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Rheological contrast at the continental Moho: Effects of composition, temperature, deformation mechanism, and tectonic regime

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ABSTRACT

The rheological contrast at the Moho is an important factor in continental tectonics. This paper explores systematically the effects of composition, temperature, deformation mechanism, and tectonic regime on the strength contrast, considering four compositions for the lower crust (felsic granulite, mafic granulite, wet diabase, dry diabase) and two for the lithospheric mantle (dry and wet peridotite). The strength contrast of the resulting eight compositional layerings is estimated as a function of Moho temperature which is varied from 600 to 1500 K. The Moho temperature can be converted to surface heat flow if the thickness and composition of the crust are known. Besides a “standard” case (crustal thickness 35 km), the cases of a thick (50 km) and thin (20 km) crust are also considered (with wet quartzite crustal rheology in the latter case). Results show a great variety of strength contrasts according to different conditions. Excluding the case of very low Moho temperature ($T_M \leq 600$ K), when the behaviour of both lower crust and upper mantle is frictional brittle and therefore the strength contrast vanishes, the strength contrast (at a given strain rate) is a strong function of composition, temperature, and tectonic conditions. Weak compositional stratification (e.g., soft lower crust/soft lithospheric mantle or hard lower crust/hard lithospheric mantle) results in lower contrasts than strong compositional stratification. For any given compositional combination, the absolute value of the strength contrast is higher in compressional as compared to extensional tectonic environments, and tends to decrease with increasing temperature from a maximum of hundreds of MPa at low-to-intermediate Moho temperatures ($600 < T_M < 1000$ K) to values less than a few MPa at higher temperatures ($T_M > 1200$ K). Therefore, rheological layering is favoured by strong intrinsic (i.e., compositional) strength contrasts between lower crust and upper mantle and relatively low Moho temperatures.

Contents

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1. Introduction

The continental lithosphere is a compositionally layered body. For the purpose of large-scale rheological modelling, it is usually assumed to consist of three layers: upper crust, lower crust and lithospheric mantle, whose brittle or ductile strengths are primarily dependent on composition and temperature. A large literature exists on the variations of rheological properties of the lithosphere as a function of depth, and the construction of "strength envelopes" (also termed "rheological profiles") is a well-established procedure (*cf.* e.g. Afonso and Ranalli, 2004; Burov, 2010; Cloetingh and Burov, 1996; Kirby and Kronenberg, 1987; Kohlstedt et al., 1995; Ranalli, 1995, 1997). Despite being subject to considerable uncertainties, they provide a first-order estimate of the rheology of the lithosphere.

Both modelling and observation show that the spectrum of rheological behaviours of the lithosphere varies between two end members, which have been termed "jelly sandwich" and "crème brulée" (Burov, 2010; Maggi et al., 2000). In the former, a frictionally brittle and relatively strong upper crust is separated from a strong (brittle or ductile) uppermost mantle by a soft ductile lower crust, and consequently the Moho is a major rheological discontinuity. In the latter, the only strong layer is the upper crust, which overlies a ductile lower crust and lithospheric mantle, and the Moho is a minor or negligible rheological discontinuity. However, when the rheological behaviour is modelled strictly on the basis of the constitutive equations of lithospheric materials, it becomes clear that the difference between the two models is not a dichotomy, but reflects the end members of a continuous spectrum of behaviours, depending on composition and temperature (Afonso and Ranalli, 2004).

This paper focuses on the rheological contrast at the continental Moho (a discussion of the oceanic lithosphere as a function of age and composition can be found in Mahatsente et al., 2012). The Moho discontinuity is taken in the compositional sense (petrological Moho; for a discussion of the discrepancies between petrological and seismological Moho *cf.* O'Reilly and Griffin, 2013–this volume). The main purpose is to provide a baseline for predicting the strength variations at the Moho under different conditions of composition, crustal thickness, temperature, tectonic regime, and strain rate, which can be used as a basis for more detailed regional studies.

Rheological predictions based on experimental results on rock deformation are subject to intrinsic uncertainties which are mainly a consequence of the necessary simplifications on the composition of the relevant rocks and the reproducibility of laboratory data. These are not easily quantifiable (*cf.* e.g. Karato, 2008; Kirby and Kronenberg, 1987; Korenaga and Karato, 2008; Ranalli, 1995 for discussions), but from the present viewpoint results of rheological modelling can be probably considered valid within an order of magnitude. Potentially more important limiting factors are the assumption of constant strain rate and the choice of predominant deformation mechanisms. The constant strain rate assumption can be overcome by incorporating the time dependence of stresses, strains, and strain rates and the effects of the applied force on bulk lithosphere deformation (*cf.* e.g., Ershov and Stephenson, 2006). The possibility of additional deformation mechanisms, besides the usual low-temperature frictional brittle fracture and high-temperature power law creep, is considered in this paper (see Section 2.3).

The plan of the paper is as follows. Section 2 describes the main features of the model: choice of crustal thickness and composition (Section 2.1); estimation of crustal geotherms and corresponding surface heat flow for a given Moho temperature, crustal thickness and composition (Section 2.2); and rheological behaviour of the model materials (Section 2.3). Section 3 presents the estimated strength contrast at the Moho as a function of composition and temperature for the "standard case" (crustal thickness 35 km; Section 3.1), followed by a discussion of the possible effects of variations of strain rate and pore fluid pressure (Section 3.2), crustal thickness (Section 3.3), and the possibility of high-pressure failure (Section 3.4). Section 4 summarises the results and discusses their implications and limitations for geodynamic modelling.

2. Model

2.1. Lithospheric structure and composition

The "standard" model has a crustal thickness $h = 35$ km. The crust consists of two layers: upper crust ($h_1 = 20$ km) and lower crust ($h_2 = 15$ km), of densities ρ_1 and ρ_2 respectively, overlying the lithospheric mantle of density ρ_m (parameter values are shown in Table 1). For the purposes of comparison, we have considered also a thick crust ($h = 50$ km, $h_1 = 20$ km, $h_2 = 30$ km) and a thin crust ($h = 20$ km, consisting of one layer only). The thickness of the lithospheric mantle need not be specified, as the focus is on the change of rheological properties at the Moho, but the lithosphere/asthenosphere boundary can be assumed to be defined in the usual thermal sense as the intersection of the geotherm with the 1570 K mantle adiabat (Artemieva, 2011; Artemieva and Mooney, 2001).

The behaviour of the upper crust is assumed to be controlled by the rheology of wet quartzite, but this assumption does not enter the estimation of strength contrast except in the case of thin crust where the entire crustal layer is assumed to have this composition. The behaviour of the lower crust is estimated for four different compositions, two of which can be considered relatively soft (felsic granulite, wet diabase) and two relatively hard (mafic granulite, dry diabase). The behaviour of the upper mantle is assumed to vary between relatively soft (wet peridotite) and relatively hard (dry peridotite). Therefore (except in the case of thin crust) there are eight possible compositional contrasts across the Moho, which we examine as functions of Moho temperature varying between 600 and 1500 K.

2.2. Lithospheric geotherm

The thermal state of the continental lithosphere depends on many factors (*cf.* the extensive discussions in Artemieva, 2011; Jaupart and Mareschal, 2010). In the present context, we need to establish a correspondence between Moho temperature T_M and surface heat flow Q_o, so that the estimated strength contrast can be expressed as a function of both. For this purpose, we estimate type geotherms by solving the steady-state conductive heat transfer equation. The assumption of steady-state is strictly valid only for areas where the age of the last tectonothermal event is of the order of tens of Ma or more. However, since for a given crustal thickness and composition the heat flow across the Moho is a function of T_M (see below), the transient response to relatively recent tectonothermal events is taken into account by increased mantle heat flow.

Assuming continuity of both temperature and gradient at interfaces within the lithosphere, the temperature at the Moho depth z_2 is given by (Afonso and Ranalli, 2004)

$$T(z_2) = T_o - \frac{A_2}{2K_2} Z_2^2 + \left[\frac{A_2}{K_2} Z_1 + \frac{Q_M}{K_1} + \frac{A_2}{K_1}(Z_2 - Z_1)\right] Z_2 + \frac{z_1^2}{2}\left(\frac{A_1}{K_1} - \frac{A_2}{K_2}\right) \quad (1)$$

where $T_o = 285$ K is surface temperature; A and K are volumetric heat generation rate and thermal conductivity, respectively; z is depth to the bottom of the relevant layer (subscripts 1 and 2 refer to upper and lower crust); and Q_M is the Moho heat flow (heat flowing from the mantle across the Moho). Note that "Moho heat flow" as used in this paper is different from "basal heat flow" (see e.g. Artemieva and Mooney, 2001) which is the contribution to surface heat flow coming from below the enriched upper crust, i.e. including also the lower crustal heat production. The Moho heat flow can be written as

$$Q_M = Q_o - Q_c = Q_o - (A_1 h_1 + A_2 h_2) \quad (2)$$