High-pressure, high-temperature deformation of dunite, eclogite, clinopyroxenite and garnetite using in situ X-ray diffraction

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A B S T R A C T

The rheology of eclogite, garnetite and clinopyroxenite in the peridotitic upper mantle was experimentally investigated in a large volume press combined with *in situ* synchrotron X-ray diffraction techniques to study the impact on mantle convection resulting from the subduction of oceanic lithosphere. Experiments were carried out over a range of constant strain rates (2×10^{-6}–3×10^{-5} s^{-1}), pressures (4.3 to 6.7 GPa) and temperatures (1050 to 1470 K). Results show substantial strength variations among eclogitic garnet and clinopyroxene and peridotitic olivine. At low temperatures ($<$1200 K), eclogite is over 1 GPa stronger than dunite. On the other hand, at high temperatures ($>$1400 K) eclogite is weaker than dunite by 0.2 GPa or more. Garnetite and clinopyroxenite exhibit higher strength than dunite at approximately 1200 K. However, at higher temperature (1370 K), clinopyroxenite is significantly weaker than garnetite (and dunite) by more than a factor of five. We explain these observations by transitions in deformation mechanisms among the mineral phases. In clinopyroxene, high temperature dislocation creep resulting in a strength reduction replaces low temperature twinning. Whereas garnet remains very rigid at all experimental conditions when nominally anhydrous ('dry'). Microstructural observations show phase segregation of clinopyroxene and garnet, development of a crystallographic and shape preferred orientation in the former but not in the latter, suggesting an overall weak seismic anisotropy. Detection of eclogite bodies in the peridotite-dominated mantle may only be possible via observation of high V_P/V_{S1} ratios. A comparable or weaker rheology of eclogite to dunite suggests effective stirring and mixing of eclogite in the convecting mantle.

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One sentence summary

We performed, for the first time, quantitative deformation experiments on eclogite, garnetite, clinopyroxenite and dunite up to pressures up to 6.7 GPa, at 1050 to 1470 K and various constant strain rates (2×10^{-6}–3×10^{-5} s^{-1}) to evaluate the effects of the viscosity contrasts of these mantle materials on large-scale deep Earth mantle processes such as subduction and convection, essential to improve our understanding of mantle dynamics and seismic observations.

1. Introduction

The transformation of oceanic crust and mafic cumulates to eclogite assemblages composed of clinopyroxene and garnet with minor accessory phases such as rutile, quartz, coesite/stishovite, kyanite, and orthopyroxene has important significance for the recycling processes in the mantle and the creation of chemical and lithological heterogeneities (Allègre and Turcotte, 1986; Hofmann et al., 2003; Pearson and Nowell, 2004). Due to slow rates of chemical diffusion, eclogitic bodies have been proposed to remain distinct in the mantle (van Mierlo et al., 2013) and may even be recycled into the sources of mantle derived magmas (Hirschmann and Stolper, 1996; Hofmann et al., 2003; Pearson and Nowell, 2004; Sobolev et al., 2007). The rheology of such heterogeneities particularly in comparison to the surrounding peridotite mantle may be chiefly important for their survival and potentially for their accu-

mulation (e.g. Allègre and Turcotte, 1986). If eclogitic layers are soft and deformable they may be stretched and thinned to length scales where they can be homogenised by diffusion. Alternatively, it has been proposed that given suitable rheological contrast, subducted mafic crust might separate from underlying peridotite via mechanisms of strain localization and accumulate in the upper mantle or transition zone (Lee and Chen, 2007).

Following the model established in previous studies (Spandler et al., 2008; Rosenthal et al., 2014), subducted slabs may suffer suspension by approaching thermal equilibrium with ambient mantle, resulting in subsequent upwelling and partial melting of recycled eclogite and its residues along adiabatic upwelling paths. Exhumation of eclogite bodies in orogenic peridotite massifs from ~100 km depth can be found in localities such as in Norway (Fountain et al., 1994; Renedo et al., 2015), the European alps (Angiboust et al., 2012), and China (Shi et al., 2010), which are unequivocally deformed and typically well-foliated. They are characterized by cm- to m-scale alternating interlayers of garnet lherzolite to dunite, a wide range of garnet-free to garnet-bearing clinopyroxenites, garnetites, wehrlites, websterites, granulites, and eclogites. However, from greater depths/pressures no direct information is available on the mechanical behaviour of discrete units of eclogite, pyroxenites and garnetites in the ambient olivine-rich residual to refractory peridotitic mantle. Note that the diverse compositional variation of eclogite and corresponding properties not only influences rheology, but also assist in the study of the mantle in many other diverse ways to understand deep subduction dynamics (>100 km) (Ducea and Saleeby, 1998; Angiboust et al., 2012; Beyer et al., 2015 and references therein).

To date, only a few pioneering studies have investigated the rheology of eclogite and its mineral constituents and these are limited to a narrow pressure range of 2.5–3.5 GPa (~80–110 km depth) using the Griggs deformation apparatus (Jin et al., 2001; Zhang et al., 2006; Zhang and Green, 2007). These experimental determinations have demonstrated that a reconstituted eclogite composition (50 vol.% garnet, 40 vol.% clinopyroxene, and 10 vol.% quartz) has similar flow properties as peridotite, yet flow stress strongly increases within 1 GPa of increasing pressure (from 2.5 to 3.5 GPa) (Zhang and Green, 2007). Additionally, at 3 GPa, garnetite is shown to be only 2–3 times stronger than harzburgite (Jin et al., 2001). Hence, further work is necessary to investigate the rheology of nominally 'dry' eclogite under a wider range of pressure, temperature, and strain rate conditions without a significant fraction of secondary phases (e.g. 10% quartz), which accumulate substantial strain and are not in high abundance in eclogite in the deep mantle (Ji, 2002 and references therein).

Here, residual eclogite (containing <2 wt.% coesite), eclogitic garnetite and clinopyroxenite as well as dunite samples were deformed under a range of controlled conditions of strain rate $(2 \times 10^{-6}$–3×10^{-5} s$^{-1})$, pressure (4.3–6.7 GPa) and temperature (1050–1470 K). The rock samples are called residual because maximum excess SiO$_2$ is removed (via partial melting). Also, fewer phases help to reduce the complexity of interpreting stress and strain partitioning in the rock samples. The model presented by Rosenthal et al. (2014) assumes the preservation of intrinsic ancient and modern eclogitic heterogeneities in peridotite-dominated convecting mantle on cm to km scales. Hence, the experiments are designed to investigate the consequences of this heterogeneity and the rheological variation that could be exhibited by subducted crustal material in the convecting mantle. For example, short- and long-term preservation of enriched mantle components within both the convecting asthenospheric and rigid lithosphere has been frequently proposed (e.g. Nowell et al., 2004).

2. Experimental procedure

2.1. Choice and preparation of starting compositions

The starting materials in this study are based on a model of an average altered mid-oceanic ridge basalt (MORB) (GA2, Spandler et al., 2008), a significant component of subducting oceanic crustal material. In order to obtain a bimineralic eclogite (or eclogite with a low abundance of secondary minerals), we calculated a residual composition with as much excess SiO$_2$ removed as possible. The new starting material (REC100) is thus calculated as a residual eclogite (residual garnet and clinopyroxene only) after loss of ~46% basaltic andesite melt fraction from GA2 at 5 GPa and 1773 K (i.e. above coesite-out) during adiabatic ascent (run #MH31 of Spandler et al., 2008). The REC100 bulk compositions were synthesised in the multianvil apparatus into eclogite at the Bayerisches Geoinstitut, University of Bayreuth (BGI) at 5 GPa and 1433–1513 K and at long run durations (up to 120 h) to ensure that chemical and textural equilibrium of the eclogitic rock was reached (Table A.1 and Supplementary Materials). Some starting materials contained a melt fraction in the rim closest to the graphite furnace where the temperature is hottest. These melt-bearing regions were excluded when coring smaller diameter samples for deformation experiments.

Similarly, the compositions of the garnet and clinopyroxene of residual garnetite and clinopyroxenite, respectively, are derived from the melt residue of REC100 at 5 GPa and 1470 K after 2.3% extraction of a dacitic melt (run #Z1336, see Table A.1). Therefore, the garnet and clinopyroxene solid solutions in the garnetite and clinopyroxenite are very similar to the residual garnet and clinopyroxene of REC100 (this study), and therefore of MH31 (Spandler et al., 2008). The respective oxide bulk starting mixtures are synthesised into garnetite and clinopyroxenite at 5 GPa and 1433–1473 K using the same multianvil apparatus (Table A.1). Although, the eclogite, clinopyroxenite and garnetite samples should be classified as 'residual', from this point forward we refer to the samples without this classification.

Polycrystalline dunite samples were prepared from natural San Carlos olivine, as follows. Optical impurity-free grains were hand-picked, crushed and sieved to obtain a grain size fraction up to 60 μm. The smallest grain size fraction of <3 μm was removed by ethanol suspension. The olivine powders were sintered into polycrystalline aggregates representative of dunite at 0.7 and 1.0 GPa and 1523–1573 K for 17 h using the piston cylinder apparatus at BGI (Table A.1).

2.2. Deformation experiments

We carried out deformation experiments at the ID06 beam line of the European Synchrotron Radiation Facility (ESRF) in Grenoble, France using the 20 MN Voggenreiter LPO 2000-1000/200 press (Guignard and Crichton, 2015). Preparation procedures for deformation experiments are described in the Supplementary Materials and in Fig. A.1. We used the following methods for carrying out deformation experiments. The prepared cubic assemblies $(9 \times 9.2 \times 9.2$ mm), composed of B-epoxy, a graphite heater and inner h-BN sleeves with samples and crushable alumina pistons inside, were loaded between 6 first-stage anvils with 6 mm truncations. Two adjacent downstream anvils of Co-doped sintered diamond, with carbide supporting rings, were used to widen the exit window for X-ray diffraction. We compressed each sample assembly for 2 h to reach the target oil pressure/press load previously calibrated at 5 GPa. The assembly pressure was checked at room temperature based on a calibration of hBN (Le Godec et al., 2000). Once at pressure, we incrementally heated the sample to a given power by routinely checking the temperature and pressure using