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Preferred Orientation Evolution of Olivine Grains as an Indicator of Change in the Deformation Mechanism

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Abstract. The paper presents the results of investigations of deformed natural polycrystalline olivine. The relationship of the structure of polycrystalline olivine grains to three modal size distributions has been revealed. Grains of different size were observed to be strained at threshold temperatures of 950, 775, and 650°C. It has been demonstrated that the microstructure develops as the dislocation mechanism changes from diffusion creep to grain boundary sliding. The changes in deformation mechanisms promote the change in the preferred crystallographic orientations of olivine from type A to type D and then to type B. The relation of the transitions between different types of orientations to the conditions of deformation in the lower layers of the lithosphere at the plate boundaries is discussed.

1. Introduction

Olivine is considered an important indicator of the deformation regime of the lower layers of the lithosphere that carry information about the stress pattern of the crust–mantle interface. Information of this kind can serve to gain insight into the stress relaxation mechanisms that underlie seismic events [1, 2]. Much attention drawn to olivine is due to the fact that the olivine rock (dunite) contains 90–95% of olivine, which therefore can be considered to be responsible for the physicochemical and deformation processes occurring in the rock. Dunites are characterized by high plasticity, which occurs at temperatures ranging between 400 and 2000°C and pressures ranging between 0.3 and 20 GPa [3–6]. These parameters vary with rock occurrence depth and characterize the state of different layers of the lithosphere. Consequently, the deformational microstructures of dunite indicate the stress state in different layers of the earth crust and upper mantle. Therefore, to gain an understanding of the mechanisms of plastic deformation of olivine is of considerable scientific importance.

There are two main lines of research in this field associated with examination of experimentally or naturally deformed mono- and polycrystalline olivine by using optical methods, electron microscopy, and x-ray analysis [10, 14–16]. The first one is to study the structures that are formed in a material subject to deformation under known experimental conditions and the other is to examine the microstructure of naturally deformed olivine and reconstruct the stress pattern of the lithosphere [1, 2; 11, 12]. The most common techniques of reconstruction of plastic deformation mechanisms are based on using functions of the preferred orientation of material in the active stress field [7–10, 13, 15]. Therefore, the present study was aimed to reveal the mechanisms by which the olivine grains of a polycrystalline aggregate had been naturally deformed by analyzing the aggregate morphology and orientation structure.

2. Materials and method

Samples of four structural types of naturally deformed olivine were selected as test objects. The selected structural types demonstrate different steps of deformation [7, 8, 15–17]. The morphology of polycrystalline olivine was examined by optical and scanning electron microscopy. The crystallographic orientation of grains was determined by the electron backscatter diffraction technique with the use of a Leica DM 2500P optical microscope attached to a Tescan Vega II LM scanning electron microscope. The chemical composition of the olivine and associated spinel was determined using an INCA Energy 300 energy dispersive x-ray spectrometer. The data obtained were statistically processed to identify the grain size distribution and the preferred crystal orientation (the source information was derived from electron micrographs and grain orientation maps).

3. Results

3.1. Phase and component composition. The test samples contained olivine (93–98.5 ± 3%) and spinel (1.5–7 ± 3%). The olivine was found to belong to a rhombic crystal system and have mmm symmetry. Its composition featured by a significant predominance of magnesium in A_2SiO_4 cations and by an iron content no more than 12%. The spinel belonged to a cubic crystal system and had m3m symmetry. Its composition was identified as a mixture of bivalent and trivalent $AO*B_2O_3$ oxides (here A stands for magnesium or iron and B for chromium or aluminum). In the test samples, a significant dominance of Cr_2O_3 (47–56 ± 0.2%) over Al_2O_3 (8–18 ± 0.3%) and of FeO (18–24 ± 0.2%) over MgO (6–9 ± 0.4%) was observed. The results obtained allowed us to determine the temperature of formation of the coexisting olivine and spinel. Using Fabri's phase equilibrium equations [18], the temperature range in which the material of the test samples was formed was estimated to be 650– 955°C.

3.2. Types of deformation microstructures. Structure analysis of the samples has revealed four types of structure in the polycrystalline olivine: protogranular, porphyroclastic, porphyrolastic, and mosaic. These structures were different in volume fraction (V) of grains of three modal sizes: coarse (more than 1 mm), medium (0.1–1 mm), and fine (less than 0.1 mm) (Table 1), indicating an increasing degree of deformation of the polycrystalline olivine.

Table 1. Characteristics of grains in the deformation microstructures and the temperatures of their formation.

Structure type	Grain type								
	coarse			medium			fine		
	D^{mod} [mm]	V [%]	T [°C]	D^{mod} [mm]	V [%]	T [°C]	D^{mod} [mm]	V [%]	T [°C]
Protogranular	5.5	81	955	0.75	19	795			
Porphyroclastic	3.0	44	945	0.65	42	780	0.06	14	655
Porphyrolastic	2.5	32	930	0.60	27	774	0.05	41	668
Mosaic				0.40	24	766	0.03	76	650

The protogranular type of structure featured a prevalence of the coarse fraction compared to the medium one. The medium size grains were localized mostly in triple joints of grains. This suggests that they had been formed as a result of recrystallization. The porphyroclastic structure was characterized by an increased fraction of medium grains and by the presence of fine grains, which where absent in the protogranular structure (see Table 1). It can be supposed that this effect was due to the evolution of primary recrystallization. The porphyrolastic type of structure featured nearly the same volume fractions of the three grain sizes. Besides, coarse grains showed a pronounced preferred orientation. The mosaic type of structure was distinguished by an obvious prevalence of fine grains over medium ones and by the absence of coarse grains.

Calculations of the phase equilibrium of olivine grains of different size at the sites adjoined to spinel [18] made it possible to estimate the temperature of formation of the polycrystalline structure types (see Table 1). Analysis has shown that the grains diminished in size as the temperature of their deformation decreases in the range 950–930°C for coarse grains, 795–765°C for mid-sized grains, and 670–650°C for fine grains.

3.3. Preferred orientation. The preferred orientation of grains for each type of olivine was determined by the EBSD technique. Stereographic projections of the basic crystallographic lines are given in Figure 1 where the elements of anisotropic structures, such as foliation and lineation, are marked. Foliation is associated with a plane similar to the rolling plane at pressure metal treatment and lineation with the direction of statistical pulling of grains, i.e. with the direction of maximal extension. For the protograinular structures, the maximum [100] axis orientation density corresponds to lineation. The [010] axes are arranged normal to foliation. The effect of orientation blurring over several maxima was due to the statistical contribution of coarse grains (figure 1a). Similar but more orderly orientations are typical for porphyroclast structures (figure 1b). This is A type of preferred orientations, which arise due to the activity of the [100] (010) slip system at high temperatures and low stresses [13]. The stereographic projections of the olivine crystallographic axes in porphyrolaste structures show a pronounced maximum of parallel linear [100] axes and girdle dispersion of [010] and [001] axes (figure 1c). The orientations of this kind corresponds to the D type and arise due to the activity of the [100] {0kl} slip system. The orientations of mosaic olivine are determined by the maximum concentration of [010] axes normal to the foliation and by the girdle distribution of [100] and [001] axes (figure 1d). In this case, the [001] axes form a weak maximum along lineation which allows the obtained pattern to be associated with B-type preferred orientations. This type of orientations is formed due to the activity of the [001] (010) slip system at low temperatures and high stresses [9, 13].

4. Discussion and Conclusions

The investigations performed have shown that the formation of olivine grains of three modal sizes in the test deformation system occurred at three threshold temperatures: 950, 775, and 650°C. Knowledge of the temperatures of formation and size of olivine grains makes it possible to use a Jung and Carato piezometer [19] to determine the differential stress. The obtained data were plotted on a map of deformation mechanisms (fig. 2). The dots corresponding to the three main sizes of grains are arranged in three areas on the graph. The dots corresponding to coarse grains are concentrated in the area of deformation by the dislocation creep mechanism, and the dots corresponding to fine grains are localized in the area of deformation by the diffusion creep mechanism. The dots associated with mid-size grains are on the boundary between the two areas. It was shown [12] that under these conditions, the deformation can occur by the mechanism of sliding along the grain boundaries. Consequently, the activity of this mechanism can be related to a separate area on the map of deformation mechanisms.

In view of that the grains of each of the isolated modal sizes make a certain volumetric fraction in a structure of particular type (see Table 1), we can suggest that its deformation occurred by successively changed or simultaneously operated deformation mechanisms. The dislocation creep mechanism prevailed in the formation of the protogranular polycrystal. A combination of two mechanisms – dislocation creep and grain boundary sliding – was characteristic of the porphyroclast type structure.

Diffusion creep was probably responsible for the formation of the fine-grain aggregate in the porphyrolaste type structures, and we believe that this mechanism prevailed in the formation of the mosaic polycrystalline structure.

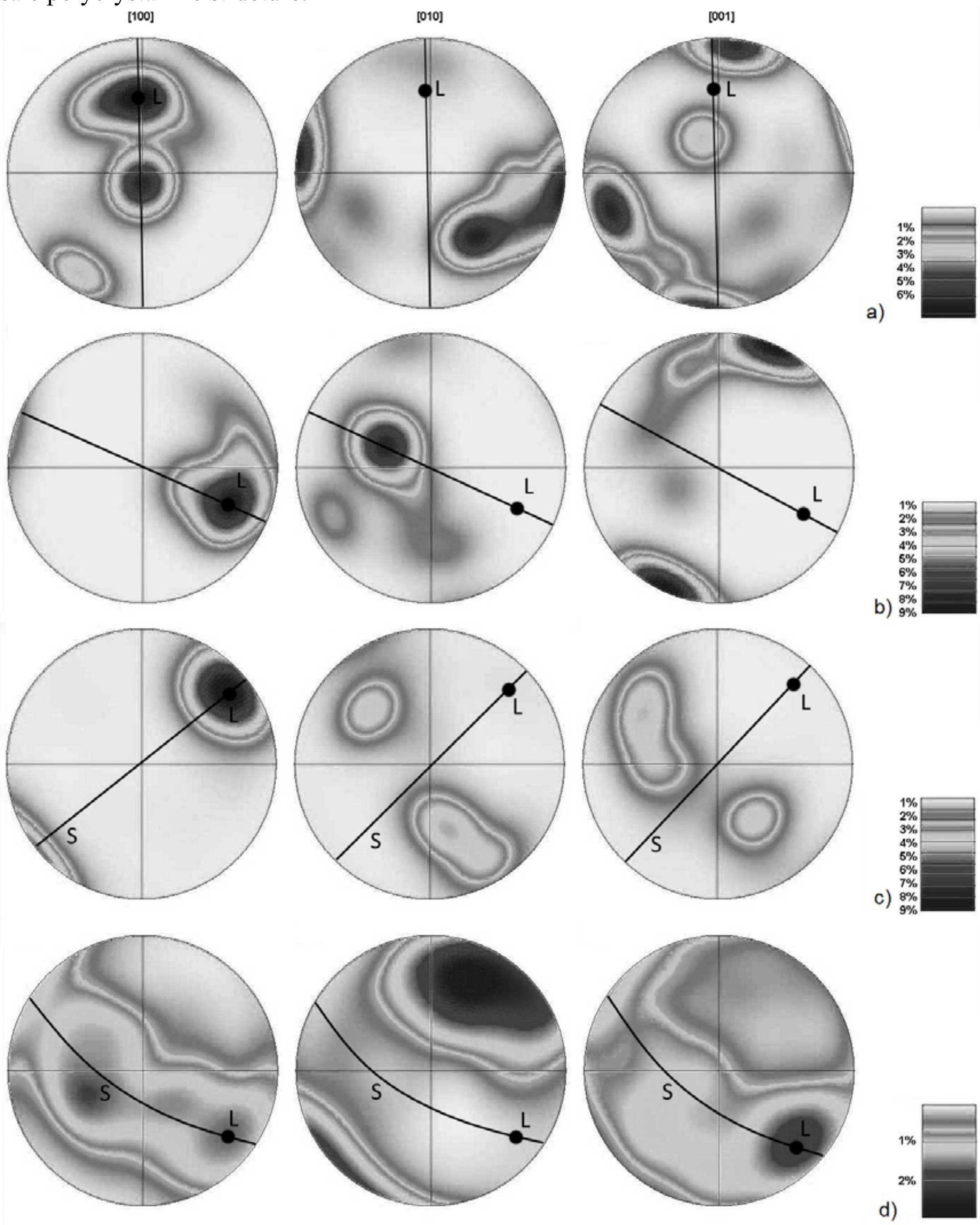

Figure 1. Direct pole figures with preferred crystallographic orientations of polycrystalline olivine of protogranular, porphyroclastic, porphyrolastic, and mosaic structure. The black line (S) and the dot (L) indicate the plane projections of foliation and lineation, respectively.

The features of the preferred orientations display their identity in protogranular and porphyroclast structures where they correspond to the A type [13]. The porphyrolaste structures are characterized by D-type orientations, which differ from A-type orientations by a higher degree of dispersion of [010] and [001] axes and by the occurrence of girdle dispersion (figure 1, a–d). The more significant misorientation of olivine grains in the porphyrolaste aggregates can be accounted for by different creep mechanisms. In our early studies [17], we have shown that the deformations of coarse grains are caused by consecutive activation of the (010)[100] → {0kl}[100] → {100}[001] slip system.

For mid-size grains, a combination of grain boundary sliding and translation by {0kl}[100], {110}[001], and (100)[010] slip systems is characteristic. Consistent activation of different slip systems in translation and grain boundary sliding promotes the development of rotation plasticity and re-orientation of grains. The deformation processes have the result that the fine-grain aggregate shows B-type preferred orientations, which are most pronounced in the mosaic polycrystal (figure 1, d).

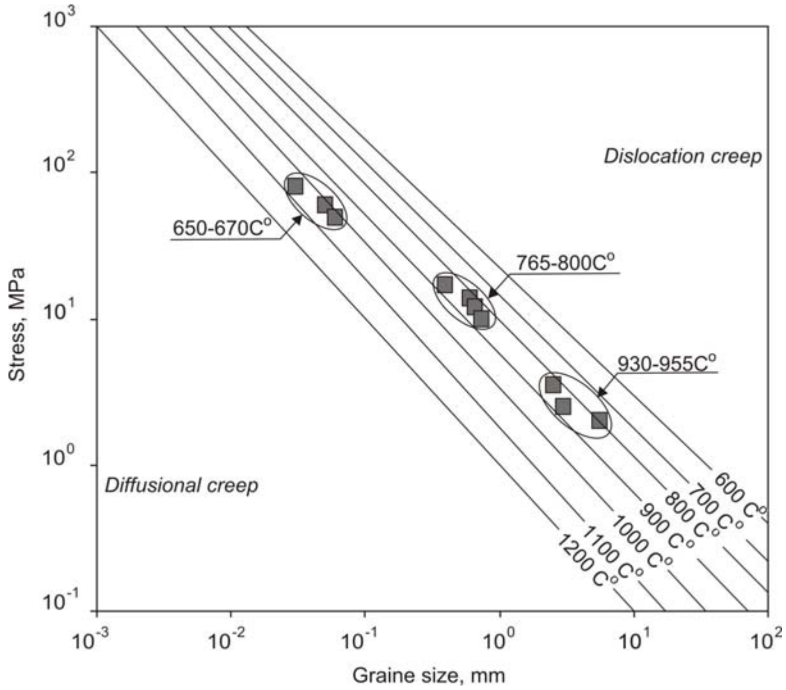

Figure 2. Map of deformation mechanisms of olivine showing the changes in grains size against the magnitude of differential stress according to [3] and the boundaries of the dislocation slide-to-diffusion transition in the temperature ranges 600–900°C [4–5] and 1000–1200°C [6].

B-type orientations occurring under the conditions of diffusion sliding are often mentioned in the literature [2, 9, 11, 12], as a rule, in the context of the transition from the C-type to the B-type orientation. A-type orientations are seldom and they bear witness to the deformation processes that took place during horizontal movements of the earth crust and mantle. C-type orientations are observed for subduction of the oceanic crust. B-type orientations are associated with tectonic acretion of the lower layers of the lithosphere at continental boundaries. The lack of C-type orientations in the test samples indicates the territorial features associated with the small angle of dipping of the oceanic plate under the continental plate.

Thus, the investigations performed revealed the deformation mechanisms, orientation types, and conditions of formation of the basic structural types of natural polycrystalline olivine.

Acknowledgements

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