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Low-temperature plasticity of olivine during high stress deformation of peridotite at lithospheric conditions — An experimental study

Anthony Druiventak *, Claudia A. Trepmann [1], Jörg Renner, Karin Hanke

Ruhr-Universität Bochum, Institut für Geologie, Mineralogie und Geophysik, Universitätsstraße 150, Sonderforschungsbereich 526, D-44801 Bochum, Germany

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A B S T R A C T

Deformation experiments on natural peridotite from the Almklovdalen complex, Norway, were carried out in a Griggs-type apparatus at temperatures of 20, 300, and 600 °C, confining pressures of 1.0 to 2.5 GPa, and strain rates of $3 \cdot 10^{-6}$ to $8 \cdot 10^{-5}\ s^{-1}$. The experiments yield maximum differential stresses in the range of 1.0 to 2.9 GPa falling mostly between Byerlee's law and Goetze's criterion and thus indicating semi-brittle behaviour. Whereas strength of samples deformed at 20 °C increases significantly with increasing confining pressure, a systematic pressure-dependence of strength is not obvious at 300 and 600 °C. The intracrystalline deformation features of the main constituent olivine were analysed by light and electron microscopic techniques (SEM/EBSD, TEM). Deformation microstructures systematically vary with temperature, but are insensitive to confining pressure. Samples deformed at 20 °C reflect predominantly brittle failure by intragranular microcracks and shear zones. Microstructures from samples deformed at higher temperatures show evidence of low-temperature plasticity of olivine in the form of pronounced undulatory extinction associated with high dislocation densities. Pile-up of dislocations leads to the formation of either fracture arrays at 300 °C or deformation lamellae parallel (100) and cellular structures at 600 °C, indicating intragranular work hardening. A gradual increase in glide-controlled crystal–plastic deformation of olivine at increasing temperature is interpreted to be responsible for the variation in mechanical behaviour and microstructural characteristics. The mechanical data and microstructural observations consistently suggest a temperature for the transition from the strength-controlling dominance of brittle to crystal–plastic deformation mechanisms close to 600 °C. The tested peridotite samples show a lower strength than quartzite samples at comparable experimental conditions, possibly related to crystallographic differences of olivine and quartz. The agreement between microfabrics of experimentally and naturally deformed peridotites demonstrates the importance of low-temperature plasticity of olivine during high-stress deformation at lithospheric conditions related in particular to seismic activity in the mantle.

1. Introduction

The oceanic lithosphere is generally considered to have a fairly simple composition compared to continental lithosphere. When formed at mid-ocean ridges, the volumetrically lesser part, oceanic crust, is originally composed of basaltic rocks that overlie depleted peridotites, i.e., aggregates dominated by the mineral olivine containing also some orthopyroxene. Subsequent serpentinisation due to water circulation may alter oceanic lithosphere, though, with a significant effect on elastic (Kern et al., 1997) and inelastic (Escartin et al., 2001) properties. In the oceanic lithosphere, earthquake hypocentres in the upper mantle are apparently limited by the 600 °C isotherm (Abercrombie and Ekström, 2003; Boettcher et al., 2007; McKenzie et al., 2005; Wilcock et al., 1990). The occurrence of pseudotachylytes and related high-stress crystal-plastic deformation in peridotite give microstructural evidence of earthquake-driven deformation in mantle rocks at lithospheric conditions (Andersen and Austrheim, 2006; Obata and Karato, 1995; Souquière and Fabbri, 2010; Ueda et al., 2008).

The nucleation of an earthquake requires instability in frictional sliding on a pre-existent or evolving fault plane. In agreement with the depth distribution of earthquake hypocentres, experiments on olivine-gouge indicate that the 600 °C-isotherm limits the occurrence of stick–slip, i.e., unstable sliding (Boettcher et al., 2007). Previous studies on the deformation behaviour of peridotite, however, leave a distinct gap in pressure–temperature space corresponding to lithospheric conditions. Compressive strength of natural rocks is reported from experiments at room temperature and confining pressures up to 3 GPa (Byerlee, 1968; Escartin et al., 2001; Shimada et al., 1983). Crystal–plastic deformation of olivine single crystals was investigated at temperatures up to 1500 °C

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* Corresponding author.
E-mail addresses: anthony.druiventak@rub.de, anthony.druiventak@koeln.de (A. Druiventak), claudia.trepmann@lmu.de (C.A. Trepmann), joerg.renner@rub.de (J. Renner), karin.hanke@rub.de (K. Hanke).

[1] Present address: Ludwig-Maximilians-Universität München, Department für Geo- und Umweltwissenschaften, Luisenstraße 37, D-80333 München, Germany.

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by constant load tests at ambient pressure (Bai and Kohlstedt, 1992) and indentation tests (Dorner, 2002; Evans and Goetze, 1979; Gaboriaud et al., 1981). Natural and synthetic polycrystalline aggregates composed dominantly of olivine were deformed in conventional triaxial tests at pressures of 0.3 to 2 GPa and temperatures of 300 to 1400 °C (Blacic and Christie, 1973; Boettcher et al., 2007; Chopra and Paterson, 1981; Demouchy et al., 2009; Katayama and Karato, 2008; Phakey et al., 1972; Raleigh, 1968). In addition, Raterron et al. (2004) performed relaxation experiments on cold pressed and sintered San-Carlos olivine powder in a cubic-anvil apparatus at pressures up to 9 GPa. Mei et al. (2010) conducted experiments at pressures of 4 to 9 GPa and temperatures of 400 to 1000 °C on anhydrous polycrystalline olivine using a deformation-DIA.

The correlation between the occurrence and absence of seismic activity and the temperature distribution in oceanic lithosphere strongly suggests a temperature-controlled change in deformation mode from brittle faulting to plastic flow. The transition from seismic to aseismic behaviour likely occurs just before the maximum lithospheric differential stresses are reached, at the transition from the brittle to the semi-brittle regime (e.g., Kohlstedt et al., 1995; Scholz, 2002). Two simple relations have proven reliable and valuable for the delineation of brittle, semi-brittle, and plastic deformation regimes: Byerlee's law, indicating frictional strength on pre-existing fault planes (Byerlee, 1978), and Goetze's criterion, predicting that plastic flow occurs when strength as expressed by differential stress falls below confining pressure (Evans and Kohlstedt, 1995). Failure strength is found to be scale-dependent (e.g., Lockner, 1995) and thus laboratory constraints on small samples provide upper bounds for in-situ strength. In contrast, friction characteristics are considered scale-independent (Byerlee, 1978). Furthermore, the scale dependence is expected to diminish with increasing contribution of grain-scale plasticity to yield.

The objective of our study is to constrain the high-stress deformation behaviour of peridotites at lithospheric conditions and to investigate the associated strength-controlling deformation mechanisms at grain scale. While the occurrence of an instability requires strain or velocity softening, the prime pre-requisite for an earthquake is that actual stresses are high in a relative sense, i.e., that they reach the strength of the involved rocks. Thus, the mechanical behaviour of peridotite at maximum possible stresses is especially relevant for understanding deformation associated with seismic activity in the mantle, e.g. during oceanic intraplate earthquakes and earthquakes in downgoing slabs or in the mantle wedge of subduction zones. Well founded constraints on maximum stresses ultimately also improve thermal models for oceanic lithosphere (Behn et al., 2007).

2. Experimental and analytical methods

2.1. Deformation experiments

Triaxial deformation experiments were performed in a servohydraulically-controlled solid-medium Griggs-type deformation apparatus (Griggs, 1967; Rybacki et al., 1998) and at 20, 300, and 600 °C, nominal confining pressures of 1.0 to 2.5 GPa, and strain rates of $3 \cdot 10^{-6}$ to $8 \cdot 10^{-5}\,\mathrm{s}^{-1}$. Cylindrical samples with a diameter of 3.3 mm and a length of 7 to 8 mm were prepared from natural peridotite. The majority of samples were drilled with the cylinder axis parallel to the foliation; three samples were drilled normal to the foliation (Table 1). Samples were dried in a furnace at 150 °C and jacketed by a mechanically sealed gold capsule before mechanical testing. The confining pressure is generated by a hydraulic ram driving a piston into the vessel and is transmitted to the sample by a weak solid. For experiments at 20 °C, the entire assembly in the vessel consists of tin. In experiments at 300 and 600 °C, NaCl served as confining medium within an assembly comprising a graphite furnace (see Moghadam et al., 2010). Two Ni–CrNi thermocouples are placed parallel to the sample in a pyrophyllite tube, at the upper and lower ends of the sample for controlling and measuring the temperature inside the graphite furnace. Apart from few exceptions, the readings of the two thermocouples differ by less than 5% (Table 1). The oil pressure inside the hydraulic ram, the axial load and the axial displacement are digitally recorded by two external displacement transducers and an external load cell, respectively. Reported confining pressure values constitute nominal values calculated

Table 1

Assembly and sample characteristics, experimental conditions, and results of performed deformation experiments. *piston specifications*: TC = one-piece piston made of tungsten carbide (length 67.0 mm); $\mathrm{TCAl_{23}}$ = two-piece piston made of tungsten carbide (length 50 mm) and AL23 (length 16 mm), diameter given in square brackets; *sample parameters*: L_0 = sample length before deformation; D_0 = sample diameter before deformation; *deformation conditions*: T_c = thermo-element at the upper end of the sample assembly for controlling of the temperature; T_m = thermo-element at the lower end of the sample assembly for measuring of the temperature; P_c = confining pressure; SR = strain rate; $\Delta\sigma_{max}$ = maximum differential stress; ε_{max} = maximum strain (total elastic and inelastic strain) (*note: samples normal to foliation).

Sample number	Piston	L_0 (mm)	D_0 (mm)	T_c (°C)	T_m (°C)	P_c (GPa)	SR (s^{-1})	$\Delta\sigma_{max}$ (GPa)	ε_{max} (%)
KH03	TC [4.7 mm]	8.52	3.28	20	20	1.5	$2.8 \cdot 10^{-5}$	2.29	19
KH04	TC [4.7 mm]	8.52	3.28	20	20	2.5	$1.8 \cdot 10^{-5}$	2.86	25
KH06	$\mathrm{TCAl_{23}}$ [4.7 mm]	6.82	3.28	601	592	1.0	$3.0 \cdot 10^{-5}$	1.43	26
KH07	$\mathrm{TCAl_{23}}$ [4.7 mm]	6.82	3.28	591	559	1.5	$3.0 \cdot 10^{-5}$	1.22	25
KH08	$\mathrm{TCAl_{23}}$ [4.7 mm]	6.82	3.28	301	221	1.0	$3.0 \cdot 10^{-5}$	1.36	22
KH09	$\mathrm{TCAl_{23}}$ [4.7 mm]	6.82	3.28	301	296	1.5	$2.7 \cdot 10^{-5}$	1.50	25
KH10	$\mathrm{TCAl_{23}}$ [4.7 mm]	6.82	3.28	601	587	1.0	$2.9 \cdot 10^{-6}$	1.85	35
KH12	TC [5.0 mm]	6.82	3.28	20	20	1.0	$3.1 \cdot 10^{-5}$	2.22	23
KH13	TC [5.0 mm]	6.82	3.28	20	20	1.0	$3.2 \cdot 10^{-5}$	1.90	15
KH14	TC [5.0 mm]	6.82	3.28	20	20	1.5	$3.0 \cdot 10^{-5}$	2.03	16
KH15	TC [5.0 mm]	6.79	3.28	20	20	2.0	$3.1 \cdot 10^{-5}$	2.46	20
KH16	TC [5.0 mm]	6.79	3.28	20	20	1.0	$3.0 \cdot 10^{-5}$	2.18	30
KH17	TC [5.0 mm]	6.79	3.28	260	326	1.0	$3.0 \cdot 10^{-5}$	1.61	25
KH19	TC [5.0 mm]	6.79	3.28	301	293	2.0	$2.9 \cdot 10^{-5}$	1.49	20
AD01	TC [5.0 mm]	6.80	3.25	20	20	2.0	$6.3 \cdot 10^{-5}$	2.52	19
AD02	TC [5.0 mm]	6.75	3.27	300	285	2.0	$5.8 \cdot 10^{-5}$	1.62	8
AD03	TC [5.0 mm]	6.79	3.29	594	645	1.0	$8.2 \cdot 10^{-5}$	0.99	18
AD04	TC [5.0 mm]	6.68	3.27	601	602	2.0	$7.8 \cdot 10^{-5}$	1.45	22
AD07	TC [5.0 mm]	6.74	3.31	300	311	1.5	$7.0 \cdot 10^{-5}$	1.62	21
AD09	TC [5.0 mm]	6.83	3.30	301	316	1.5	$7.4 \cdot 10^{-5}$	1.46	23
AD10	TC [5.0 mm]	6.80	3.31	602	625	1.5	$7.6 \cdot 10^{-5}$	1.30	28
AD11	TC [5.0 mm]	6.79	3.32	20	20	1.5	$8.5 \cdot 10^{-5}$	2.22	22
B9001*	TC [5.0 mm]	6.81	3.31	601	613	1.0	$8.5 \cdot 10^{-5}$	1.07	19
B9009*	$\mathrm{TCAl_{23}}$ [5.0 mm]	6.78	3.31	599	592	1.0	$7.9 \cdot 10^{-5}$	1.29	24
B9011*	$\mathrm{TCAl_{23}}$ [5.0 mm]	6.81	3.29	601	625	2.0	$7.8 \cdot 10^{-5}$	1.36	22