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Global 1° × 1° thermal model TC1 for the continental lithosphere: Implications for lithosphere secular evolution

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Abstract

This paper reports a new 1° × 1° global thermal model for the continental lithosphere (TC1). Geotherms for continental terranes of different ages (> 3.6 Ga to present) constrained by reliable data on borehole heat flow measurements (Artemieva, I.M., Mooney, W.D. 2001. Thermal structure and evolution of Precambrian lithosphere: a global study. J. Geophys. Res 106, 16387–16414.), are statistically analyzed as a function of age and are used to estimate lithospheric temperatures in continental regions with no or low-quality heat flow data (ca. 60% of the continents). These data are supplemented by cratonic geotherms based on electromagnetic and xenolith data; the latter indicate the existence of Archean cratons with two characteristic thicknesses, ca. 200 and > 250 km. A map of tectono-thermal ages of lithospheric terranes complied for the continents on a 1° × 1° grid and combined with the statistical age relationship of continental geotherms ($z = 0.04 * t + 93.6$, where z is lithospheric thermal thickness in km and t is age in Ma) formed the basis for a new global thermal model of the continental lithosphere (TC1). The TC1 model is presented by a set of maps, which show significant thermal heterogeneity within continental upper mantle, with the strongest lateral temperature variations (as large as 800 °C) in the shallow mantle. A map of the depth to a 550 °C isotherm (Curie isotherm for magnetite) in continental upper mantle is presented as a proxy to the thickness of the magnetic crust; the same map provides a rough estimate of elastic thickness of old (> 200 Ma) continental lithosphere, in which flexural rigidity is dominated by olivine rheology of the mantle.

Statistical analysis of continental geotherms reveals that thick (> 250 km) lithosphere is restricted solely to young Archean terranes (3.0–2.6 Ga), while in old Archean cratons (3.6–3.0 Ga) lithospheric roots do not extend deeper than 200–220 km. It is proposed that the former were formed by tectonic stacking and underplating during paleocollision of continental nuclei; it is likely that such exceptionally thick lithospheric roots have a limited lateral extent and are restricted to paleoterrane boundaries. This conclusion is supported by an analysis of the growth rate of the lithosphere since the Archean, which does not reveal a peak in lithospheric volume at 2.7–2.6 Ga as expected from growth curves for juvenile crust.

A pronounced peak in the rate of lithospheric growth (10–18 km^3/year) at 2.1–1.7 Ga (as compared to 5–8 km^3/year in the Archean) well correlates with a peak in the growth of juvenile crust and with a consequent global extraction of massif-type anorthosites. It is proposed that large-scale variations in lithospheric thickness at cratonic margins and at paleoterrane boundaries controlled anorogenic magmatism. In particular, mid-Proterozoic anorogenic magmatism at the cratonic margins was caused by edge-driven convection triggered by a fast growth of the lithospheric mantle at 2.1–1.7 Ga. Belts of anorogenic magmatism within cratonic interiors can be caused by a deflection of mantle heat by a locally thickened lithosphere at paleosutures and, thus, can be surface manifestations of exceptionally thick lithospheric roots. The present volume of continental lithosphere as estimated from the new global map of lithospheric thermal thickness is 27.8 (±7.0) × 10^9 km^3 (excluding submerged terranes

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with continental crust); preserved continental crust comprises ca. 7.7×10^9 km^3. About 50% of the present continental lithosphere existed by 1.8 Ga.
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1. Introduction

Laboratory measurements on upper mantle rocks and rock-forming minerals reveal strong dependence of seismic velocities and electrical conductivity on temperature (Kampfmann and Berckhemer, 1985; Jackson, 2000; Constable et al., 1992). Although recent high-resolution global and regional seismic tomography and electromagnetic surveys image strong lateral and vertical heterogeneities within the continental upper mantle (e.g., Freybourger et al., 2001; Jones et al., 2003), no reliable interpretations of their origin (thermal, structural, or compositional) are possible in the absence of data on upper mantle temperatures. The contribution of thermal versus compositional variations to observed geophysical anomalies remains controversial. Forte et al. (1994) conclude that much of seismic velocity variations in the mantle can be attributed to temperature variations. On the other side, Poupinet et al. (2003) found that P-wave travel time delays correlate well with geological ages and concluded that temperature variations alone cannot explain short-wavelength offsets in P-vertical travel times, but require mineralogical differences within the lithosphere. Griffin et al. (1998a) argue that compositional anomalies can account for at least 50% of the velocity anomalies observed in seismic tomography models. This conclusion agrees with the results of a global analysis of correlations between seismic and thermal anomalies, which indicate that in the upper 150 km of the continental mantle temperature variations alone are sufficient to explain seismic *Vs* only in ca. 50% of continental regions; in other continental regions temperature variations can account for not more than 50% of the amplitude of seismic velocity anomalies (Artemieva et al., 2004).

Clearly, estimates of upper mantle temperatures from seismic tomography (e.g., Furlong et al., 1995; Sobolev et al., 1996; Godey et al., 2004) or electrical conductivity models (e.g., Dobson and Brodholt, 2000; Ledo and Jones, 2005) cannot be used to assess the relative contributions of thermal and compositional variations to geophysical anomalies, because such inversions require certain assumptions on mantle composition, fluid regime, and the amount of melt, while anisotropy can also significantly affect the results. A more advanced approach has been recently proposed by Shapiro and Ritzwoller (2004a), who assimilated heat flow data into seismic inversion and used seismic tomography data to estimate mantle temperatures beneath Antarctica. Alternatively, xenolith data can be used to estimate mantle geotherms. However, the number of localities with mantle-derived peridotites is very limited and their areal distribution is much more scarce than heat flow measurements (Fig. 1).

The present study reports a new consistent global thermal model TC1 for the continental upper mantle constrained primarily by heat flow data and thus suitable for interpretations of seismic, gravity, or electromagnetic models in terms of thermal versus non-thermal anomalies. A thermal model for stable continental lithosphere constrained by reliable surface heat flow (Artemieva and Mooney, 2001) provides the basis for the present study. However, because the coverage of borehole measurements is uneven and sparse in many regions (Fig. 1), heat flow data permit constraints on lithospheric geotherms for only about 40% of the continents. In particular, high-quality heat flow measurements are absent for ~80% of South America, ~70% of Africa, large areas in Asia, all of Antarctica, most of Greenland, the Arctic regions of North America, and the Russian Far East. Nevertheless, a number of heat flow measurements in continental terranes of different geological ages permits statistically significant analysis of lithospheric geotherms for different tectonic settings allowing expansion of the previous thermal model (Artemieva and Mooney, 2001) to all continental areas (excluding submerged terranes with continental crust such as oceanic plateaus and shelves). Xenolith *P–T* arrays as well as data on electrical conductivity of the upper mantle have been compiled for different cratonic settings and compared with lithospheric geotherms constrained by surface heat flow. For tectonically active regions with transient thermal regimes, lithospheric temperatures are based primarily on xenolith geotherms.

A compilation of ages of the continental crust averaged on a 1°×1° grid formed the basis of the

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