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3-D dynamic modeling of Taiwan orogen-Ryukyu trench subduction system
Annual progress report for the period up to 5/2007

NSC grant number: NSC 95-2119-M-002-044
Shu-Chuan Lin (National Taiwan University,
Distinguished Postdoctoral Research Fellow)

Summary

The broad objective of this project is to better understand the dynamical processes and evolution of the northern Taiwan-southern Ryukyu subduction zone system by fluid dynamical modeling. To achieve the goals the computational facility has been built. This has been followed by the development and benchmark tests for the modeling tools and a series of preliminary numerical experiments. The effects of three-dimensional geometry of the slab and plate boundaries and the thermal and flow fields in this region are being studied through numerical experiments. This may optimally help to gain a more quantitative, refined and dynamically consistent interpretation for the magma genesis and regional dynamics of this region and provide a basis for future studies.

Research results

The main results to date include the deployment and performance tests of computational facility, the development and benchmark of the modeling tools for models with kinematic plate and a series of numerical models in which the effects of slab buoyancy is considered. Benchmark tests for models with kinematic plate (plate with prescribed velocity) in a two-dimensional geometry are performed using a three-dimensional, thermal convection code, using multigrid, finite-volume methods. The tests include models with isoviscous, temperature- and stress-dependent viscosity for the mantle wedge. Different subduction angles are considered (45 and 90 degrees). The comparison and test of this code agree well with benchmark work for subduction zone problems designed by Prof. Peter E. van Keken in the Department of Geological Sciences, University of Michigan and his coworkers from other institutions. This code will be the main basis for further experiments.

The effects of buoyancy and three-dimensional geometry are further explored in a series of 2-D and 3-D preliminary tests. The experiments model thermal convection for a viscous, Boussinesq, Newtonian fluid with temperature-, pressure-dependent viscosity. Viscosity is reduced in the region near wedge corner to include the effects of water content. Various subduction rates, directions and trench curvatures are considered for models in three-dimensional geometry. Slab is driven by both the surface kinematic boundary and negative buoyancy due to the anomalous temperature of slab. A strong overriding lithosphere is considered. The results suggest that the oblique collision has limited effect on the flow and thermal structure in the mantle wedge, but trench curvature may influence the material transport in the region near the plate edge. Further investigation will help to better understand the effects.

Figure 1: 2-D cross-sections showing (a) temperature field and (b) flow field for selected models. The thermal field of (a) is used as the initial thermal condition for models in Figure 2.

(a) (b)

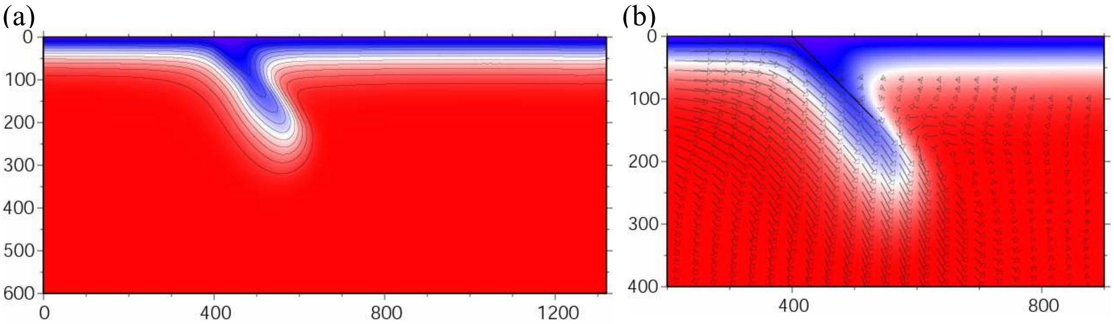
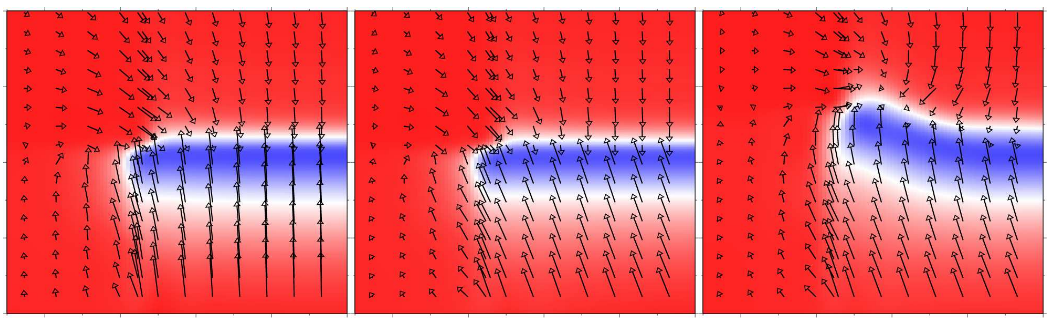


Figure 2: Cross-sections showing the horizontal plane at depth of ~120-km for models with (a) subduction, (b) oblique subduction, (c) oblique subduction with curvature changes of trench and slab at snapshots of 3 Myr after the model initiation. The horizontal dimensions of the 3-D box are 1080 km and 1320 km and the vertical dimension is 600 km, shown here are regions near the plate edge (450 km x 400 km). The combined effects of the shear coupling caused by the sinking plate and the low viscosity mantle wedge induce significant lateral flow around the plate edge, but the velocity decayed within short distance due to the effect of strong overriding plate. Blue to white colors delineate the down-going slab. Notice that the imposed surface velocity in the model for (a) is greater than that in models of (b), (c).

(a) (b) (c)



Documentation of attended meeting

The PI attended AGU (American Geophysical Union) Fall Meeting in San Francisco during 11-15 December 2006 and gave an oral presentation entitled 'Plumes originating from a thermochemical boundary layer and implication for mapping mantle plumes' (with coauthor Peter van Keken). The published abstract and another two conference abstracts are attached.

<u>Outlook</u>

Progress is being made on the benchmark tests for the subduction zone problems. The multigrid, finite-volume code will be parallelized first. The transport equation will be included. Various rheologies will be considered. Numerical modeling for a better understanding for the dynamical processes and evolution of the northern Taiwan-southern Ryukyu subduction zone system will be soon followed.

<u>List of publications (including submissions)</u>

Shu-Chuan Lin and Peter E. van Keken, Deformation, stirring and material transport in thermochemical plumes, *Geophysical Research Letters*, 33, L20306, doi:10.1029/2006GL027037, 2006.

MN: 2006 Fall Meeting

INVITED

TI: Plumes originating from a thermochemical boundary layer and implications for mapping mantle plumes

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AF: Department of Geosciences, National Taiwan University, 1, Section 4, Roosevelt Road, Taipei, 106 Taiwan

AU: van Keken, P E

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AF: Department of Geological Sciences, University of Michigan, 2534 C. C. Little Building, 1100 North University Avenue, Ann Arbor, MI 48109 United States

AB: We study the formation of plumes originating from a thermochemical boundary layer at the base of the mantle in an attempt to complement fluid dynamical studies of plumes with purely thermal origin. Using a series of high-resolution numerical experiments in an axisymmetric spherical shell, we systematically investigate the effects of the chemical density contrast and the thickness of the compositionally distinctive layer. We find that small-scale convection and secondary instabilities develop due to the interplay between the thermal and chemical buoyancy forces under a wide range of conditions. This leads to strongly time-dependent variations in the morphology, temperature and flow fields of the plume. Diverse and intricate features of thermochemical plumes that frequently deviated from the classical plume head-plume tail structure are observed. For models with thin layer and small density contrast, the chemical effect is not sufficient to strongly modify the plume formation and the overall plume morphology is similar to that of purely thermal plume. When the thickness of the compositional layer and the intrinsic density contrast are large, a significant volume of the dense material is sucked toward the plume and piles up at the base of the plume. It forms a large-scale undulation of the interface between the compositional layer and the overlying mantle. Plumes with multiple pulsations with variable strengths may occur when the density and thickness of the compositional layer are intermediate. The entrainment of the compositionally distinctive material is commonly a transient process. The deformation and convective stirring can be significantly enhanced in the thermochemical plumes and the dispersion of compositional heterogeneity can be much more effective than that in the purely thermal plumes. We propose that the intrinsic density contrast of the distinct composition may reduce the associated topography of some large igneous provinces such as Ontong Java. Our model results support the idea that the dynamics of the mantle plumes can be much more complicated than that derived from the studies of purely thermal plumes. The widely used criteria for mapping mantle plumes, such as a vertically continuous low seismic velocity signature, a single event of major eruption of flood basalt provinces and strong surface topography swell, may not be universally applicable.

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TI: Mantle-lithosphere interaction beneath the Yellowstone-Snake River province
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AB: The Yellowstone-Snake River province (YSRP) is one the few currently active continental hotspot locations and the only one with a clear age progression from 16-17 Ma eruptions at the Oregon-Nevada border to the present day activity at in Western Wyoming. The province has a number of characteristics that are quite similar to oceanic hotspot regions, which include a topographic bulge and geoid anomaly. The initial silicic magmatism is contemporaneous with the Columbia River Basalts, but this would require significant northward transport of basalt from the hotspot track, which is potentially accommodated by lateral transport in the crust or by a sideways transport from more competent lithosphere to a weaker spot. We will present 3D models of plumes and plume heads interacting with the lithosphere for the YSRP following the approach of Lin et al. (2005). We are particularly interested in the role of the variable properties of the lithosphere and surface tectonics influence the magmatic emplacement. We investigate the type conditions under which we can generate the Columbia River Basalts as a part of a single Yellowstone plume rising below the western US. This provides important estimates of the original size of the plume head, the current buoyancy flux and the lateral transport of mantle below the lithosphere.

Goldschmidt2007

Thermochemical coupling in deep mantle plumes: a case study of Turkana, N. Kenya

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Subducted oceanic crust forms the likely source for a dense and more fertile layer at the core-mantle boundary. Numerical modeling predicts that entrainment of this dense material by an upwelling thermal plume will result in episodic volcanism occurring at episodic intervals on time scales of several to hundreds of millions of years (Lin & van Keken 2005).

Our study of 40 my of mafic eruptive activity in Turkana, Kenya reveals volcanological and geochemical features that are fully compatible with the numerical models, suggesting that magmatism in this part of the East African Rift System reflects deep entrainment of recycled oceanic crust by a thermally-driven plume. Volcanism at Turkana occurred in three distinct pulses separated by several million years each. No flood basalt province typical of strictly thermal plume head volcanism is associated with any of the pulses. The most voluminous pulse (26-16 Ma) led to rift propagation to both north and south, with fault growth and new rift basin development. Episodic volcanism is also reported from Samburu, Kenya, 200 km to the south (Tatsumi & Kimura 1991) and 100 km to the north in Ethiopia (George et al. 1998) in each case subsequent to peak Turkana episodes. These features contrast with observations in Afar, where plume head volcanism occurred 30 Ma and modern basalts are erupted along extensional features in the rift axis.

Mafic lavas from the major episode in Turkana – including abundant picrites – are geochemically distinctive. They have Sr-Nd-Pb-He isotopic signatures characteristic of high-μ ocean island basalts, and olivine Ca, Ni contents indicative of a pyroxenitic source (Sobolev et al. 2005, Herzberg 2006). We postulate that fertile pyroxenite is currently melting at lithospheric depths beneath Turkana.

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