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Thermal expansivity and elastic properties of the lithospheric mantle: results from mineral physics of composites

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Abstract

The elastic properties and the coefficient of thermal expansion (CTE) of the lithospheric mantle are important parameters that affect the results of lithospheric modelling. However, there is still no consensus on which values are the most appropriate to model the lithosphere, and various average values are used for lithospheres of different age, thermal state, and composition. We present an integrated approach to calculate the elastic properties and the CTE of mantle rocks, based on the mineral physics of composites and considering the spatial heterogeneity of the lithospheric mantle. The method considers the dependence of parameters on pressure and temperature, following a procedure based on an extension of the shear-lag model and thermal expansivity systematics.

Representative values are calculated for three lithospheric domains: (a) Archean lithosphere, (b) Phanerozoic continental lithosphere, and (c) oceanic lithosphere. For the case of Archean lithosphere, values of CTE between (3.04 and 3.11) $\times 10^{-5}\,\mathrm{K}^{-1}$ are found to be suitable for modelling, and a constant depth-derivative for P-waves $\partial V_p/\partial z \sim 2.30 \times 10^{-3}\,\mathrm{s}^{-1}$ is estimated. Results for Phanerozoic lithosphere show that no single average value of CTE can be used in modelling. Values range non-linearly between (3.25 and 3.47) $\times 10^{-5}\,\mathrm{K}^{-1}$ at pressures equivalent to depths of 25 and 100 km, respectively. The P-wave velocity variation with depth exhibits a decrease in the range of 25–40 km, followed by almost a constant value of $\sim$8.08 km s^{-1} between 40 and 60 km, and a systematic increase with a depth-derivative $\partial V_p/\partial z \sim 1.12 \times 10^{-3}\,\mathrm{s}^{-1}$ from 60 km downwards. The variation in the CTE is largest in oceanic lithosphere. In young plates ($\lesssim$20 Ma), values of the CTE range non-linearly from (3.25 to 3.82) $\times 10^{-5}\,\mathrm{K}^{-1}$ at pressures equivalent to depths of 10 and 50 km, respectively. In old oceanic lithosphere ($\sim$100 Ma), the CTE is slightly smaller, showing values in the range of (3.0–3.7) $\times 10^{-5}\,\mathrm{K}^{-1}$ at 10 and 80 km, respectively, giving a typical average value of $\sim 3.45 \times 10^{-5}\,\mathrm{K}^{-1}$. P-wave velocity in young oceanic lithosphere decreases from $\sim$8.14 to 8.0 km s^{-1} in the first 30 km, then follows a nearly constant path downwards. In old oceanic lithosphere, on the other hand, a systematic reduction from $\sim$8.2 to 8.1 km s^{-1} in P-wave velocities is predicted as depth increases from 10 to 80 km.

The effects of heterogeneities in CTE and elastic parameters are particularly noticeable in Archean lithosphere, where difference in predicted elevations and geoid heights can reach values of $\geq$300 and $\sim$6 m, respectively, when compared to standard models.

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These effects are less ($\lesssim$40 and 0.25 m, respectively) in Phanerozoic continental and oceanic lithospheres. Uncertainties in experimental data and geotherms indicate that compositional effects cannot be completely resolved by seismic tomography in regions with P-wave and S-wave anomalies $\lesssim\pm1.5$ and $\pm3\%$, respectively.

Keywords: Lithospheric mantle; Elastic properties; Thermal expansivity; Mineral physics; Lithospheric modelling

1. Introduction

Lithospheric modelling provides critical information for understanding the dynamics of plate tectonics. The main goal is to obtain a model of the thermal, mechanical, and structural characteristics of the lithosphere, which in turn gives insights about geodynamic processes such as subduction, delamination, rifting, etc. The lithospheric mantle plays a major role in determining the total strength, buoyancy and thickness of the lithospheric plate. Several methodologies have been proposed, all of them making use of regional geophysical observables as constraints to the model. Half-space and plate cooling thermal models predict a $t^{1/2}$ dependence of the ocean-floor topography and heat flow, where t is age, as well as a progressive decrease of the geoid and deflection of isotherms away from the oceanic ridge (e.g. Parsons and Sclater, 1977; Stein and Stein, 1992; Schubert et al., 2001). The continental lithosphere behaves in a more complex way than the oceanic lithosphere, due in part to the presence of a relatively thick and heterogeneous continental crust, and its thermal modelling requires a detailed knowledge of the crustal geometry and its thermophysical parameters (e.g., Čermák et al., 1993; Zeyen et al., 2002; Fernàndez et al., 2004). Deep seismic profiling and regional tomography also provide images of the lithospheric structure based either on the interpretation of absolute wave propagation velocities or the travel time residuals relative to a global reference model (e.g. Lay and Wallace, 1995; Levshin et al., 2001).

Some of the main parameters controlling the final outputs of thermal and seismic models are the elastic parameters (i.e. bulk and shear modulus) and the coefficient of thermal expansion (CTE) assumed for the lithospheric mantle. The former controls wave velocities, and therefore the interpretations regarding the thermal state and composition of the mantle. The latter also affects wave velocities, but more importantly, it determines the density of the materials, and consequently the calculated elevation, gravity, and geoid fields. Although there have been numerous attempts to obtain representative values of the CTE for the whole mantle, there are still ambiguities as to which are the appropriate values for the lithospheric mantle. Proposed average values given by different authors range from as low as $1.6\times10^{-5}\,\mathrm{K}^{-1}$ (Stacey, 1992) to as high as $4.2\times10^{-5}\,\mathrm{K}^{-1}$ (Doin and Fleitout, 1996), and they are commonly used indistinctly for lithospheres of different composition and thermal state. Similarly, P_n wave velocities are also assumed to be homogeneous (with typical values of $\sim$8.0 km s^{-1}) over long distances, while they have been shown to be highly variable, ranging from $\sim$7.6 to 8.6 km s^{-1} for lithospheres of different ages (e.g. Németh and Hajnal, 1998; Levshin et al., 2001). Moreover, geophysical models usually consider a homogeneous lithospheric mantle, with a composition rich in olivine, mechanically strong, and denser than the underlying asthenosphere. This picture is rather simplistic, and it is in disagreement with recent data that indicates that lithospheres of different nature (i.e. oceanic versus continental) and ages have distinct compositional and mechanical properties (e.g. Griffin et al., 1999; Peccerillo and Panza, 1999; O'Reilly et al., 2001; Niu et al., 2003; Afonso and Ranalli, 2004; and references therein). Hence, it is of interest to determine representative values of the elastic properties and CTE for different lithospheres that permit a more accurate modelling.

In this paper, we explore systematically the heterogeneity of the lithospheric mantle and determine representative values of CTE and elastic parameters for lithospheres of different nature and ages. The first two sections of the paper are devoted to introduce the models used to calculate both elastic parameters and CTE of rocks. Subsequently, we discuss the composition and lateral heterogeneities of the lithospheric mantle, and the applicability of our methodology to estimate P-wave velocities and CTE in this region.