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The continental lithosphere: Reconciling thermal, seismic, and petrologic data

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ABSTRACT

The goal of the present study is to extract non-thermal signal from seismic tomography models in order to distinguish compositional variations in the continental lithosphere and to examine if geochemical and petrologic constraints on global-scale compositional variations in the mantle are consistent with modern geophysical data. In the lithospheric mantle of the continents, seismic velocity variations of a non-thermal origin (calculated from global V_s seismic tomography data [Grand S.P., 2002. Mantle shear-wave tomography and the fate of subducted slabs. Philosophical Transactions of the Royal Society of London. Series A, 360, 2475–2491.; Shapiro N.M., Ritzwoller M.H. 2002. Monte-Carlo inversion for a global shear velocity model of the crust and upper mantle. Geophysical Journal International 151, 1–18.] and lithospheric temperatures [Artemieva I.M., Mooney W.D., 2001. Thermal structure and evolution of Precambrian lithosphere: A global study. Journal of Geophysical Research 106, 16387–16414.] show strong correlation with tectono-thermal ages and with regional variations in lithospheric thickness constrained by surface heat flow data and seismic velocities. In agreement with xenolith data, strong positive velocity anomalies of non-thermal origin (attributed to mantle depletion) are clearly seen for all of the cratons; their amplitude, however, varies laterally and decreases with depth, reflecting either a peripheral growth of the cratons in Proterozoic or their peripheral reworking. These cratonic regions where kimberlite magmas erupted show only weakly positive compositional velocity anomalies, atypical for the "intact" cratonic mantle. A reduction in the amplitude of compositional velocity anomalies in kimberlite provinces is interpreted to result from metasomatic enrichment (prior or during kimberlite emplacement) of the cratonic mantle, implying that xenolith data maybe non-representative of the "intact" cratonic mantle.

1. Introduction

The concept of a solid, non-deformable outer layer of the Earth (initially estimated to be about 100 km thick) and its fluid, deformable interior has appeared as a result of the early gravity studies of the 18th–19th centuries, although the term "lithosphere" did not come into existence until the late 19th–early 20th century (see Watts (2001) for a detailed review). Soon afterwards, the term "asthenosphere" was introduced (Barrel, 1914) to describe a fluid, deformable layer (initially estimated as several hundred kilometers thick) below the "lithosphere". With the booming development of seismological methods in the first half of the 20th century, which led to a discovery of the seismic low velocity zone (the LVZ) at 100–150 km depth (Gutenberg, 1954) and its base (the Lehmann discontinuity) at ca. 220 km depth (Lehmann, 1961, 1962), the term "lithosphere" acquired a new, seismic, justification. Since, surprisingly, the top of the seismic LVZ was found to be at about the same depth as the transition between solid outer layer of the Earth (the "lithosphere") and its low-viscous, deformable interior (the "asthenosphere"), as defined from early isostatic gravity models, it was tempting to explain both gravity and seismic observations by the same physical mechanisms.

The first heat flow measurements have been initiated more than a century ago by Everett (1883), with the first modern measurements of the terrestrial heat flow reported in the late 1930's for the continents and in the 50's for the oceans (Benfield, 1939; Bullard, 1939; Krige, 1939; Revelle and Maxwell, 1952). Maturation of geothermics as an independent technique to assess the physical state of the deep Earth's interior allowed the calculation of crustal and upper mantle geotherms for a large range of continental and oceanic regions (e.g. Jaeger, 1965; McKenzie, 1967). Combined with experimental and theoretical studies of the mantle composition and melting conditions in the upper mantle (Uffen, 1952; Ito and Kennedy, 1967; Kushiro et al., 1968), mantle geotherms were employed to explain the seismic LVZ in terms of peridotite partial melting. It was a big step forward as it allowed observations, which came from independent fields of geophysics, to be incorporated into a joint picture of the physical state of the upper mantle. Thus, the term "lithosphere" acquired an additional interpretation.

Further development of geophysical techniques and a gradual accumulation of extensive data sets in seismic, thermal, electromagnetic, rheological, and petrologic studies has led to much controversy in the use of the term "lithosphere". Although the term became a

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convenient and widely used concept in geosciences, some authors argue that at present "it has become an unnecessarily confusing concept" (Anderson, 1995) due to an excessive number of different definitions of the "lithosphere". Indeed, depending on the geophysical techniques (and physical properties measured), the lithosphere has different practical definitions. Most of them (i.e. seismic, electrical, elastic) are based on a sharp change in temperature-dependent physical properties at the transition from conductive (and rheologically strong) to convecting (and rheologically weak) upper mantle and thus crucially depend on the thermal regime of the upper mantle (Fig. 1).

This paper starts with a brief review of different concepts and definitions of the lithosphere. It then compares global thermal and seismic tomography models of the structure of the continental lithospheric mantle (CLM). Such a multi-data approach permits to specify the robust characteristics of the continental lithosphere and its evolution since the Archean. Data on the thermal regime of stable continental lithosphere provides exceptional information on lithospheric properties as it permits us to separate thermal and non-thermal effects in global geophysical models, such as seismic tomography. The goal of the present study is to perform a joint analysis of seismic and thermal data in order to extract a non-thermal signal from seismic models and to distinguish compositional (both vertical and lateral) variations in the CLM. This approach provides a basis for comparing the thickness of the continental lithosphere as defined by seismic, thermal, and compositional variations. The conclusions of the study are then compared with the results of petrologic studies of mantle peridotites. Since xenoliths provide random, uneven, and in many areas sparse sampling of the Earth's deep interior, it is challenging to examine if geochemical constraints on global-scale compositional variations in the mantle are consistent with modern geophysical data.

2. What is the lithosphere?

2.1. Some semantics

In the classical, plate tectonics definition, the "*lithosphere*" is the upper rigid layer, which moves mechanically coherently with plate motions (the *mechanical boundary layer,* MBL). The base of the MBL is commonly interpreted as being associated with mantle zones of reduced viscosity and asthenospheric flow and, in petrologic studies, is constrained by variations in texture of xenoliths (sheared or non-sheared) brought to the surface from different depths in the mantle (Nixon and Boyd, 1973). Since mantle viscosity is strongly temperature-dependent, the thickness of the MBL should be proportional to the thickness of the *thermal boundary layer* (TBL, i.e. the layer with dominating conductive heat transfer above the convecting mantle), unless weak mantle rheology is caused by presence of fluids.

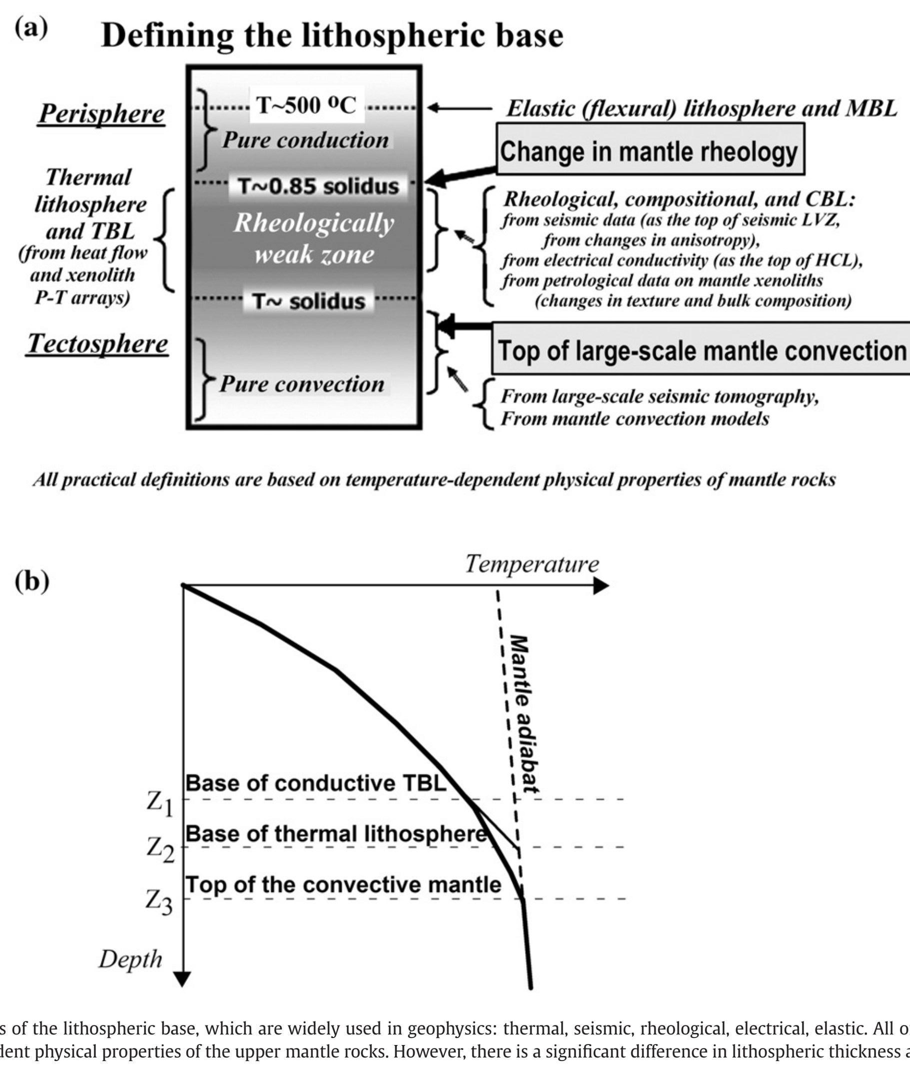

Fig. 1. (a) Different definitions of the lithospheric base, which are widely used in geophysics: thermal, seismic, rheological, electrical, elastic. All of these definitions are based on different temperature-dependent physical properties of the upper mantle rocks. However, there is a significant difference in lithospheric thickness as defined by different methods. See text for explanations. (b) Relationships between thicknesses of thermal boundary layer (z_1), thermal lithosphere (for simplicity calculated as the depth z^2 where a linear continuation of the geotherm intersects a mantle adiabat), and seismic lithosphere (z_3) (modified after Jaupart and Mareschal, 1999).