Geophysical Research Abstracts, Vol. 7, 03129, 2005
SRef-ID: 1607-7962/gra/EGU05-A-03129
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Numerical models of the generation of lithospheric plates, continents and the depleted mantle reservoir

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We developed two new models of the evolution of the Earth's mantle. The first model, K3, consists of a 2-D FD Boussinesq convection model with heating from within and from below combined with a simple model of chemical differentiation. Continent and depleted mantle evolve by differentiation of a mantle reservoir which is rich in incompatible elements, yet. In the center of this first part of the paper is the important question: How does the change, over time, of mantle properties (e.g. viscosity and heat production) affect the evolution of the Earth's mantle? There are several main conclusions:

a) The profile of the laterally averaged viscosity evolves with time and exhibits always a higher viscosity in the transition layer and in the lower part of the lower mantle.

b) Not only the asthenosphere, but also the upper part of the lower mantle is a low-viscosity zone.

c) The high-viscosity transition zone may divide the mantle into two principal reservoirs. It acts as a barrier, but a permeable one, to flow across the mantle transition zone.

d) The chemical differentiation takes place only in the asthenosphere. Therefore, the depleted mantle gathered mainly in the upper mantle.

We obtained a series of reasonable flow-line pictures and the proper order of magnitude of the mantle-creep velocity. It is quite understandable that the highest velocity magnitudes are in the two low-viscosity layers. Three feed-back mechanisms contributed to the non-steady-state character of the system. One mechanism is generated by the growing inhomogeneity of the heat-source distribution, a second one by the lateral movability of the continent. The third feed-back mechanism is mainly generated by the profile of the laterally averaged viscosity which evolves with time. Each single mechanism is basically simple. The choice of the initial conditions was determined by considerations on the cosmogony of the Earth. The relatively high viscosity hill in the lower mantle seems to be the cause for the low lateral movability of the plumes. Contrary to our model K2A, only a few K3A plumes are able to penetrate the transition layer. On the other hand, secondary plumes appear more often in K3A. They are thermically induced in the transition layer. The direct application of seismically derived quantities in order to determine the radius-dependent factor of the viscosity is an essential new feature of this paper.

The second model of this paper, S2, consists of a 3-D FE compressible spherical-shell convection model with a newly derived mantle viscosity profile, called *eta3*, that is deduced from PREM and solid-state physics. Although the profile is related to the viscosity profile of K3, it differs in many details. Also the derivation is different in several respects. There is no chemical fractionation in S2, up to now, but S2 has a homogeneous, exponentially decaying heating from within using the BSE abundances by McCulloch and Bennett (1994). Just this should be the starting point for a future unification of K3 and S2 to form a 3-D FE compressible spherical-shell convection-fractionation model. We hope to be able to simultaneously model not only the growth and the lateral movements of the continents but also the generation of the oceanic plates. Here is the summary of the main results of the present model S2:
A) Based on geophysically observable quantities and on an experimentally derived thermal expansion coefficient as a function of pressure, we derived the Grüneisen parameter, the specific heat at constant pressure, the specific heat at constant volume and the melting temperature, T_m, as a function of radius.
B) Using the findings of A) and results of the Karato group, a new viscosity profile, *eta3*, was derived. We found the following new features: A high-viscosity transition layer with very steep viscosity gradients near the 410-km and 660-km phase transitions lies under the conventional asthenosphere. Now the code can produce stable numerical solutions of the balance equations for the mentioned steep gradients. A second low-viscosity layer beneath the 660 was found. Going deeper, the viscosity gradually rises to a thick, highly viscous central layer of the lower mantle. Also the usual high-viscosity boundary layer on top of the mantle and the low-viscosity boundary layer above the CMB are included. However, no continental chemical boundary layer is present in S2, up to now.
C) Viscoplastic yield stress, σ_y, and the existence of *two* low-viscosity layers in the interior of the mantle facilitate plate-like behavior near the surface and sheet-like downwellings with an Earth-like distribution.
D) A greater area with stable, plate-like solutions was found by variation of $Ra_H(2)$ and σ_y. There are three other types of planforms out of this area, yet.
E) The temporal evolution of the laterally averaged heat flow at the surface, the Urey

number, the Rayleigh number and the kinetic energy of the upper-mantle convection have been computed. They show realistic numerical values. The distribution of the laterally averaged temperature as a function of depth is similar to results of Schubert et al. (2001). Preliminary results of this investigation have been published by Walzer et al. (2004a,b).

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