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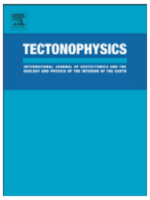

Thermo-chemical structure of the lithospheric mantle underneath the Siberian craton inferred from long-range seismic profiles

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ABSTRACT

Based on a self-consistent thermodynamic–geophysical approach and xenolith-based constraints, we map the 2-D seismic, thermal and density structure of the mantle beneath the Siberian craton along the long-range profiles (Craton, Kimberlite, Rift and Meteorite) carried out in Russia with peaceful nuclear explosions. Structural peculiarities of the cratonic mantle are manifested by changes in seismic velocities, the degree and nature of layering and the relief of seismic boundaries. The results predict appreciable lateral temperature variations within the root to a depth of about 200 km, which are the main cause of seismic velocity variations. We find that the cratonic mantle is 300–400 °C colder than the tectonically younger surrounding mantle in this depth range. At greater depths, lateral changes in temperatures have little effect implying that thermal heterogeneity rapidly decreases. The present-day geotherms pass close to the 32.5–35 mW m^{-2} conductive models and suggest low mantle heat flow. Within the model resolution, the thickness of the thermal boundary layer, TBL (defined as the depth of the 1300 °C adiabat) beneath Siberia does not depend significantly on the composition and can be estimated as 300 ± 30 km; temperature at the base of the TBL is close to the 1450 ± 100 °C isotherm. Changes in the composition from depleted to fertile material reveal a negligible effect on seismic velocities, which are practically unresolved by seismic methods, but remain the most important factor for the density increase of the cratonic root. Density variations in the lower part of the root due to the chemical composition are greater than those caused by temperature. We find that both compositional and thermal anomalies are required to explain the Siberian mantle by a keel model consisting of depleted garnet peridotite at depths of 100 to 180 km and more fertile material at greater depths.

1. Introduction

Investigations of the mantle beneath the Siberian craton (SC) have been performed in a number of geochemical, geophysical and thermal studies (Artemieva and Mooney, 2001; Ashchepkov et al., 2010; Boyd et al., 1997; Pavlenkova, 2011; Rosen et al., 2006; Sobolev, 1977; Thybo, 2006). However, temperature–composition–grain size–density–seismic velocity–depth profiles important for the study of evolution and stability of the continents are uncertain and merit further investigation. Seismic, gravity and surface heat-flow data provide only indirect information about the composition and temperature of the deep interior (Artemieva, 2009; Fuchs, 1997; Kaban et al., 2003; Shapiro and Ritzwoller, 2004).

Mantle xenoliths are often used to constrain mantle temperatures at the time of kimberlite eruptions and to estimate some petrophysical properties of cratonic mantle and thickness of the petrologically distinct layer by xenolith *P*–*T* arrays (Kobussen et al., 2006; Lee et al., 2005; O'Reilly and Griffin, 2006, 2010). Thermobarometric results for Siberian mantle xenoliths of garnet, garnet–spinel, spinel peridotites, and pyroxenites (Ashchepkov et al., 2010; Boyd et al., 1997; Griffin et al., 2003; Ionov et al., 2010) provide unique information about the compositional heterogeneity and evolution of the cratonic mantle, but do not give direct information about its seismic structure. Combinations of surface heat flow measurements, geophysical data, xenolith thermobarometry and additional thermodynamic principles reduce some of the ambiguity in interpretations of mantle structure and provide the tighter constraints on mantle chemistry and thermal state (Anderson, 1989; Artemieva, 2006; Dalton and Faul, 2010; Deen et al., 2006; Jones et al., 2009; Khan et al., 2008; Kronrod and Kuskov, 2006, 2007; Lebedev et al., 2009; Simmons et al., 2009; Sobolev et al., 1996; Stixrude and Lithgow-Bertelloni, 2011).

Seismic studies are probably one of the best tools to infer the thermal state of the upper mantle because seismic velocities are more sensitive to temperature than to composition (e.g., Goes et al., 2000; Poupinet et al., 2003). A set of geophysical data (global *P*- and *S*-wave travel times, surface-wave phase velocities, travel time data from the deep seismic sounding) or simply seismic velocity–depth profiles can be

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converted to temperature–depth profiles using petrological constraints on the mantle composition or the composition of xenoliths brought to the surface and a thermodynamic-based inversion scheme (Afonso et al., 2008, 2013; Cammarano et al., 2003, 2009; James et al., 2004; Khan et al., 2011, 2013; Kuskov and Kronrod, 2006, 2007; Röhm et al., 2000; Shapiro and Ritzwoller, 2004; Sobolev et al., 1996).

In this work, we present a joint seismic, thermo-chemical and density model for the upper mantle of the Siberian craton. We use the approach of Kuskov et al. (2006, 2011) where isotropic velocities are converted to temperatures and vice versa based on a method of minimization of the Gibbs free energy incorporating equations of state of minerals, phase transformations, anharmonicity and attenuation effects. The major purpose of the present study is to deduce a family of geotherms permitted by absolute velocities and to estimate the thickness of cratonic mantle and its density from long-range seismic profiles (Craton, Kimberlite, Rift and Meteorite) carried out in Russia with peaceful nuclear explosions (Fig. 1). For comparison of the internal structure of a cold cratonic mantle with the surrounding mantle, it is instructive to use the AK135 and PREM reference models (Dziewonski and Anderson, 1981; Kennett et al., 1995). With this in mind, the main objectives of our study are as follows: (1) to map the 2-D seismic, thermal and density state of the Siberian craton upper mantle; (2) to compare the inferred temperatures with heat-flow models and mantle paleotemperatures estimated from thermobarometric results for Siberian xenoliths from kimberlites; (3) to provide the better constraints on the seismic structure, thermal state, composition and density of the mantle in central Siberia.

2. Data and method

The thermodynamic basis for modeling phase equilibria and physical properties of the Earth's mantle and various databases have been discussed in a series of papers (e.g., de Capitani and Brown, 1987; Saxena and Eriksson, 1983; Stixrude and Lithgow-Bertelloni, 2011). We basically use the same method as that described in detail in our previous publications (e.g., Kuskov et al., 2006, 2011). Briefly, this is a thermodynamically self-consistent approach based on a method of minimization of the Gibbs free energy in conjunction with the thermal equation of state for solids written in a Mie–Grüneisen–Debye form. The approach relates the equilibrium mineral assemblage for an assumed mantle composition and equations of state (EOS) of minerals with seismic properties. The phase composition and physical properties of the mantle were modeled within the dry $Na_2O–TiO_2–CaO–FeO–MgO–Al_2O_3–SiO_2$ (NaTiCFMAS) system including the non-ideal solid solution phases (Table 1). The pressure–depth correlation was taken from the PREM model.

Input data for the thermodynamic quantities are summarized in the THERMOSEISM database. The database was established by supplementing the calorimetric data for low-pressure phases and the EOS for low- and high-pressure phases with data calculated from high-*P*–*T* experiments (Fabrichnaya and Kuskov, 1994; Kuskov, 1997). The output *P*–*T* results contain the self-consistent information on phase assemblage (the mineral phases, their proportions and individual chemical compositions), the total density and seismic velocities. The

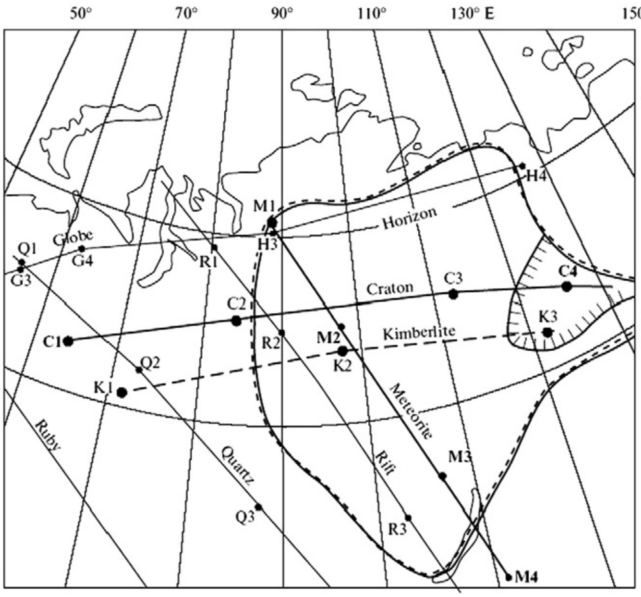

Fig. 1. Schematic location of the long-range seismic profiles carried out in the Siberian Craton with peaceful nuclear explosions (after Egorkin, 2001, 2004; Pavlenkova and Pavlenkova, 2006). Letters indicate location of the shots.

Table 1
Bulk composition models (wt.%), phase composition (mol%) and physical properties of garnet harzburgite (Hzb), garnet lherzolite (Lh), average garnet peridotite (GP) and primitive mantle (PM) composition in the NaTiCFMAS system [a].

Composition	GP	PM	Hzb	Lh
SiO_2	45.42	45.25	45.7	46.15
TiO_2	0.08	0.21	0.02	0.05
Al_2O_3	1.32	4.50	0.40	1.21
FeO	7.03	8.48	6.14	6.55
MgO	45.28	37.58	47.51	45.25
CaO	0.78	3.64	0.20	0.71
Na_2O	0.09	0.34	0.03	0.08
Total	100.0	100.0	100.0	100.0
MG#	92.00	88.80	93.20	92.5
Phase composition, physical properties				
100 km (P = 2.9 GPa, 600 °C)				
Ol	65.8($Fo_{92.8}$)	55.8($Fo_{92.5}$)	67.3($Fo_{93.4}$)	61.7($Fo_{93.2}$)
Gar	1.5	5.4	0.37	1.3
Opx	27.0	10.0	30.9	32.0
Cpx	5.6	28.4	1.4	4.9
Ilm	0.1	0.4	0.03	0.1
ρ, g cm^{-3}	3.334	3.403	3.309	3.325
V_p, km s^{-1}	8.320	8.332	8.323	8.314
V_s, km s^{-1}	4.724	4.695	4.739	4.730
K_S, GPa	131.58	136.25	130.13	130.64
G, GPa	74.40	75.02	74.31	74.40
310 km (P = 10.25 GPa, 1450 °C)				
Ol	65.8($Fo_{92.4}$)	56.1($Fo_{91.2}$)	67.47($Fo_{93.2}$)	61.9($Fo_{92.8}$)
Gar	1.5	5.6	0.40	1.4
Opx	25.7	0.0	31.0	31.1
Cpx	6.9	37.9	1.1	5.5
Ilm	0.1	0.4	0.03	0.1
ρ, g cm^{-3}	3.416	3.488	3.391	3.409
V_p, km s^{-1}	8.610	8.633	8.612	8.609
V_s, km s^{-1}	4.671	4.657	4.684	4.679
K_S, GPa	153.86	159.10	152.31	153.12
G, GPa	74.53	75.70	74.40	74.65

GP: (100 km/2.9 GPa/600 °C).
65.8% Ol ($Fo_{92.8}$) + 27% Opx ($En_{92.2}OrthoDi_{0.4}oFs_7OrthoHed_{0.2}OrthoCor_{0.2}$) + 1.5% Gar ($Py_{70}Alm_{24}Gros_6$) + 5.6% Cpx ($ClEn_{24}Di_{42}ClFs_{6.2}Hed_{13}Jd_{14}ClCor_{0.8}$).
GP: (310 km/10.25 GPa/1450 °C).
65.8% Ol ($Fo_{92.4}$) + 25.7% Opx ($En_{89}OrthoDi_{2.7}OrthoFs_7OrthoHed_{1.2}OrthoCor_{0.1}$) + 1.5% Gar ($Py_{85}Alm_{12}Gros_3$) + 6.9% Cpx ($ClEn_{46}Di_{25}ClFs_5Hed_{12}Jd_{11.8}ClCor_{0.2}$).
PM: (100 km/2.9 GPa/600 °C).
55.8% Ol ($Fo_{92.5}$) + 5.4% Gar ($Py_{68}Alm_{25}Gros_7$) + 10% Opx ($En_{92}OrthoDi_{0.4.}OrthoFs_{7.2}$ $OrthoHed_{0.2}OrthoCor_{0.2}$) + 28.4% Cpx ($ClEn_{23}Di_{44.5}ClFs_{6.5}Hed_{14}Jd_{11.3}ClCor_{0.7}$).
PM: (310 km/10.25 GPa/1450 °C).
56.1% Ol ($Fo_{91.2}$) + 5.6% Gar ($Py_{82}Alm_{14}Gros_4$) + 37.9% Cpx ($ClEn_{38.7}Di_{31.8}ClFs_6$ $Hed_{14.8}Jd_{8.5}ClCor_{0.2}$).

[a] The NaTiCFMAS system includes the following solid solution phases: olivine (Ol), spinel (Sp), plagioclase (Pl) and ilmenite (Ilm) – binary solutions; garnet (Gar: almandine, pyrope, grossular); orthopyroxene (Opx: $MgSiO_3$, $FeSiO_3$, $Ca_{0.5}$ $Mg_{0.5}SiO_3$, $Ca_{0.5}Fe_{0.5}SiO_3$, Al_2O_3); clinopyroxene (Cpx: same components as in Opx plus jadeite end-member). Bulk compositions normalized to 100% were taken from Griffin et al. (2003) for garnet harzburgite and garnet lherzolite (Daldyn Field, Siberia, Archon) and from McDonough (1990) for average garnet peridotite and primitive mantle composition. Total Ti is included in ilmenite. The compositions of phase assemblages (mol%) are given as an example.