

Textures in experimentally deformed olivine aggregates: the effects of added water and melt.

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Abstract. The texture development in experimentally sheared aggregates of olivine was monitored as a function of increased water content and added melt. In dry samples, an alignment of {010} with the shear plane and <100> and <001> with the shear direction, respectively, was observed, consistent with intracrystalline glide on the (010)[100] and (010)[001] slip systems. Samples with high water content showed consistently stronger textures of the (010)[100] component for comparable shear strains indicating that water may especially ease glide on this slip system. Samples with added melt showed an increased alignment of {010} and <001> subparallel to shear plane and shear direction respectively, whereby the maxima were consistently rotated 10 to 20° against the sense of shear. This type of texture can be explained by a combination of increased glide on the (010)[001] slip system in combination with a partitioning of the strain between melt rich bands and relatively melt free regions in the sample. Physical anisotropies calculated from the textures indicate that increased water content causes enhanced anisotropy for longitudinal and transverse seismic waves. The addition of melt on the other hand may change the type of anisotropy that develops during deformation, but does not significantly change the magnitude of anisotropy compared to samples of pure olivine.

Introduction

Olivine ((Mg,Fe)₂SiO₄, orthorhombic crystal symmetry) is the dominant mineral in the upper mantle of the Earth (30 to 410km depth). Its rheological behaviour is crucial for the understanding of the deformation processes at a depth, where convective flow of the mantle is coupled to the movement of the lithospheric plates that constitute the uppermost 100 km of the Earth. The development of texture and consequently anisotropy of physical parameters during plastic deformation of olivine is of special interest since they can be directly compared to geophysical observations of seismic wave velocities of these rocks at depth [1]. The crystallographic *a* direction corresponds both to the shortest Burgers vector of the olivine structure as well as the fast propagation direction of the compressional (*p*) seismic waves. The {010} plane constitutes the dominant slip plane and, at the same time, is the plane containing the largest shear wave splitting. A strong alignment of the {010}<100> slip system parallel to the shear plane and shear direction respectively, leads to a strong seismic anisotropy for compressional and shear (*s*) waves. Observed anisotropy patterns in the upper mantle can then be interpreted in terms of deformation geometry and plastic flow, e.g. [2]. This simple picture may however be complicated by factors such as varying water contents or an additional melt phase (among others). In this study we explore experimentally the influence of these factors on the texture development and consequently on the formation of physical anisotropy.

Experimental

Deformation tests. We have performed a series of deformation experiments in a HT-HP gas medium testing apparatus ('Paterson rig'). The starting material for the samples was prepared by hot pressing powders of San Carlos olivine at 1523 K and 300 MPa. The average duration of the hot press runs were 4 - 6 hours and the samples had <1 vol% porosity after hot press. For wet samples with increased water content ('wet'), free water was added before hot pressing, and for samples with added melt, powders of a melt phase of basaltic composition (MORB) of 1 μm size were added at different amounts (2 to 12%) and intimately mixed with the olivine powders. The grain size of olivine was about 10 μm after hot pressing for both types. The deformation samples in form of 600 – 800 μm thick discs were cut from a cylindrical shaped hot pressed sample. The discs were then shaped to ellipses with 6.3 mm minor radius and 8.4 mm major radius. One disc was used for each deformation experiment. Each disc was cut into two halves along the minor axis and a thin Ni foil strain marker was placed between the halves. The disc and the strain marker were placed between two cylindrical thoriated W pistons cut at an angle of 45° to the axis of the cylinder. The ends of the pistons were grooved in order to avoid slippage between the sample disc and the pistons. Constant load deformation experiments were carried out at 1523 K and 300 MPa. The internal load was calculated such that shear stresses in the sample ranged from 30 to 180 MPa. These shear stresses were high enough to deform the samples in the dislocation creep regime (with a stress exponent of about 3). Shear strains of up to 4.6 were reached. The shear strains were derived both from the rotation of the Ni strain marker as well as the displacement of the pistons.

Texture analysis. Lattice preferred orientations (LPOs) were analyzed with electron backscattering diffraction (EBSD) in the scanning electron microscope (SEM). The SEM was a Leo 1530 with a Schottky-Emitter and was operated at an accelerating voltage of 20keV and a beam current of 4nA (120 μm aperture). The working distance was about 20mm. EBSD patterns were analyzed online and fully automatic with the Channel 5 software by HKL Technology. After standard polishing the samples were additionally polished with a high pH silica solution (particle size 40nm) in order to remove surface damage from the previous polishing steps. Finally the samples were coated with 3 to 4 nm of carbon in order to remove charging. To measure the bulk texture, the samples were measured completely in 10 or 20 μm steps. Due to the small grain size, additional phases (melt, chromite) and difficulties with the preparation of the sample (thin soft sample between two very hard pistons) hit rates were relatively low (20 to 30%). The resulting pole figures were smoothed with a Gaussian of 15° FWHM.

Calculation of seismic anisotropies. The seismic anisotropies were calculated directly from the single crystal orientation data employing the Voigt-Reuss-Hill averaging scheme as implemented in the petrophysics software by D. Mainprice [3]. The single crystal elastic parameters of olivine are for ambient conditions and a density of 3.355 g/cm³ was used in the calculations.

Results

Dry sample. The texture in the dry sample (Fig. 1) is characterized by the alignment of {010} planes parallel to the shear plane and by <100> and <001> forming girdles in the shear plane. The maximum of {010} as well as the girdles of <100> and <001> are slightly rotated against the sense of shear.

Water content. All wet samples show a strong alignment of {010} with the shear plane and an even stronger alignment of <100> along the shear direction. A small sub-maximum of <001> in the shear direction is also discernible. The strength of the preferred orientation, measured by multiples of uniform density (m.u.d.) contour shows a steady increase with increasing shear strain (Fig. 1). Most strikingly, the strengths of the LPOs in the wet samples are much higher compared to the dry sample at similar shear strain.

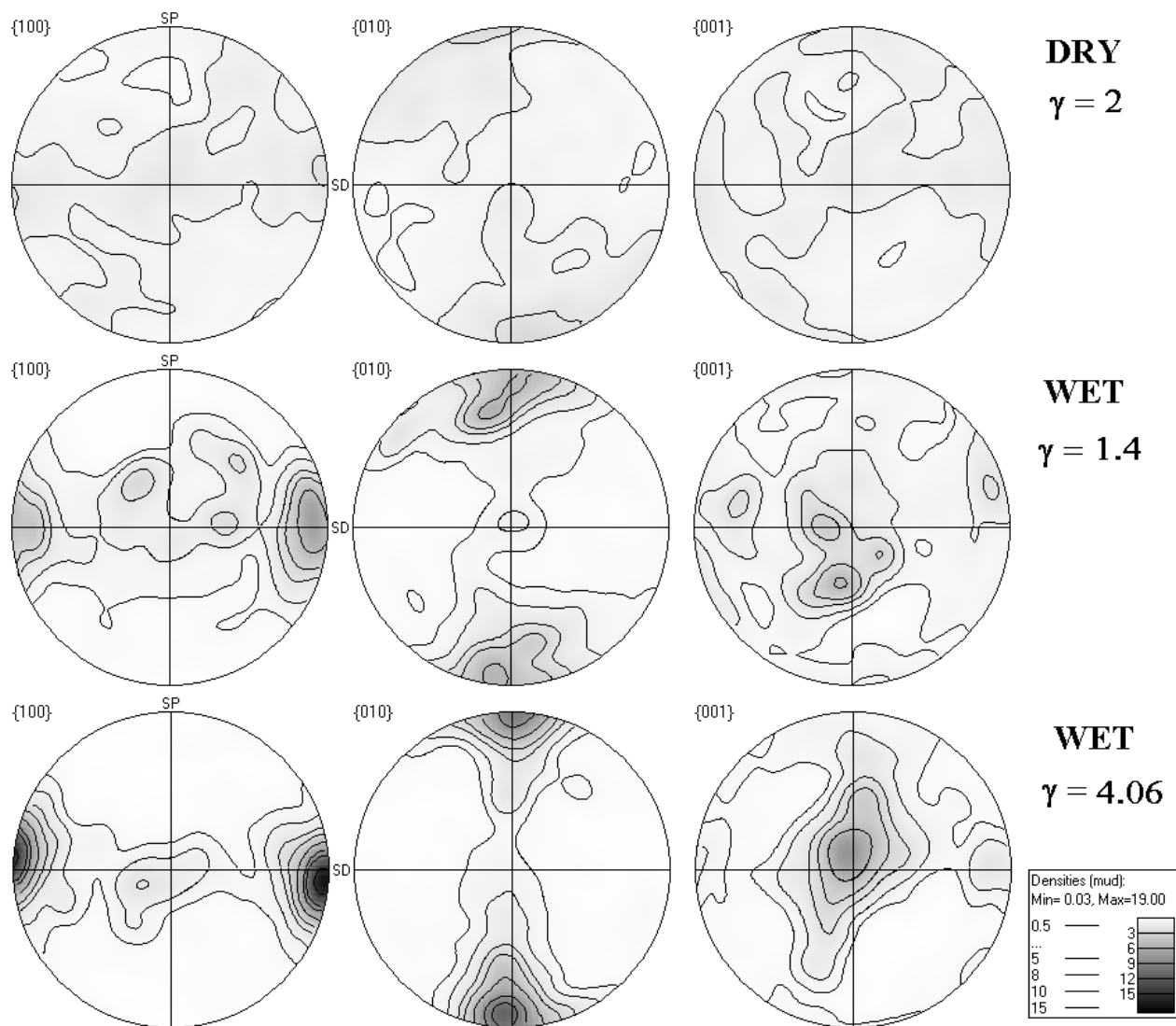
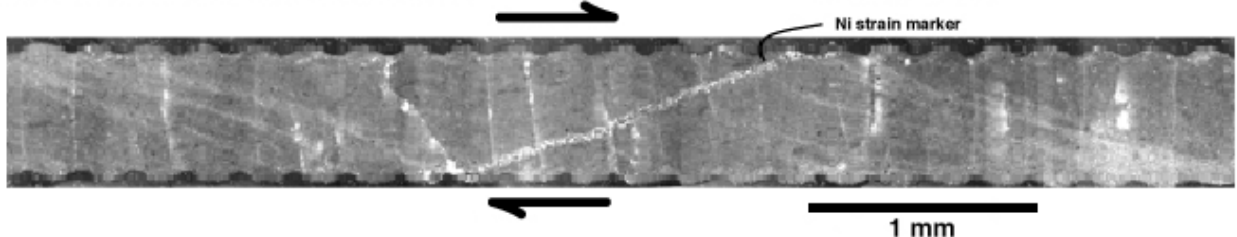


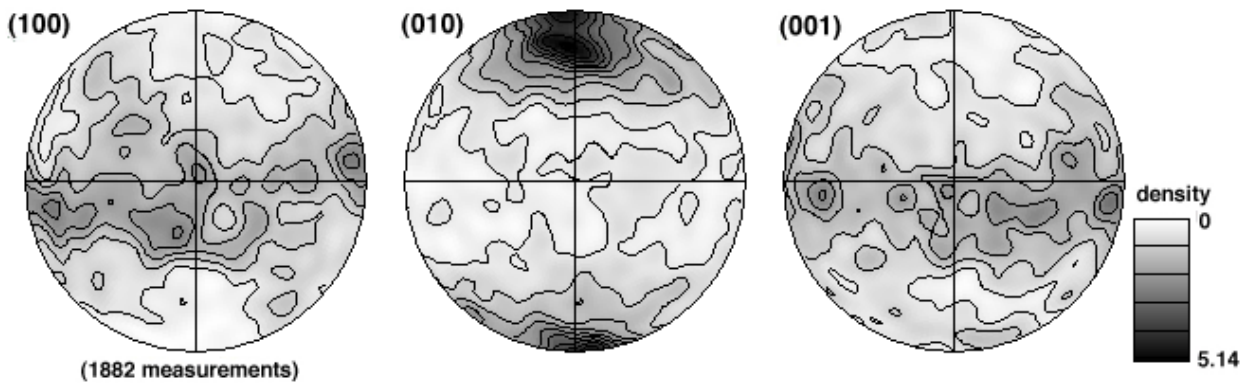
Figure 1: LPOs of deformed olivine aggregates without ('dry') and with added water ('wet'). SP indicates the pole of the horizontal shear plane and SD the shear direction. Shear sense is dextral and the projection is onto the lower hemisphere.

Added melt. In the olivine + MORB system, an applied deviatoric stress causes melt pockets to align at about 20° to the principle compressive stress. The texture in these samples shows an alignment of $\{010\}$ planes parallel to the shear plane and girdles of $\langle 100 \rangle$ and $\langle 001 \rangle$ in the shear plane (Fig. 2b). In the samples with additional chromite, the melt segregates into melt-rich bands at least several grains wide, separated by melt-poor regions. These bands form consistently at about 20° to the shear plane (sample walls), as illustrated in Figure 2a. Samples with this type of melt structure show an alignment of $\{010\}$ and $\langle 001 \rangle$ subparallel to shear plane and shear direction respectively, whereby the maxima were consistently rotated 10 to 20° against the sense of shear (Fig. 2b). This pattern does not change significantly with increasing shear strain.

a. olivine + chromite + 2 vol% MORB



b. olivine + 3 vol% MORB, no bands



c. olivine + chromite + 2 vol% MORB, bands present

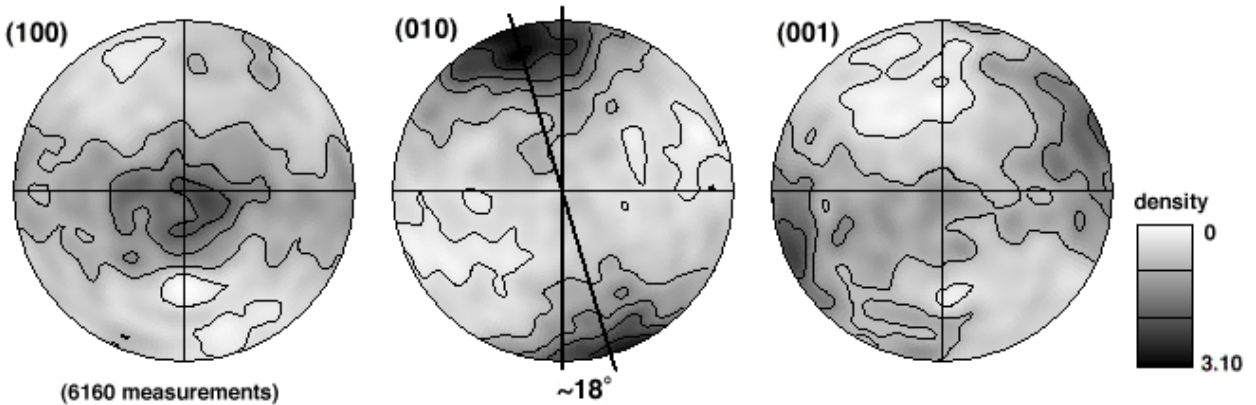


Figure 2: a) SEM micrograph of sheared sample of olivine + chromite + MORB; b) and c) olivine pole figures of sheared samples without melt bands (b) and with melt bands (c). Projection in b) and c) is the same as in Figure 1.

Seismic anisotropy. The strongest anisotropies for both p- and s-waves are produced by the highly textured wet olivine samples (Fig. 3b). The fastest p-waves for this sample travel in the shear direction and the slowest perpendicular to the shear plane. The strongest s-wave splitting lies in the shear plane, but also perpendicular to it it reaches 6 to 7%. For both the dry sample and the sample with melt bands (Fig. 3a and c), anisotropies are much lower since the LPO is not as strong. For those samples, anisotropies look quite similar, except that the fastest p-wave direction in the sample with melt bands is perpendicular to the shear direction whereas in the dry sample it is still near the shear direction.

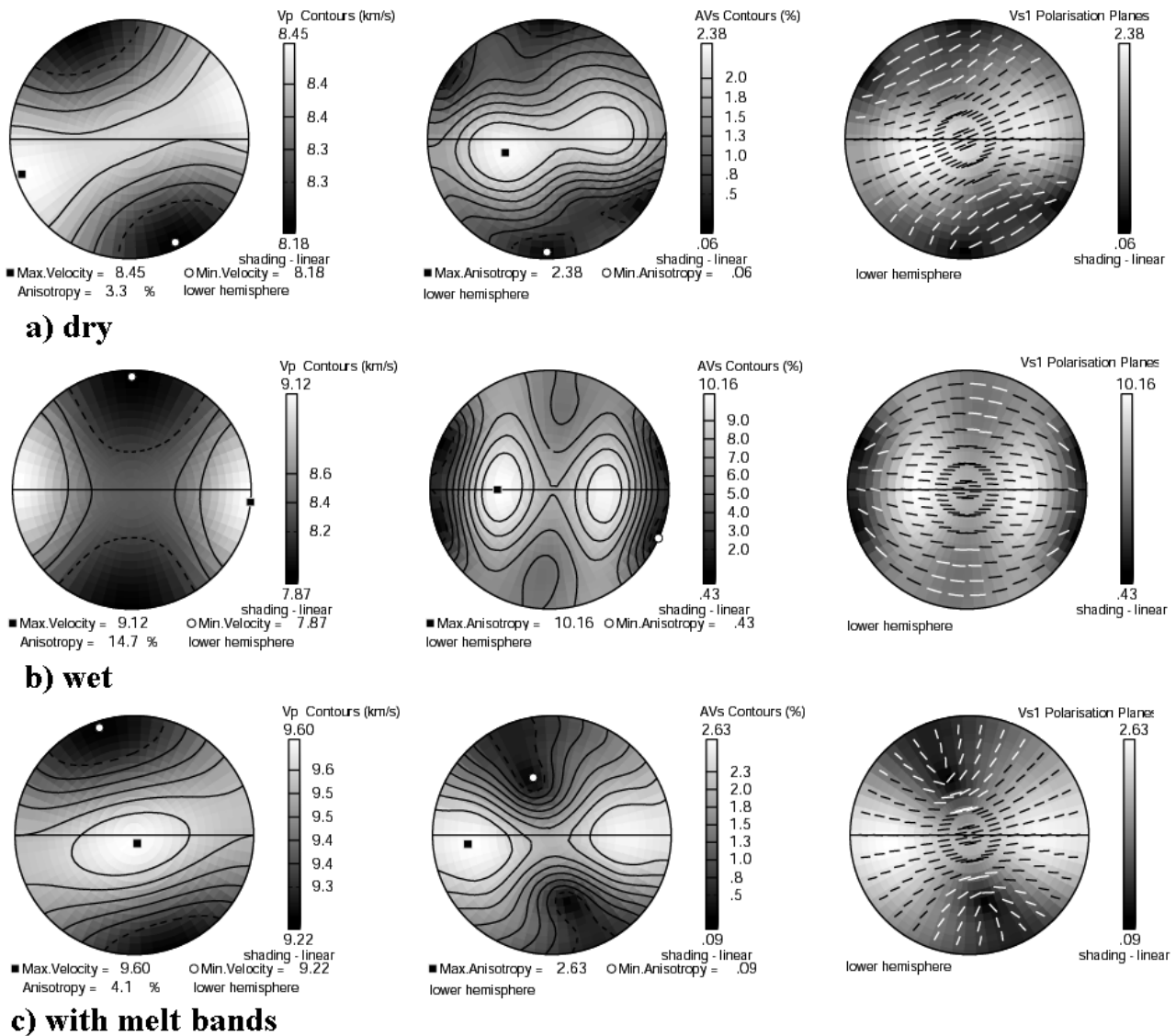


Figure 3: Calculated seismic anisotropies for olivine aggregates deformed dry (a), wet (b) and with an additional melt phase. Projection is the same as in Figure 1.

Discussion

The texture of the dry sample indicates that both **a** and **c** slip on the $\{010\}$ plane were active during deformation. The stresses were high enough to activate the harder $(010)[001]$ slip system in addition to the softer $(010)[100]$ slip system. The slight rotation of the LPO relative to the shear plane and shear direction is likely due to the relatively low shear strain.

For the samples with increased water content, we interpret the LPOs as a result of dislocation creep on the $(010)[100]$ slip system with a minor component of slip on $\{010\}\langle 001 \rangle$. Slip on $(010)[100]$ seems to increase dramatically relative to the dry sample indicating that water may especially soften this system resulting in a very strong alignment of this slip system with the shear plane and shear direction, already at relatively low shear strains.

The texture in the melt bearing samples can be explained by a combination of increased glide on the $(010)[001]$ slip system with a partitioning of the strain between melt rich bands and relatively melt free regions in the sample [4]. We have found that we can predict the occurrence of melt band formation by looking at the initial compaction lengths of the samples, which is a function of the

sample permeability and the solid and fluid viscosities. When this length scale is approximately equal to the thickness of the sample, then bands form, as is the case for all samples described above, except olivine + MORB alone. When the compaction length is longer than the sample thickness, as in the olivine + MORB, then the melt segregation does not occur. When the melt segregates, the strain also partitions in the sample between the bands (weak) and the non-band regions (strong). Based on the kinked geometry of the Ni-foil strain marker placed between two halves of the sample before an experiment (Fig. 2a), we inferred that the strain partitions into the bands. This observation lead to a simple prediction that the shear plane recorded in the olivine LPO will be rotated relative to the shear plane, unlike that in a sample without shear bands. We tested this prediction using the EBSD measuring olivine LPOs (lattice preferred orientations) in samples of olivine + chromite + MORB and olivine + MORB. The predicted rotation of the shear plane in the non-band regions, recorded in the (010) poles, appeared exactly as this rotation in the samples with bands (with chromite) relative to the olivine + MORB, in which the shear plane was parallel to the sample walls.

The strong alignment in the wet samples causes also a stronger anisotropy of physical properties such as seismic wave speeds. From our observations, we suggest that the anisotropy will be stronger in water rich regions of the flowing mantle than in the dry regions. The mantle wedge beneath volcanic arcs is probably a good example of such a wet region. The mantle deforms by the corner flow and water is released from the nominally hydrous minerals in the subducted oceanic crust beneath. Spatial variations of degree of anisotropy in this environment can therefore be at least partially due to spatial variations in water content.

The pattern of seismic anisotropy in the samples with melt bands shows a qualitative difference relative to the other samples (dry and wet): the direction of fast p-waves is perpendicular to the shear direction. This unusual pattern may possibly help to explain seismic anisotropies in regions of the mantle where partial melts are likely to occur, e.g. at mid-ocean ridges and mantle wedges above subduction zones.

Summary

We have performed deformation experiments of olivine aggregates under dry and wet conditions as well as with an added melt phase and at different stress levels. All samples deformed in the dislocation creep regime and developed characteristic LPOs. In all samples, {010} is the main slip plane and is aligned subparallel to the shear plane after deformation. Dry samples showed textures indicative of combined **a**- and **c**-slip. In wet samples **a**-slip appeared to be strongly enhanced leading to very strong textures and physical anisotropies. In samples with added melt, partitioning of strain between melt bands and melt free regions caused a concentration of **c** axes close to the shear direction changing the overall pattern of p-wave anisotropy. Consequently, regions of the upper mantle with high water content may be characterized by high seismic anisotropies and parts of the mantle containing partial melts may show unusual seismic wave speed distributions.

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