The Izu-Bonin-Mariana and Costa Rican Subduction Factories Modeled by GyPSM-S: Evidence for a Low-Viscosity Channel

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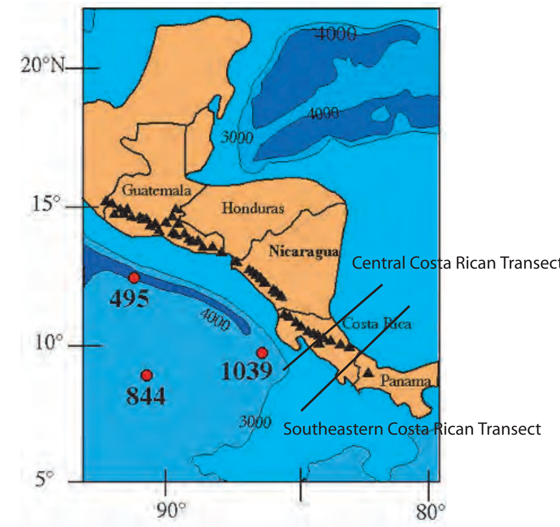
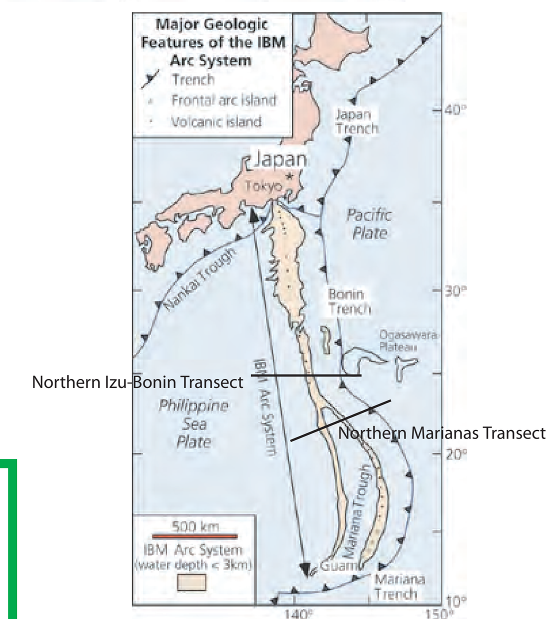
Abstract:

We use GyPSM-S, a model that fully couples the petrological model pHMELTS with ConMan, a 2D thermal and variable viscosity flow model, to describe and compare fundamental processes occurring within the Izu-Bonin-Mariana and Costa Rican subduction zones. By prescribing forcing functions within GyPSM-S we are able to establish the thermal state and phase equilibria of the subducting oceanic slab and adjacent mantle wedge and constrain fluid flux specific to different subduction zones. This allows us to describe the process of hydration of the mantle wedge adjacent to the slab, which leads to the development of a low-viscosity channel. We discuss the impact of the low-viscosity channel on geophysical observables such as dynamic topography and gravity. Also, we define regions of melting, and discuss melt and residue chemistry. This leads to predictions of major and trace element chemistry of arc volcanics.

Parallel computing within the context of GyPSM-S uses a Lagrangian particle distribution to perform thousands of thermodynamically equilibrated calculations during each timestep, allowing for a continuously updating chemical dataset, and a strong feedback mechanism with the fluid dynamics. Allowing the viscosity to be both compositionally and thermally dependent permits a consistent linkage between the effect of water addition to the mantle wedge and the wedge velocity field, leading to large-scale changes in the flow field of the hydrated wedge relative to the anhydrous example and predictions as to the fate of the hydrated material as subduction proceeds. Additionally, we account for chemical feedback in the energy balance by introducing latent heat effects using the isentropic capability of pHMELTS. The flexibility of pHMELTS allows fractional melting to be included and for the calculation of a realistic compositional buoyancy term.

We present four cases, encompassing the Costa Rican and Izu-Bonin-Mariana subduction zones (Southeastern Costa Rica, Central Costa Rica, Northern Izu-Bonin, and Northern Marianas), and compare our model results with geophysical and geochemical observables from these localities. Among these examples, model-specific changes in potential temperature, slab dip, slab thermal age, subduction velocity, and overriding lithospheric thickness allow us to discuss results in a comparative way. The full coupling between the chemistry and the dynamics results in notable behaviors previously unresolved by geodynamic models of subduction. A continuous, slab-adjacent low-viscosity channel defined by hydrous mineral stability and higher concentrations of water in nominally anhydrous minerals develops.





Parallel-computing structure allows thousands of pHMELTS calculations to occur at each iteration:

FEM: calculates impact of new temperature field and water solubility on viscosity; solves conservation of energy using a finite difference method and adjusts entropy field attached to the numerical mesh; advects particles according to the updated velocity field solved for by a finite element formulation which includes the influence of compositional buoyancy

WATER ADVECTION: moves free water on the numerical mesh, performs nodal updates of entropy, volume, and water information after particles complete pHMELTS calculations

MASTER: calls FEM, calls free water advection step, processes text files, distributes new particles, and implements dynamic load balancing; calls CLIENTS to initiate thermodynamic calculations

CLIENT: runs pHMELTS calculations; runs alternate solvers when pHMELTS stalls or particles are out of calibrated range

pHMELTS: given pressure, entropy, and a bulk composition, pHMELTS uses a thermodynamically-based energy-minimization algorithm to calculate T, F, major and trace element chemistry of melt and solid phases, including water in both hydrous and nominally-anhydrous phases; if fractional melting is implemented, melts are extracted above a certain threshold; solid volume and density are also calculated

Method:

GyPSM-S (Geodynamic and Petrological Synthesis Model for Subduction) couples two models: ConMan, a 2-D thermal and variable viscosity flow model (King et al.,1990), and pHMELTS, a thermodynamic minimization algorithm for chemical analyses of melts, solids, and water solubility in nominally-anhydrous minerals (via a text-driven interface adiabat_1ph, Smith & Asimow, 2004) with governing Perl scripts. GyPSM-S is built to run in a parallel environment on CiTerra.

GyPSM-S is a fully-coupled formulation, whereby iterative transfer of pHMELTS-solved particle data to the finite element nodal mesh resolves the dynamic feedbacks between the dynamics and the chemistry that are unobserved in other, more simplistic models.

The evolution of the pressure-temperature state of the down-going slab produces free water via dehydration reactions as per Hacker et al. (2003). The water is vertically advected and then reacted with surrounding material by a pHMELTS calculation, producing hydrous phases, or an increase in hydrogen concentration in nominally-anhydrous minerals.

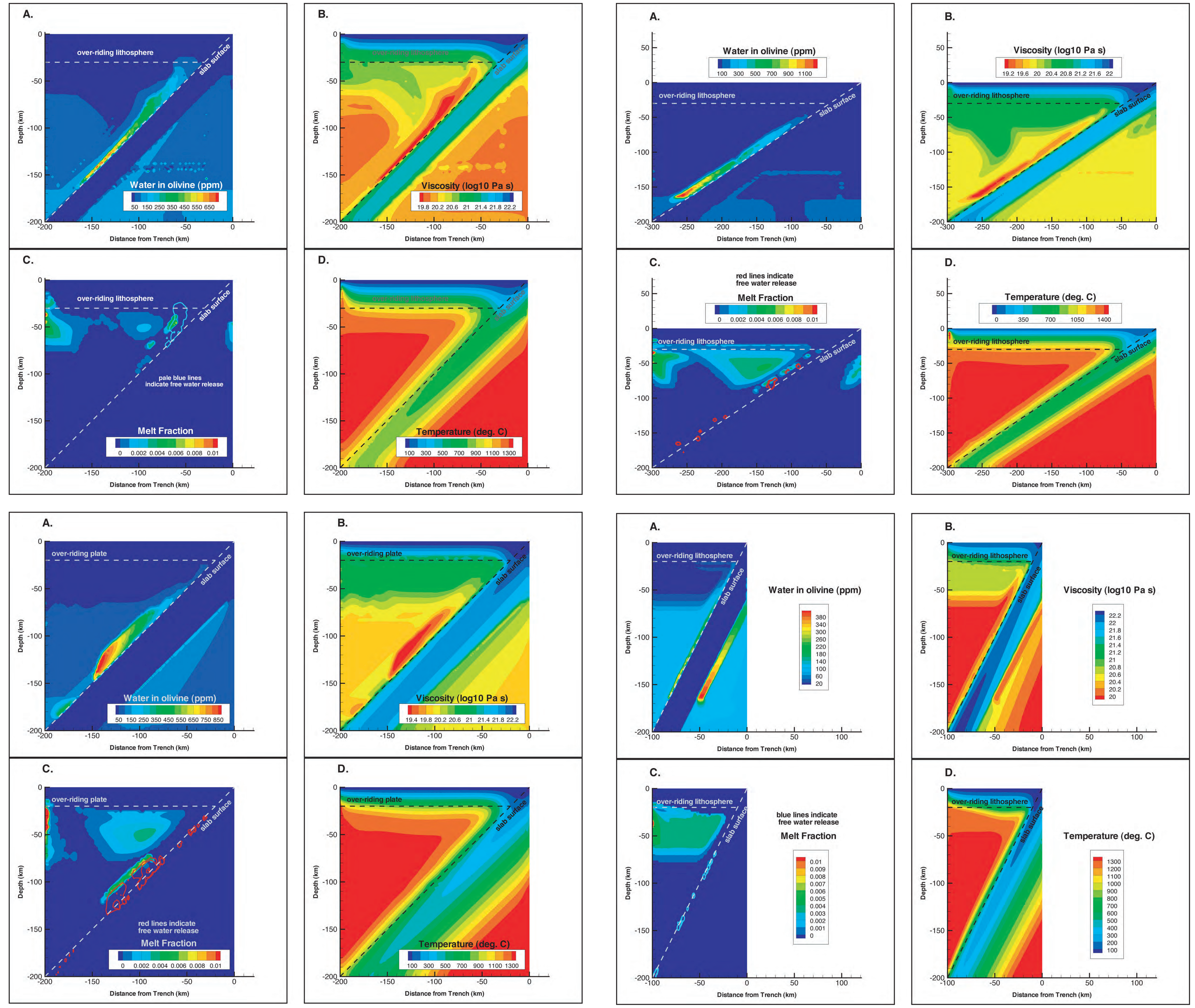
Modifications to ConMan include the use of an entropy advection scheme to allow for latent heat effects, as well as a compositional component to the viscosity formulation.

Central Costa Rica:
18 Ma subducting slab age
87.0 mm/yr convergence rate
45 degree slab dip
30 km over-riding lithosphere

SE Costa Rica:
15 Ma subducting slab age
90.0 mm/yr convergence rate
30 degree slab dip
30 km over-riding lithospherer

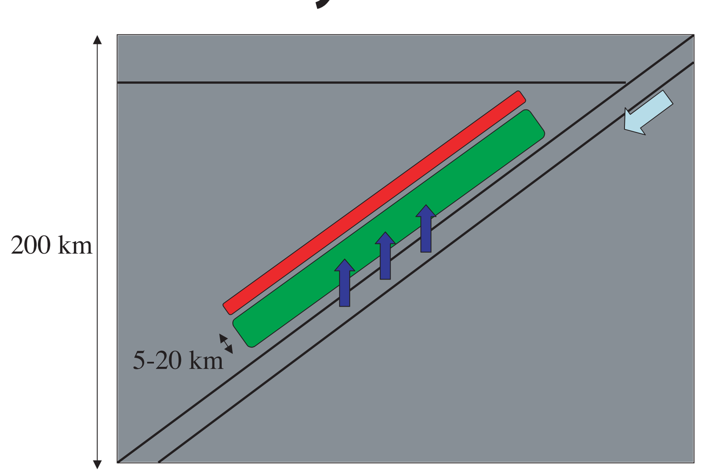
Northern Izu-Bonin:
135 Ma subducting slab age
50.0 mm/yr convergence rate
45 degree slab dip
20 km over-riding lithosphere

Northern Marianas:
165 Ma subductin slab age
47.5 mm/yr convergence rate
60 degree slab dip
20 km over-riding lithosphere



The Costa Rican and Izu-Bonin-Mariana subduction zones: (top left) Central Costa Rica (top right) Southeastern Costa Rica (bottom left) Northern Izu-Bonin (bottom right) Northern Marianas; (A) zone of hydrated nominally-anhydrous minerals defined by elevated water solubility in olivine; (B) lowering of slab-adjacent mantle viscosity due to the chemical dependence in the viscosity formulation; (C) zone of melting, lines indicate the location of free water release from dehydration reactions within the slab; (D) coupled temperature structure.

Low-Viscosity Channel:

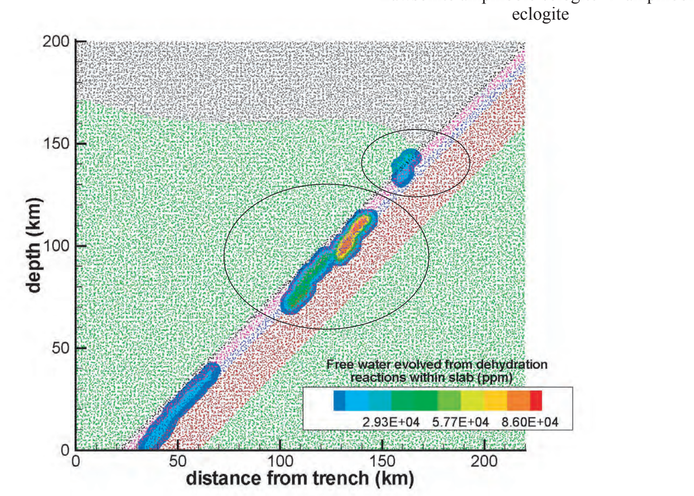


Dehydration reactions within the downgoing slab (in the altered basalt, and serpentinite layers) release free water (Hacker et al. (2003), which rises into the overlying mantle wedge and reacts with the peridotite to form hydrous phases, and to hydrate nominally-anhydrous minerals, such as olivine.

The influence of elevated hydrogen concentrations in olivine on the mantle rheology is to decrease viscosity, an effect accounted for in the coupled formulation (Hirth & Kohlstedt (1996). The relatively thin layer of hydrated nominally-anhydrous minerals is bounded by the slab and the partially-hydrated solidus.

Water rises from the slab, through the hydrated olivine layer (green), and into the hotter mantle wedge, where it crosses its solidus and melts(red) . The water is taken up by the melt phase, leading to a low-viscosity channel, of approximate width of tens of kilometers. This hydrated channel will advect with the slab-adjacent material into the deep mantle.

Lawsonite amphibole eclogite → amphibole eclogite



Water rises vertically from dehydration reactions within the slab, moving into the over-lying mantle material

Serpentine chlorite dunite (chlorite, antigorite, olivine) → chlorite harzburgite (olivine, orthopyroxene, chlorite)

Conclusions:

GyPSM-S is a powerful, flexible technique that allows for the discovery of new phenomena that can only be observed within the setting of a fully-coupled model integrating both chemistry and dynamics.

The presence of the low-viscosity channel is not a transient feature within subduction zones, being defined by the water release from dehydration reactions and by the partially-hydrated peridotite solidus. It has dynamic implications for evolution of slab dip, as the slab is allowed to decouple from the mantle wedge.

References:

Smith & Asimow (2003); Hacker et al. (2003); Billen & Gurnis (2001); Hirth & Kohlstedt (1996); King et al. (1990); Mosenfelder et al. (2006); Workman & Hart (2005); Ghiorso & Sack (1995)