Emergence of a Low-Viscosity Channel in the Northern Izu-Bonin Subduction System Through the Coupling of Mantle Flow and Thermodynamics and Implications for Melting in the Wedge

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Abstract

We couple a petrological model (pMELTS) with a 2D thermal and variable viscosity flow model (Conliburn) to describe and compare fundamental processes occurring within subduction zones. We study the thermal state and phase evolution of the subduction oceanic slab and adjacent mantle wedge and constrain fluid flux. Using a Lagrangian particle distribution to perform thousands of thermodynamically equilibrated calculations, the chemical composition of the domain is continuously updated. Allowing the buoyancy and viscosity to be compute-dependently and thermally dependent permits a consistent linkage between the effect of water addition to and flow within the mantle wedge, leading to predictions as to the fate of the hydrated material as subduction proceeds. We present a systematic study of the control by thermal and rheological parameters (e.g., convergence rate, slab dip, slab age, and upper plate thickness) on the emergence of LVCs defined by hydrous mineral stability and higher concentrations of water up to thousands of ppm in nominally anhydrous minerals (NAM). The LVC develops due to fluid ingress into the mantle wedge from the dehydrating slab, and can be responsible for slab decoupling. Large-scale changes in the wedge flow field, and a mechanism by which hydrated slab-adjacent wedge material can be transported to the deep mantle. We observe multiple locations of fluid release along the subducting slab from dehydration reactions within volcanic and serpentinitized layers, leading to a weakening of mantle peridotite and a reduction in viscosity (10 to 100 times) in a region adjacent to the slab and resulting in an LVC on average 25 kilometers thick. The LVC develops due to fluid ingress into the mantle wedge from the dehydrating slab, and can be responsible for slab decoupling, large-scale changes in the wedge flow field, and a mechanism by which hydrated slab-adjacent wedge material can be transported to the deep mantle. We observe multiple locations of fluid release along the subducting slab from dehydration reactions within volcanic and serpentinitized layers, leading to a weakening of mantle peridotite and a reduction in viscosity (10 to 100 times) in a region adjacent to the slab and resulting in an LVC on average 25 kilometers thick.

Motivation

Many aspects of subduction zone science have yet to be fully understood, including where fluid is released from the slab, how much water is deeply subducted, and how fluid transits the wedge, the role of the hydration of NAM on the fluid budget and on the rheology, and where melt initiates. We will investigate these aspects in the context of a fully-coupled geodynamic and geochemical model, allowing the chemistry to influence the dynamics, and vice versa.

Development of the LVC

Subduction parameter space includes variations in slab dip, slab thermal age, convergence velocity, and over-riding plate thickness.

Wedge calculations are solved by pMELTS, with alternate solvers employed to handle conditions outside the pMELTS realm of stability. Obscure solubility measurements from Moosendier et al. (2006) DMX mante initial composition from Workman and Hart (2005), with 110 ppm H2O bulk.

Slab dehydration reactions governed by Hacker et al. (2003) phase diagrams.

The hydration depth into the slab consists of a 7-km thick altered oceanic crustal layer, and a 5-km thick serpentinite layer. The top surface is isothermal (273 K), and the thickness of the over-riding plate and thermal age of the down-going slab determine the initial thermal conditions.

The slab velocities are kinematically imposed, with an analytical corner-flow solution (Batchelor, 1967) along the left boundary.

Model Set-up

(1) Conliburn: 2D thermal and variable viscosity numerical flow model

(2) pMELTS: thermodynamic-energy minimization algorithm that can calculate water partitioning in nominally-anhydrous minerals (NAM) in addition to hydrous phases, melt, and vapor

(3) GypSM: Geodynamic and Petrological Synthesis Model for Subduction

(4) Melting initiates immediately above fluid release locations, the saturated LVC zone

Conclusions

(1) Slab thermal age and convergence angle play important roles in determining fluid release locations and the structure of the LVC

(2) The LVC provides a potential first-stage of rapid transport in a two-stage water migration scheme

(3) Formation of the LVC has both geophysical and geochemical implications

(4) Melting is spatially restricted, bounded by the top of the LVC (water-saturated solids) and by water activity dropping below 1.0 due to partitioning in the melt phase

(5) The spatial separation of fluid sources provides for a range of primary melt compositions

(6) Progressive depletion of the mantle source leads to an angling of the melt source region away from the slab into the wedge interior

(7) Cooling of the wedge over time can lead to dramatic changes in the locations of melt production and the path length of fluid transport.