parts of subduction zones. The nose is thought to act as a kind of geochemical filter for return flow of pore waters, and then for ascending fluids derived by prograde metamorphism of subducting sediments and metabasalts. Reaction with these fluids drives hydration and carbonation – retrograde metamorphism – of mantle peridotite, forming hydrous minerals such as serpentine and talc, and carbonates such as magnesite. Fore arc cold springs and serpentine mud volcanoes demonstrate the extent of alteration, and yield clues about coupled chemical and physical processes during reactive transport of subduction zone fluids. Low seismic velocities and high attenuation in the nose are attributed to retrograde metamorphism. Serpentine and talc in the nose, particularly in the hanging wall of the master thrust, are thought to be weak materials that rheologically decouple the forearc from the subducting plate. Cooling of the nose by conduction into the underlying, subducting crust and by advective flow of cold fluids through the wedge is considered to be the cause of exceptionally low heat flow in fore arcs worldwide. Despite its low temperature, the nose is thought to be dynamically stable due to the relative buoyancy of the retrograde mineral assemblage.

While most of the views summarized in the previous paragraph are based on inferences from geophysical data, they are so widely invoked as to be considered axiomatic. Indeed, we believe that they are generally true. However, we really don’t understand chemical and physical processes in the cold nose very well. For example, alteration of peridotite is commonplace, and fundamentally important for the reasons outlined above but we don’t understand the feedbacks between fluid flow and metamorphic reactions that – under some circumstances – allow the retrograde process to proceed. Retrograde processes are thought to be uncommon because they are self-limited, via a variety of negative feedbacks described below. And yet, in the preceding paragraph we invoked nearly complete hydration to explain the properties “cold nose”, worldwide.

In igneous and metamorphic rocks, fluid porosity and permeability may be negligibly small, so retrograde processes are supply limited. Furthermore, fluids enhance diffusion and so act as catalysts for recystallization. Prograde reactions produce fluids, in a positive feedback, while retrograde reactions may consume all available fluid long before recrystallization is complete. Finally, in an initially open system, retrograde reactions may increase the solid volume. This may fill porosity, destroy permeable flow networks, and armor reactive surfaces, limiting fluid supply and slowing reaction rates. Thus, rocks overcome by these limitations often contain a hodge-podge of disequilibrium mineral assemblages formed by incipient, but arrested, retrograde metamorphism. Often, peridotites in outcrop are 10 to 60% hydrated, with abundant relicts of the original, mantle minerals.

However, 100% hydrated peridotites, known as serpentinites, are common. Less familiar, but of increasing scientific interest, are "listwanites", 100% carbonated peridotites composed of, magnesite + quartz, such as those we have recently been studying at and just above the thrust bringing mantle peridotite over metasediments in Oman. How do serpentinites and listwanites form, when retrogression is self-limiting? Two end-member explanations have been offered. Many metamorphic petrologists consider that such reactions occur at constant volume, in which expansion due to decreasing solid density is balanced by dissolution and export of chemical components in a fluid. However, with notable exceptions, most studies of serpentinites, and our work on listwanites in Oman, suggest that alteration was nearly isochemical except for addition of H2O and/or CO2.

Alternatively, MacDonald & Fyfe (T'phys 1985) proposed that increasing stress due to volume expansion in an elastically confined volume causes fractures, which in turn increase or at least maintain permeability and reactive surface area, in a positive feedback mechanism that allows retrograde reactions like serpentinization to proceed to completion. This, and other similar processes involving regulation of permeability via (bio) chemical feedbacks, forms the primary hypothesis motivating our proposed project. It has been the topic of recent theoretical work, for example by Jamtveit and colleagues, and Kelemen and co-workers. So far, theory is only qualitatively linked to observations.

Our proposed studies will establish the relative timing of fracturing and metamorphism, via documentation of statistically significant numbers of cross-cutting crack and vein relationships, to quantify the observation that alteration and fracture were coeval and hierarchical. And, we will quantitatively compare fracture and vein density to the overall extent of matrix alteration.

To pick another problem, the nature and extent of mass transfer between subducting material and overlying peridotite are variable, and difficult to understand. We observe 1 to 100 m scale, tabular bodies of 100% carbonated peridotite that formed at low temperature and pressure in Oman, under conditions in which modeling studies (Connolly and co-workers, Manning and co-workers) predict little or no decarbonation in the downgoing slab, and yet we observe very limited evidence for chemical interaction of peridotite bodies with surrounding felsic gneisses in western Norway, where these disparate lithologies – e.g., quartz and olivine – are thought to have been juxtaposed at UHP and then granulite facies conditions for many millions of years. Our studies will constrain the processes that control these very different, somewhat counter-intuitive outcomes.

Finally, the localization of deformation along the interface between altered peridotite and subducting crust is almost always assumed, and commonly observed, and yet it is not that obvious why it occurs. For materials with a temperature dependent rheology, why doesn't deformation migrate away from the cold subduction interface, into warmer material within the mantle wedge? Does this ever occur? To what extent is deformation in the cold nose controlled by fractures versus ductile flow of serpentine or talc? Our studies will provide direct observations to constrain the nature and extent of these processes, and field data that can be used to test and refine extrapolations based on laboratory investigations of rheology.