3-D TEMPERATURE AND COMPOSITION IN THE UPPER MANTLE CONSTRAINT BY GLOBAL SEISMIC TOMOGRAPHY AND MINERAL PHYSICS

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3-D Shear velocity structure of the upper mantle proposed by modern global seismic tomographic models (e.g. Su et al., 1994) has striking correlation with global tectonic features. The dominating features in the upper mantle are low velocity domains which correspond to the oceans and high velocity roots of continental cratons which extend down to at least 400 km. It is remarkable that continental roots are not as well seen in the global gravity field. Recent advances in mineral physics make it possible to interpret these tomographic models and gravity data in terms of rocks composition and physical state.

Effects on seismic velocity

The seismic velocities in the upper mantle are controlled by the following factors:
(1) Bulk chemical composition and corresponding mineralogical composition which depends on equilibrium pressure (P) and temperature (T). **(2)** Rock fabrics which is dominated by the preferential orientation of olivine grains and may cause strong seismic anisotropy. **(3)** Direct effect of temperature and pressure on density and elastic moduli. **(4)** Melt.

Composition.

To study the effect of composition on density and seismic velocities we apply the technique of petrophysical modelling (Sobolev and Babeyko, 1994). We directly minimize Gibbs free energy of multiphase, multicomponent system to calculate the mineralogical composition of the rock with the given bulk chemical composition equilibrated at given P and T. Density and isotropic elastic moduli are calculated from mineralogical composition and elastic properties of single crystals using the Hashin-Shtrikman averaging procedure. We employ room P,T elastic properties of single crystals and correct them for high P,T following a modified procedure from Duffy and Anderson (1989).

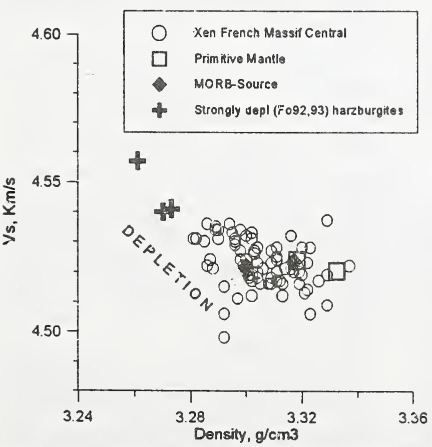

Fig. 1. Calculated Vs versus density for different garnet peridotites

Fig. 1 shows the calculated Vs versus density for rocks of different peridotitic compositions equilibrated in garnet peridotite facies at P=3 GPa and T=1200 C. As we see the depletion causes the significant increase of velocity and decrease of density (see also Jordan, 1975), which however does not exceed 1.2% for Vs. Thus composition effect is much too small to account for more than 7 % upper mantle Vs variation in the model by Su et al. (1994). Although composition effect on velocity is relatively small, its effect on density is important.

Rock fabrics.

Preferential orientation of olivine crystals can cause large variations of seismic velocities in the upper mantle (e.g. Fuchs, 1983). However tomographic model of Su et al. (1994) which we employ is constructed by simultaneous fitting a huge amount of S-wave travel times, wave forms of surface waves (both Love and Rayleigh waves) and of S- and P- body waves with different polarisation and good azimuthal coverage. Therefore the anisotropic effects should be strongly suppressed in this model, and we will treat it hereafter as truly isotropic.

Temperature, pressure and partial melt.

The direct effects of temperature and pressure are calculated from high-P,T equation of state modified from Duffy and Anderson (1989) with the correction for anelasticity. Anelastic correction is proportional to attenuation (Karato, 1993) which exponentially increases with homologous temperature (Sato et al. 1989). The parameters of the attenuation model are taken from laboratory experiments on ultramafic rocks at high T and seismic frequencies (see e.g. Karato and Spetzler, 1990) and are calibrated using the global attenuation data for the upper mantle (Anderson and Given 1982). Temperature effect incorporating anelasticity is rather strong and can cause 1-2% of velocity reduction due to temperature increase by every 100 °C. Temperature and composition effects taken in right combination can explain variations of seismic velocities without accompanying variations of density.

We assume that partial melting starts when the dry solidus temperature is reached and Vs decreases by 1-3% by every 1% of partial melt.

Inversion technique.

We divide upper mantle part of the tomographic model of Su et al. (1994) into blocks of 5°×5°×50 km. As a reference composition we take the composition of MORB source mantle by Kinzler and Grove (1992). For every block we find the absolute temperature and degree of depletion relative to reference composition by solving the non-linear equation which relates velocity to temperature and composition. By this we achieve exact fit of the observed seismic velocities. As additional constraints we impose: (1) that effects of depletion and temperature on density mutually compensate in the continental upper mantle (required by gravity observations), (2) seismological constraint on the value of average attenuation in the upper mantle.

Results.

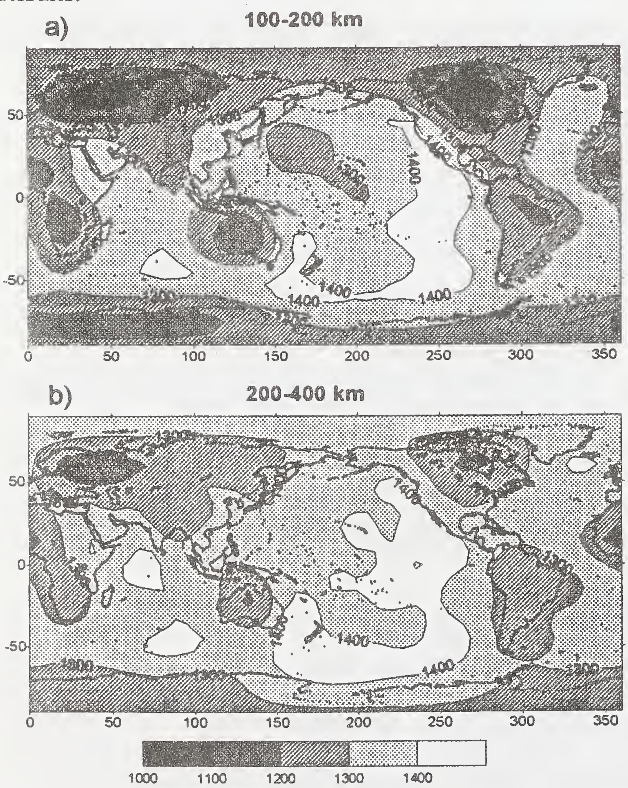

Fig. 2. Upper mantle potential T (°C) derived from tomographic model

Fig. 2 shows calculated potential temperatures at depth intervals of 100-200 km (a) and 200-400 km (b). Note that this is purely „seismological temperature" derived absolutely independently from usual temperature constraints (surface heat flow and xenoliths).

We get potential temperatures of 1300-1450 °C beneath the oceans which are remarkably close to the estimations from composition of MORB, 1290-1440 °C (Kinzler and Grove, 1992). We suggest that the coldest oceanic mantle (1300 °C) is beneath the Central Atlantic. The hottest one, T=1400-1450 °C, is beneath the Pacific and Indian Oceans and Iceland.

Potential temperature beneath the continental shields is by 300-400°C lower than beneath the oceans at depth range of 100-200 km. This difference decreases with depth, but it is still larger than 150-200 °C at the depth range of 200-400 km.

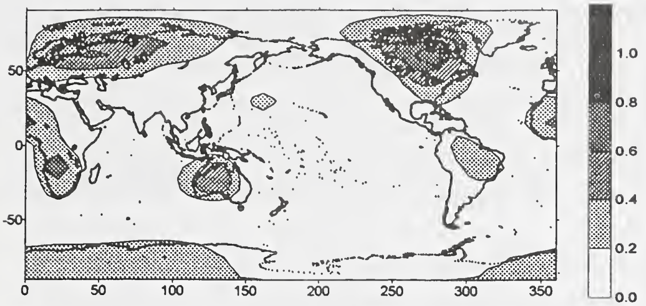

Fig. 3. Degree of depletion (0-1) relat. to MORB source mantle at 50-200 km.

Fig. 3 shows calculated degree of depletion relatively to MORB source mantle (0-1) at a depth of 50-200 km. MORB source mantle corresponds to depletion of 0 and most depleted harzburgite with Fo93 (Pearson et al.,1995) to 1. Strongly depleted mantle is restricted to the old continents and degree of depletion is maximal beneath the Precambrian cratons. Depletion degree at a depth of 200-400 km has the similar geographic pattern but is about two times less in magnitude.

Deep continental roots

The critical point is whether the modern global tomographic model (Su et al., 1994) can resolve well enough the structures at a depth of 200-400 km. If yes, then the deep roots of the continents do extend at least down to 400 km depth. In this case the plausible, if not only possible, interpretation of the seismic and gravity data suggests extremely thick, cool and depleted chemical boundary layer beneath cratons. Thus we confirm the idea of tectosphere suggested by T. Jordan (see e.g. Jordan, 1975). Our approach allows to consider the structure of tectosphere in more details.

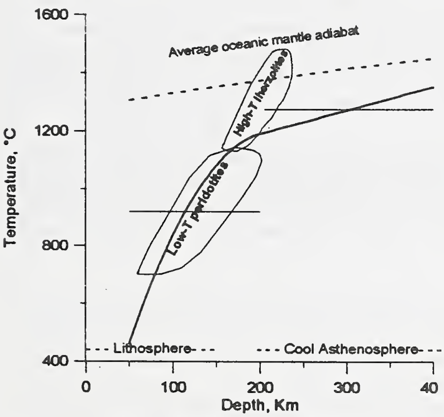

Fig. 4. Suggested shield geotherm

In Fig. 4 we plot estimated temperature beneath the Northern American shield at depth ranges of 50-200 and 200-400 km (horizontal lines). Together with the reasonable assumption about the temperature at 50 km, T(50) =400-500 °C, these average values provide rather narrow constraints on geotherms. In the depth range of 50-150 (200) km successful geothermes fit very well the range of xenolith temperatures. However, geothermal gradient have to be small (less than 1 °C/km) at 200-400 km range. We explain such a low gradient by the dominance of the convective heat transport in the deep (200-400 km) part of the continental root. Such a root looks more like a cool asthenosphere attached to the thick cold lithosphere rather than a deep lithospheric keel.

Because of the difference in chemical composition, cool asthenosphere of the continental root has almost the same density as normal asthenosphere, but it is by 1 or 2 orders of magnitude more viscous. That is why it remains attached to the continental lithosphere during the plate motion. Since deep continental roots allow for internal convection, big enough plumes are likely able to go through the roots and can reach the base of 150-200 km lithosphere causing kimberlite or flood basalt volcanism.

References

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