SEARCHING FOR SERPENTINIZATION: AN INTER-DISCIPLINARY EFFORT TOWARD CONSTRAINING THE INITIAL HYDRATION STATE OF THE SLAB MANTLE

Andrew Smye\(^1\) and Mark Caddick\(^2\)
\(^1\)Department of Geosciences, Penn State
\(^2\)Department of Geosciences, Virginia Tech

Overview

Profound uncertainties exist over the hydration state of the oceanic mantle that enters subduction zones as part of the downgoing slab. Estimates of water flux contribution from the slab mantle range between 0 and \(\sim 10^9\) Tg/Myr (van Keken et al. 2011), potentially exceeding the combined contribution from subducted sediment and oceanic crust packages. This slab mantle is expected to largely dehydrate at depths between 100 and 200 km, significantly deeper than most dehydration of sediment–crust packages, thus providing an efficient transport mechanism for water and other fluid-mobile elements past the depths of arc magma genesis and, critically, into the deep mantle. In parallel, the release of these slab-originated fluids may control the generation and disposition of arc magmas (Rüpke et al. 2002).

This water stored in the slab mantle as it enters a subduction zone is dominantly sequestered within serpentine-group minerals, which are capable of incorporating up to 14 weight percent water. Serpentine-forming reactions result from interaction of mantle lithosphere with water and are typically accompanied by the (1) formation of magnetite, (2) liberation of \(H_2\), (3) a large volume increase (> 20 %), and (4) significant heat production. In an attempt to better constrain the location and extent of serpentinization reactions, and thus quantify the hydration state of the subducting plate, we propose increased study of the active trench faulting (‘outer-rise’) environments that are thought to reactivate hydrothermal circulation and stimulate upper mantle hydration. Specifically, we suggest that measurements of heat flow, magnetism and seismicity across regions undergoing this flexural faulting can be interpreted through thermal and petrological models to place limits on the permissible magnitudes of serpentine formation. We believe that such studies, which necessarily couple new geophysical and geochemical data and models, are well-suited to the charge of the Subduction Zone Observatory.

Serpentinization Processes and Controls

Serpentinization reactions likely occur through a complex chain of processes that progressively replace olivine and orthopyroxene with a combination of serpentine \(\pm\) brucite \(\pm\) talc + accessory phases. Many well-studied examples from oceanic core complexes show almost complete replacement of primary phases and demonstrate that extreme hydration is possible. Reaction rates are thought to be fast and serpentinization liberates approximately \(10^5\) joules of energy per mole of reactant, or approximately \(10^{10}\) joules per cubic meter of peridotite hydrated, similar to the amount of energy released by burning a ton of crude oil. Magnetite and serpentine formation are likely decoupled during the earliest stages of serpentinization, but most studied serpentinized peridotites show substantial deviation in both magnetic susceptibility and rock density, relative to the anhydrous protolith.
The extent of serpentinization in the subducting slab is almost certainly limited by the availability of fluids, and the extent of serpentinization in the mantle wedge is likely controlled by the passage of fluids from footwall crustal lithologies. Hydration of even the oldest incoming oceanic lithosphere is thought to be restricted to the uppermost few kilometers, but deeply penetrating outer-rise fractures provide opportunities for water–rock interaction as deep as 20 km into the slab just before the onset of subduction, probably controlling the water budget of down-going rocks (Fig. 1; Ranero et al. 2003). Accordingly, the extent of fluid-rock interaction due to these fractures is of fundamental importance to our understanding of the global budgets of water and other volatile species in subduction zones.

Towards New Constraints on Slab Mantle Hydration

Rock samples from the cores of outer-rise fracture zones are generally unavailable, so we propose that high-spatial resolution measurements of surface heat flow and magnetic susceptibility can act as important constraints that should be coupled with thermal-petrologic models of fluid-rock reaction to estimate the extent of serpentinization and associated hydration of the rocks during their earliest stages of subduction. Existing heat flow transects across outer-rise fault zones offshore Nicaragua, Central Chile and Peru all show puzzling surface heat flow deficits relative to age-dependent conductive values (Fig. 2; Grevemeyer et al. 2005). These regions of low heat flow have been interpreted to represent net recharge of the oceanic crust and upper mantle before subduction, but the thermal effects of these hydration reactions, including serpentinization, have not been systematically addressed. For example, Ranero et al. (Ranero et al. 2003) estimate that between 1.5 and 15 volume percent of the Nicaraguan slab mantle has been serpentinized during bend faulting. This hydration would be expected to release ~ $10^9$ joules of energy per cubic meter, equivalent to about 20 million years of radiogenic decay in a granite. The fate of this energy is unclear; either it heats available fluids that can be transferred through the subduction zone and stimulate further fluid-rock reaction, or it conductively dissipates through the rock matrix. Given the slow timescales for conduction through metamorphic rocks, this scenario would lead to an elevated geotherm trenchwards of the initial site of hydration; an observation that is currently lacking.

Successful treatment of this fluid-rock reaction problem will require (i) spatially resolved heat flow and magnetic transects, (ii) constitutive laws for serpentinization reactions, and (iii) solutions to fully-coupled energy and mass conservation equations. Computational predictions of magnetite formation and bulk-rock expansion upon serpentinization can be tested against magnetic and seismic constraints, with model domains potentially constrained by seismic imaging of the prevalence and extent of bend fault systems. This has significant potential to link slab parameters (age, convergence rate, dip, etc.) with degree of hydration at bend fault fracture zones, enabling better assessment of the influence of slab fluids on the geochemical composition of arc magmas. For example, the correlation between Ba/Th and
surface heat flow along the Nicaraguan section of the Central American volcanic arc provides strong motivation to investigate the extent to which slab parameters control the initial hydration state that is imposed at bend fracture zones (Harris et al. 2010).

To summarize, we believe that the Subduction Zone Observatory is the ideal initiative to support an inter-disciplinary effort focused on constraining pre-subduction mantle hydration states in oceanic slabs. We suggest that new high-spatial-resolution heat flow and magnetic studies, performed across zones of active bend-faulting in subduction zones, be coupled with thermodynamic and geodynamic modeling of the evolution of the subducting system. Together, these will permit development and testing of a sophisticated but generalized fluid-rock interaction model that will be used to estimate degree of mantle hydration as a function of slab parameters.

References


