Geophysical Research Abstracts
Vol. 12, EGU2010-6533, 2010
EGU General Assembly 2010

Dynamics of three-dimensional hydrous thermal-chemical plumes in the mantle wedge

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As a plate subducts, fluid release from the subducting slab lowers the melting point of the surrounding mantle, which results in the configuration of more dense and viscous dry mantle overlying a thin layer of hydrated mantle with lowered density and viscosity. These processes trigger Rayleigh-Taylor (RT) type instabilities in a low-viscosity wedge with complex three-dimensional (3-D) geometries. RT-type cold plumes atop the slab were previously studied in 2-D. Here we use 3-D petrological-thermomechanical numerical simulations to investigate the dynamics of 3-D hydrous thermal-chemical plumes in the mantle wedge. The simulations were carried out with the I3ELVIS code which is based on a multigrid approach combined with marker-in-cell methods and conservative finite difference schemes. Our numerical simulations show that three types of upwelling plumes occur above the slab-mantle interface: (1) finger-like plumes forming roll/sheet-like structures parallel to the trench; (2) ridge-like structures perpendicular to the trench; and (3) flattened, wave-like instabilities propagating upward along the upper surface of the slab and forming zigzag patterns parallel to the trench. Plume-related melt productivity correlates well with volcanic activity clustering in natural intraoceanic arcs, such as in northeast Japan.

Why do the above different plume patterns form atop the slab? Variation in partially molten rock viscosity notably affects plume patterns and lateral dimensions: wave-like plumes are most pronounced at higher (10ˆ19 Pa s) viscosity, which also favors the development of larger plumes compared to models with lower (10ˆ18 Pa s) viscosity. The "effective" density contrast between solid and molten rocks, which is closely related to melt extraction processes, is the key factor in determining plume patterns. A large to moderate density contrast of >200 kg/mˆ3 (i.e. low to moderate degree of melt extraction) promotes the development of three distinct patterns of the cold plumes (finger-like, ridge-like and wave-like). In contrast, a low density contrast of 0-50 kg/mˆ3 (i.e. high to complete melt extraction) suppresses pronounced plumes and is associated with low-amplitude (50-100 km wide and 10-15 km high) cold domal structures developing atop the slab due to the chemical buoyancy of subducted hydrated non-molten rocks (oceanic crust, sediments, serpentinites). Overall melt production intensity is notably different for cases with low (larger melt production) and high (lower melt production) degrees of melt extraction. All models are characterized by both spatially and temporally variable melt production, which may explain clustering and periodicity of volcanic activity observed in magmatic arcs.

A simplified model (consisting of dry cold mantle and asthenosphere overlying the hydrated mantle) for the complex situation atop the slab is setup to systematically investigate the influence of different parameters on the development of plumes atop the slab, such as the thickness of the hydrated mantle, the viscosity contrast between the hydrated mantle and surrounding mantle and the dip angle of the slab.