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Low steady-state stresses in the cold lithospheric mantle inferred from dislocation dynamics models of dislocation creep in olivine

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ABSTRACT

Transmission electron microscopy observations on olivine crystals deformed at moderate ($\leq$1273 K) temperature evidenced dislocations interactions explaining the hardening observed in the experiments, but also recovery mechanisms by the absorption or emission of point defects. Thus we investigate the possibility that, at geological strain-rates, these recovery processes allow steady-state deformation by dislocation creep at low to moderate temperatures in the lithospheric mantle. We test this hypothesis using a 2.5-D dislocation dynamics (DD) model, which combines dislocation glide and recovery by climb. This model shows that diffusion-controlled recovery processes allow for steady-state deformation by dislocation creep in the lithospheric mantle at stresses $<$500 MPa. For stresses of 50–200 MPa, steady-state strain-rates of 10^{-15} s^{-1} may be attained at temperatures as low as 900 K. Fitting of the DD model produces a flow law, which represents a lower bound for the lithospheric mantle strength, since the models describe the deformation of an olivine single crystal in an easy slip orientation. Comparison of strain-rates and Moho temperatures inferred for different geodynamic environments and the predictions of this model-based flow law implies, nevertheless, that, except in incipient rifts, most of the observed deformation may be produced by stress levels $\leq$200 MPa, consistent with those inferred to be produced by convection. This convergence suggests that the present models, which explicitly calculate the time-dependent dislocation dynamics, may provide a correct first order estimate of the mechanical behaviour of the lithospheric mantle, which cannot be derived directly from any existing data.

1. Introduction

The strength and the active deformation mechanisms in the lithospheric mantle are one of the major open questions in plate tectonics. Extrapolation of empirical flow laws derived from high-temperature ($>$1473 K) deformation experiments on olivine single-crystals and polycrystals to geological strain-rates (10^{-12} to 10^{-15} s^{-1}) predicts stresses largely exceeding 1 GPa in the cold uppermost levels of the lithospheric mantle. Indeed, for deforming the lithospheric mantle at temperatures of 873 K and strain-rates of 10^{-14} s^{-1}, anhydrous flow laws for olivine polycrystals predict stresses ranging from 1.6 GPa to 5.07 GPa (Fig. 1). Lower stresses (375–800 MPa) are predicted by extrapolation of hydrous high-temperature flow laws (Fig. 1), but these values probably overestimate both the water contents in olivine in the lithospheric mantle (Bell and Rossman, 1992; Ingrin and Skogby, 2000; Demouchy et al., 2006; Peslier, 2010) and the effect of water on the olivine rheology, which is probably limited to a reduction in strength by a factor 2–3 (Demouchy et al., 2012; Fei et al., 2014).

The predicted strength of a 100 km thick plate is therefore significantly higher than the stresses which may be produced in a viscoelastic lithosphere by mantle convection or those inferred by modelling the deformation in response to crustal loads, such as volcanic chains (100–200 MPa; *e.g.*, Beuchert and Podladchikov, 2010; Zhong and Watts, 2013). Yet, continental plates deform. This paradox may be partially solved by proposing that the cold uppermost lithospheric mantle deforms by brittle failure or low temperature plasticity (Fig. 1). When implemented in numerical models, flow laws simulating these processes and the associated thermal dissipation allow indeed successful simulation of many geodynamic processes, in particular continental breakup (*e.g.*, Brune, 2014). However, the rarity of mantle earthquakes in

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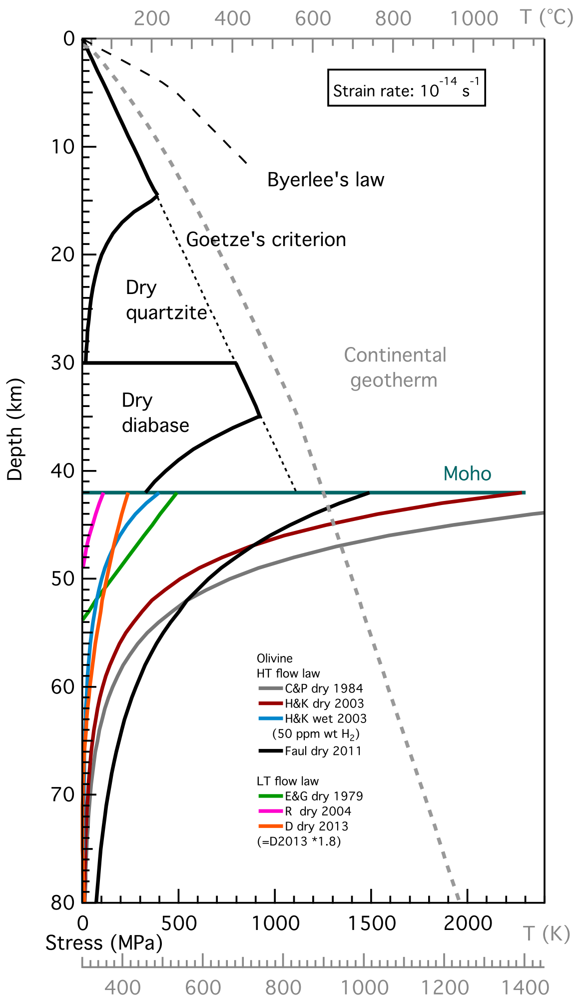

Fig. 1. Strength envelope model for a 100 km-thick continental lithosphere deforming at a vertically uniform strain-rate of 10^{-14} s^{-1}. The geotherm is plotted in grey. Yield stresses in the crust were calculated using: the frictional sliding law from Byerlee (1977) and Goetze's criterion with a density of 2700 $kg\,m^{-3}$; the flow law for anhydrous quartzite from Gleason and Tullis (1993); and the flow law for anhydrous diabase from Mackwell et al. (1998). In the mantle (below the Moho), are displayed: the low temperature flow laws from Demouchy et al. (2013), Raterron et al. (2004), and Evans and Goezte (1979), as well as the anhydrous and hydrous high temperature flow laws from Hirth and Kohlstedt (2003), the anhydrous high temperature flow law from Faul et al. (2011), and the anhydrous high temperature flow law from Chopra and Paterson (1984).

continental domains (Maggi et al., 2000; Jackson, 2002) tends to falsify the assumption of a cold mantle rheology controlled by frictional processes. Indeed, the rare earthquakes nucleating at sub-Moho depths beneath the Himalayas (Monsalve et al., 2006) or active rift zones (Lindenfeld and Rumpker, 2011) were ascribed to the underplating of the cold Indian lithosphere or to magma migration rather than tectonic processes.

On the other hand, the change from a power law to an exponential dependence of strain-rate on stress (*i.e.*, power law breakdown) is consistent with the few data on deformation of olivine single and polycrystals at temperatures <1300 K (Raleigh, 1968; Phakey et al., 1972; Durham and Goetze, 1977; Evans and Goetze, 1979; Raterron et al., 2004; Demouchy et al., 2009, 2013, 2014). These data also indicate that the shallow cold lithospheric mantle may deform at geological strain-rates under significantly lower stresses than predicted from the extrapolation of high-temperature data (Fig. 1). Indeed, at a temperature of 873 K and a strain-rate of 10^{-14} s^{-1}, the flow law from Demouchy et al. (2013) predicts stresses of ~270 MPa.

However, conducting deformation experiments on olivine at $T < 0.5T_m$ (T_m is the melting temperature, *i.e.* for olivine $Fo_{90} \approx$ 1973 K) suffers from major shortcomings. As temperature decreases, higher pressures are needed to avoid brittle deformation. Gas-medium apparatus, where confining pressures are limited to <500 MPa, provide accurate mechanical data, but do not allow to deform plastically olivine below 1100 K (Demouchy et al., 2013). Steady-state is rarely achieved in low temperature experiments; most stress strain-rate curves are characterised by marked strain hardening. Flow laws have been therefore established by fitting the data at a given strain, which is in all cases lower than the strain values expected in the mantle. Demouchy et al. (2013), for instance, used the maximum stress attained in each experiment, which corresponds to total shortenings ranging from 4.7 to 23.5%.

Below 1100 K, ductile deformation can only be achieved by applying high confining pressures, for instance using the D-DIA apparatus, which has high uncertainty in the stress data (Raterron et al., 2004; Long et al., 2011), or by using indentation measurements (Evans and Goetze, 1979), which give only indirect rheological information. In spite of these limitations, exponential flow laws, in particular the one from Evans and Goetze (1979), have been widely used to model the mechanical behaviour of the upper mantle. Yet, there are many reasons to question whether this strain-dependent data may be used to predict the mechanical behaviour of the uppermost lithospheric mantle in situations in which large deformations are expected, such as convergent plate boundaries, lithospheric scale shear zones and transform faults, or continental rifts.

In this article, we propose a new strategy to infer the rheology of olivine at low temperature and natural strain-rates by combining experimental data and numerical modelling of intracrystalline plasticity. First, we rely on a detailed analysis by Transmission Electron Microscopy (TEM) of the most recent low-temperature deformation experiments of olivine by Demouchy et al. (2013, 2014), which allow unravelling the elementary deformation mechanisms at work. These observations permit to identify the mechanisms, which lead to hardening and brittleness, but also to highlight the recovery processes, which are hindered at high strain-rates. These recovery processes are diffusion-driven and, thus, both time and temperature-dependent. At geological strain-rates, recovery should be much more effective than in the experiments, possibly allowing steady-state to be achieved. To test for this hypothesis, dislocation dynamics models are used to analyse the interplay between dislocation glide and diffusion-driven recovery processes, such as climb, in olivine. Within this model we can predict the steady-state strain-rates, which might be achieved at the stress-temperature conditions expected to prevail in the lithospheric mantle. These predictions, which represent a lower bound since we model the deformation of a well-oriented single crystal, not a polycrystal, are validated by comparison to strain-rates and Moho temperatures observed in a variety of geodynamic environments.

2. Experimental constraints

2.1. Deformation experiments

The rheology of mantle rocks at lithospheric temperatures has been essentially constrained by deformation experiments on olivine crystals and aggregates under variable confining pressures, from atmospheric (indentation experiments) to up to 3–8 GPa (D-DIA experiments), and temperatures (300–1623 K). Since the slow strain-rates relevant for geodynamics (10^{-12} s^{-1} to 10^{-18} s^{-1}) cannot be achieved in the laboratory, in mechanical testing of geomaterials time is often traded for temperature. However, the validity of this assumption is still to be tested.

Recently, tri-axial compression experiments on oriented single crystals of San Carlos olivine were performed at tempera-