

# The influence of water on the development of lattice preferred orientation in olivine aggregates

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[1] The calculation of the lattice preferred orientation of crystals in mantle flow has become a major step in the interpretation of the upper mantle seismic anisotropy. Available models for such calculations are based on experimental data obtained on dry crystal aggregates. Recent simple shear experiments showed that the presence of water may radically change the fabrics produced, which casts doubt on the validity of the models in water rich environments like subduction zones. Water may change both the mechanisms of dynamic recrystallization and the mechanical properties of the crystals. This paper illustrates how a change of the critical resolved shear stress of the slip systems is sufficient to reproduce the new experimental results. In contrast, no changes are necessary in the theory of dynamic recrystallization. For subduction zones, first order calculations predict that trench parallel flow rather than water is more likely to be responsible for the anisotropic signature. **INDEX TERMS:** 5112 Physical Properties of Rocks: Microstructure; 7218 Seismology: Lithosphere and upper mantle; 7260 Seismology: Theory and modeling; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 3902 Mineral Physics: Creep and deformation

## 1. Introduction

[2] Seismic anisotropy in the mantle is potentially a powerful tool to infer the geometry of mantle flow [e.g. *Montagner*, 1994]. This anisotropy most likely results from the lattice preferred orientation (LPO) of anisotropic crystals in convective flow [*Nicolas and Christensen*, 1987]. The interpretation of seismic anisotropy requires therefore a knowledge of the link between the crystals LPO and the deformation imposed in the mantle flow [e.g. *Ribe*, 1989; *Chastel et al.*, 1993; *Blackman et al.*, 1996; *Tommasi*, 1998].

[3] When a crystal aggregate is deformed, its LPO evolves by plastic deformation and dynamic recrystallization [e.g. *Poirier and Guillopé*, 1979; *Urai et al.*, 1986; *Karato*, 1987]. Models for plastic deformation have been available for some years [e.g. *Etchecopar*, 1977; *Ribe and Yu*, 1991; *Wenk et al.*, 1991; *Chastel et al.*, 1993; *Tommasi et al.*, 2000]. They predict that the induced LPO is a function of the deformation history as described by the finite strain ellipsoid (FSE): the *a*-axes of the olivine crystals align with the long axis of the FSE, whereas the amount of anisotropy is given by the aspect ratio of the FSE [*Ribe*, 1992]. These predictions are in agreement with experiments for shear strain smaller than 50% [*Zhang and Karato*, 1995]. For larger strain, dynamic recrystallization controls the development of the LPO which rotates away from the FSE [*Nicolas et al.*, 1973; *Zhang et al.*, 2000]. Albeit informative, models based only on plastic deformation are thus not sufficient to interpret seismic anisotropy in the mantle.

[4] Recently two new models have been proposed to account for dynamic recrystallization [*Wenk and Tomé*, 1999; *Kaminski*

and *Ribe*, 2001]. The model of *Wenk and Tomé* [1999] is based on the viscoplastic self consistent theory, whereas the model of *Kaminski and Ribe* [2001] (hereafter referred as KR01) is purely kinematic. However the two models include dynamic recrystallization in a similar way. Both of them consider nucleation and grain boundary migration. For each grain, a density of dislocations is calculated as a function of the local stress. Deformed grains nucleate strain free subgrains as a function of their density of dislocations, whereas grain boundaries migrate from grains with a low density of dislocations to the grains with large density of dislocation. In KR01, the rate of nucleation is proportional to a dimensionless nucleation parameter,  $\lambda^*$ , and the grain boundary migration occurs at a rate proportional to a dimensionless grain boundary mobility  $M^*$ . Comparison with experimental results in simple shear [*Zhang et al.*, 2000; *Bystricky et al.*, 2000] and in uniaxial compression [*Nicolas et al.*, 1973] indicates that for dry olivine aggregates,  $\lambda^* = 5$  and  $M^* = 50$  yield to the best agreement between model predictions and experimental results. For these values, “soft orientations” (which correspond to a maximum deformation accommodated on the softest slip system) dominate the LPO.

[5] In a recent publication, *Jung and Karato* [2001] presented new experimental results on the fabrics of olivine aggregates deformed in presence of water, which differ a lot from the fabrics obtained in dry aggregates. As a function of water concentration and of differential stress, the authors identify four types of fabric, A, B, C and D. Type A corresponds to a [100] axis parallel to the shear direction and a (010) plane parallel to the shear plane. It is obtained for low stress and low water content. Type B corresponds to a [001] axis parallel to the shear direction and a (010) plane parallel to the shear plane. It is obtained for high stress and/or high water content. Type C corresponds to a [001] axis parallel to the shear direction and a (100) plane parallel to the shear plane. It is obtained for moderate stress and high water content. Type D corresponds to a [100] axis parallel to the shear direction and girdles of [010] and [001] normal to the shear direction. It is obtained for high stress and low water content. Fabrics of type A have been described by *Zhang et al.* [2000] and fabrics of type D have been described by *Bystricky et al.* [2000]. They both have been reproduced by KR01 [see Figures 2 and 3 of *Kaminski and Ribe*, 2001]. However, KR01 does not predict either type B or type C.

[6] Water is supposed to influence both diffusion and dislocation creep, and dynamic recrystallization by enhancing diffusion process [*Mei and Kohlstedt*, 2000]. This paper discusses the effect of water on both plastic deformation and dynamic recrystallization, and shows which one is the most likely to explain the observed LPO. It shows how KR01 can be modified to reproduce the results of *Jung and Karato* [2001].

## 2. The Influence of Water on Dislocation Creep

[7] The influence of water on dislocation creep is the most well documented [*Carter and Lallemand*, 1970; *Chopra and Paterson*, 1984; *Mackwell et al.*, 1985; *Karato et al.*, 1986; *Kohlstedt et al.*, 1995; *Hirth and Kohlstedt*, 1996; *Mei and Kohlstedt*, 2000]. These

studies indicate that the relationship between stress and strain rate in the dislocation creep regime is described by the same power law for both wet and dry samples. However, wet olivines deform faster than dry crystals, which can be interpreted as an enhanced concentration of point defects allowing larger migration rates in wet olivine [Mei and Kohlstedt, 2000]. The so called weakening effect of water in olivine as documented by these studies has been interpreted in term of viscosity reduction in wet zones in the mantle [e.g. Mei and Kohlstedt, 2000]. In contrast, its effect on the development on LPO was only addressed recently by the study of Jung and Karato [2001].

[8] The development of lattice preferred orientation in a polycrystal aggregate is due to the rotation of the crystallographic axes of the crystals. The rotation depends on the shear rate accommodated on the different active slip systems as a function of their orientation and of their critical resolved shear stress [Ribe and Yu, 1991; Wenk et al., 1991; Tommasi et al., 2000]. As a function of temperature, applied stress and amount of water, activate slip systems in olivine can be (010)[100], (001)[100], (010)[001] and (100)[001] [see review in Tommasi et al., 2000]. In dry aggregates, the major contribution to deformation comes from glide of dislocations with Burgers vector  $\mathbf{b} = [100]$ , indicating that the easiest slip systems are (010)[100] and (001)[100] [Kohlstedt and Goetze, 1974; Durham and Goetze, 1977; Bai et al., 1991; Bai and Kohlstedt, 1992; Hanson and Spetzler, 1994; Jin et al., 1994]. In contrast, experimental data for wet olivine crystals indicate major glide of dislocations with Burger vector  $\mathbf{b} = [001]$ , corresponding to easiest slip on the systems (010)[001] and (100)[001] [Jung and Karato, 2001]. We can use KR01 to estimate the influence of the two latter slip systems on the LPO development.

### 3. The Influence of Water on Dynamic Recrystallization

[9] Dynamic recrystallization is a function of the dislocation microstructure in the polycrystal [Wenk and Tomé, 1999; Kaminski and Ribe, 2001]. The effect of water on the evolution of dislocations and thus on the process of dynamic recrystallization itself can be inferred from deformation of both single crystals and aggregates [Carter and Lallemand, 1970; Chopra and Paterson, 1984; Mackwell et al., 1985; Karato et al., 1986; Kohlstedt et al., 1995; Hirth and Kohlstedt, 1996; Mei and Kohlstedt, 2000; Jung and Karato, 2001]. Two key observations are enlightened by these studies: (1) grain boundary migration is more active in presence of water and (2) the density of neoblasts is larger in presence of water. A faster grain boundary migration is a direct consequence of enhanced diffusion processes in presence of water [Mei and Kohlstedt, 2000]. A larger density of neoblasts can be interpreted as a larger rate of climb - due to enhanced diffusion - which favors the formation of dislocation walls [Mackwell et al., 1985] and thus increases the rate of sub-grain rotation [Poirier, 1985].

[10] The effect of water on both grain boundary migration and sub-grain rotation can be incorporated quantitatively in KR01. The rate at which sub-grain rotation occurs in KR01 is given by a dimensionless nucleation parameter  $\lambda^*$ , defined by

$$\lambda^* = \lambda \rho_0^2, \quad (1)$$

where  $\lambda$  is a dimensional parameter defining the efficiency of nucleation, and  $\rho_0$  is a reference density of dislocations. Wet crystals correspond to a larger rate of climbing, thus to an enhanced formation of walls of dislocations, thus to a larger rate of nucleation and thus to a larger  $\lambda$ . The reference density of dislocations  $\rho_0$  is given by Orowan's equation [Poirier, 1985],

$$\dot{\epsilon}_0 = \rho_0 b v, \quad (2)$$

where  $\dot{\epsilon}_0$  is a reference strain rate and  $v$  is the velocity of the dislocations. We have seen that the presence of water enhanced the diffusion processes, and thus increased the velocity of the dislocations. From Orowan's equation (2) for a given reference strain rate, a larger velocity of dislocations corresponds to a smaller density of dislocations. In other words, a smaller number of dislocations is necessary to accommodate a given strain rate if they move faster. In wet aggregates, this predicts the occurrence of a smaller reference density of dislocations  $\rho_0$ . Because the value of  $\lambda^*$  is the product of  $\lambda$  (increased by enhanced climb) and of  $\rho_0$  (decreased by enhanced glide), one can postulate that its value is hardly affected by the presence of water. Furthermore, Kaminski and Ribe [2001] have shown that the value of  $\lambda^*$  only affects the LPO if its value is smaller than 3. For  $\lambda^*$  smaller than 3, hard orientations dominate the LPO [see Figure 4 of Kaminski and Ribe, 2001] and the resulting fabrics is never observed in experiments. I will then use in the following the same value as in KR01,  $\lambda^* = 5$ , and I will show that it yields indeed to a very good agreement with the observations.

[11] The rate at which GBM occurs in KR01 is given by a dimensionless grain boundary mobility  $M^*$ , defined by

$$M^* = \frac{A \mu b M}{v}, \quad (3)$$

where  $A$  is a dimensionless constant independent of the material [Kaminski and Ribe, 2001, equation 11]  $\mu$  is the shear modulus, and  $M$  is the dimensional grain boundary mobility. On the one hand, in presence of water, diffusion is enhanced and thus the value of  $M$  should be larger. On the other hand, we have already noticed that the velocity of dislocation  $v$  is increased in wet crystals. Because  $M^*$  depends on the ratio of  $M$  and  $b$  which vary in the same direction, one can make the hypothesis that  $M^*$  is hardly affected by the presence of water. Furthermore, the value of  $M^*$  changes the rate of evolution of the LPO but does not affect the final fabrics [Kaminski and Ribe, 2001], and cannot explain the new LPO. In the following, I will use the best fit value of KR01,  $M^* = 50$ , and show that it yields again to very good agreement with the observations.

[12] In conclusion, the influence of water on LPO is probably mainly due to the change of the mechanical behavior of the slip systems, rather than to a change of the efficiency of dynamic recrystallization. In the next section are presented numerical results supporting this conclusion.

### 4. Predicted Olivine LPO in Presence of Water

[13] The evolution of olivine LPO in KR01 is a function of the plastic deformation of the crystals, which depends on the relative strength of three independent slip systems in olivine. In the dislocation creep regime, the strength of a slip system  $s$  is quantified by a normalized (dimensionless) reference resolved shear stress,

$$\tau_o^s = \frac{\tau_{ref}^s}{\tau_{ref}^1}, \quad (4)$$

with  $\tau_{ref}^s$  is the shear stress corresponding to a strain rate  $\dot{\epsilon}_{ref}$  on the slip plane  $s$ , and where  $s = 1$  corresponds to the softest slip system (by definition  $\tau_o^1 = 1$ ).

[14] To account for the effect of water on the activity of the slip systems, I used various combinations of critical resolved shear stresses, given in Table 1. If (010)[100] is the softest slip system, the LPO is of type A [Zhang et al., 2000; Kaminski and Ribe, 2001]. If (010)[100] and (001)[100] are of similar strength, then the LPO is of type D [Bystricky et al., 2000; Kaminski and Ribe, 2001]. In wet aggregates, the dominant slip systems are supposed

**Table 1.** Reference Resolved Shear Stress for the Slip Systems of Olivine

(010)[100]	(001)[100]	(010)[001]	(100)[001]	Fabric
1	2	3	inactive	A
3	2	1	inactive	B
3	2	inactive	1	C
1	1	3	inactive	D

to be (100)[001] and/or (010)[001] *Jung and Karato* [2001] Figure 1. Figure 1 shows the LPO obtained using KR01 with (010)[001] as the softest slip system. The predicted LPO corresponds to type B observed by *Jung and Karato* [2001], Figure 1. In Figure 1 is also given the LPO obtained using KR01 with (100)[001] as the softest slip system. The predicted LPO corresponds to type C observed by *Jung and Karato* [2001, Figure 1]. All other combinations of slip system activities lead to LPO not (yet) observed either in dry or in wet experiments.

[15] In conclusion, it appears that KR01 can be used to predict the LPO observed in wet aggregates if the activity of the slip systems is changed to account for enhanced glide of dislocations with  $\mathbf{b} = [001]$  rather than  $\mathbf{b} = [100]$ , in agreement with the microstructure observations of *Jung and Karato* [2001]. In contrast, no change is required in the treatment of dynamic recrystallization. The dimensional parameters involved in the model are affected by the presence of water but the dimensionless parameters defined by their combination is indeed not likely to be much affected by the presence of water. A finer tuning of the model parameters might be necessary but will require a more complete data set, like the evolution of the LPO as a function of finite strain.

## 5. Discussion and Conclusion

[16] The results obtained by *Jung and Karato* [2001] have given birth to a debate in the community of experimentalists, and still have to be confirmed by other experiments. Two points are worth noting on the subject. (1) First, even if only few natural samples are in agreement with the new LPO [see discussion in *Jung and Karato*, 2001], these samples still have to be explained, and until now they have not been so by other experiments. (2) Second, the new data of *Jung and Karato* [2001] are now part of the literature, and they are going to be used by seismologists. Modelers should thus not ignore them but should rather give an independent insight into the new observations. This paper shows that the theoretical basis of KR01—which has been validated by comparison with many different experiments [*Kaminski and Ribe*, 2001]—does not have to be modified to reproduce the new LPO. No new ad hoc parameter needs to be added to the theory as one would expect if something was wrong with the experimental data. The agreement between the experiments and an independent theoretical model is a valuable argument in favor of the experiments.

[17] The fabrics induced by the presence of water stand as a seductive candidate to explain “non-conventional” anisotropic data [*Jung and Karato*, 2001]. Non-conventional anisotropic data correspond basically to geodynamical area in which the fast polarization axis is not aligned with the absolute plate motion, like in subduction zone. Until now, such anisotropy was interpreted as the result of trench parallel flow [*Russo and Silver*, 1994; *Hall et al.*, 2000].

[18] The two hypotheses for trench parallel anisotropy can be discussed in the light of the known conditions of deformation in the Earth. We have seen that the fabrics induced by the presence of water, type B and type C, correspond to a dominant glide of dislocations with  $\mathbf{b} = [001]$ . Such glide is actually very rare in natural samples, as 95% of the samples correspond to a dominant glide of dislocations with  $\mathbf{b} = [100]$  [*Ben Ismail and Mainprice*, 1998]. Furthermore only fabrics of type B correspond to a fast

polarization direction perpendicular to the shear direction. Fabrics of type B correspond to large stress and large strain rate whereas fabrics of type C correspond to low stress and low strain much closer to the conditions of deformation in the Earth mantle. The probability of finding type B fabrics in the mantle does not seem very large then. The water hypothesis is therefore less likely to apply than the trench parallel flow one.

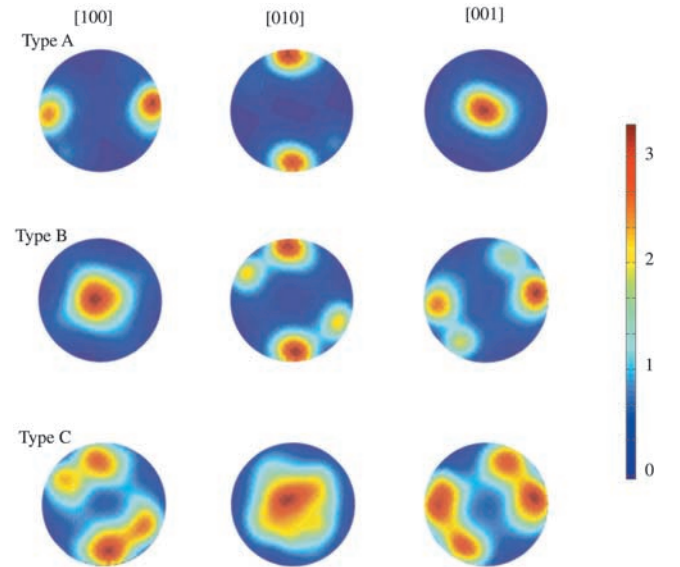
[19] A more quantitative way to discuss these hypotheses is to estimate the amount of strain necessary to realign the LPO from the direction of the absolute plate motion (away from the subduction zone) to the direction of the trench (at the subduction zone). To do so, I use the numerical results of the back arc mantle flow of *Hall et al.* [2000]. The model of *Kaminski and Ribe* [2001] - which has been validated here for wet olivine - indicates that for a given local deformation (i.e. a given velocity gradient tensor), the crystals will align with the long axis of the infinite strain ellipsoid, or ISA, which coincides with the direction of shearing in case of simple shear [*Kaminski and Ribe*, 2002]. The time necessary for the crystals to align with ISA is  $\tau_{ISA}$  [*Kaminski and Ribe*, 2002],

$$\tau_{ISA} \sim \frac{3}{\dot{\epsilon}}, \quad (5)$$

where  $\dot{\epsilon}$  is the strain rate. If  $V$  is the velocity of the plate, then the distance required to change the orientation of the crystal is  $L = V \tau_{ISA}$ . The strain rate is given by  $\dot{\epsilon} = V/D$  with  $D$  the depth of localized shearing under the plate. The distance  $L$  can then be expressed as a function of  $D$  only and is

$$L = 3 D. \quad (6)$$

In *Hall et al.* [2000], the extent of the shearing zone lies between 150 and 300 km as a function of the viscosity, which leads to  $L$  between 450 and 900 km. If the reorientation of the crystals is due to water, the extent of the affected zone is given by the



**Figure 1.** Poles figures for the [100], [010], and [001] crystallographic axes (Lambert equal-area projection, colors correspond to the density of the orientation distribution function expressed as multiples of uniform distribution). The deformation is an horizontal dextral simple shear. For type A, (010)[100] is the softest slip system, for type B, (010)[001] is the softest slip system, and for type C, (100)[001] is the softest slip system.



distribution of fluids in the subduction zone. Water is released by dehydration reaction in the subducted material at depth. Because of the pressure gradient in the wedge, two phase flow models predict that the fluids (either melt or water) are drawn to a zone about 100 km wide, close to the intersection between the upper plate and the subducting slab [e.g. *Spiegelman and McKenzie, 1987*]. According to the previous estimate for  $L$ , 100 km is not a sufficient distance to allow the development of a trench parallel anisotropy.

[20] In conclusion, if water has potentially a large influence on the LPO, the required conditions (large stress and large amount of water) are not common in the mantle, and water should not be used blindly to explain complex anisotropic signature. The best way to proceed is first to choose a candidate flow, and then to calculate the associated LPO using either the “dry” or the “wet” version of *Kaminski and Ribe* [2001]. Only then the precise comparison between seismic data and model predictions can discriminate between different hypotheses.

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