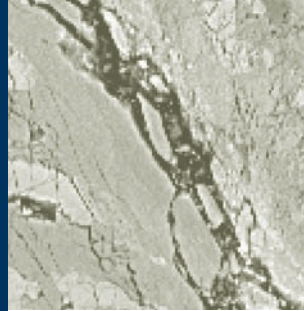


Fluids, Faulting, and Flow

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Geological fluids affect deformation of rocks both physically and chemically. The presence of fluids can lead to faulting (earthquakes) or enhance flow, depending on the level of stress. At higher stresses, fluids with a density less than their host generate Mode I microcracks, whereas fluids with a density greater than their host generate Mode I microanticracks; both can self-organize and cause faulting. At lower stresses, fluids segregate to grain boundaries at small strains and, at large strains, fluid-enriched zones develop that experience a higher strain rate than the bulk. Dissolved H₂O enhances flow (e.g., by water-weakening). Consequences include earthquakes, differentiation, melt separation/volcanism, and seismic anisotropy.

KEYWORDS: fracture, earthquake, anticrack, water-weakening, lattice-preferred-orientation (LPO), seismic anisotropy, differentiation

INTRODUCTION

The presence of fluids in rocks has both physical and chemical effects. Moreover, at least in the case of H₂O, the fluid component(s) can have significant, even profound, effects at concentrations sufficiently low that no free fluid phase exists. At one extreme, the effects of fluid are primarily physical and enable brittle shear fracture through reduction of the effective stress due to elevated pore-pressure (see Scholz 2002 and references therein). At the other extreme, the effects are primarily chemical and are the result of dissolved H₂O in the crystals and the consequent reduction in flow strength and changes in flow mechanisms (Griggs and Blacic 1965; Griggs 1967; Jung and Karato 2001a). Between these extremes, fluids have both physical and chemical effects when they are generated by mineral reactions and/or phase transformations resulting from changes in physical conditions during burial or subduction. Depending on the stress level and fluid viscosity, fluids can enhance flow, leading to chemical differentiation, or they can trigger faulting and earthquakes. Lastly, to encompass all of the systems in which these kinds of behavior exist, one must consider pseudo-fluids. These are actually polycrystalline solids, but the conditions under which they arise are such that the grain size of the material is so fine (nanocrystalline) that the aggregates behave as low-viscosity fluids (e.g., Shan et al. 2004). Production of small amounts of such pseudo-fluids within an otherwise much stronger material yields the mechanical equivalent of a pore fluid.

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In this review, we will address how these various effects arise during *in situ* generation of a fluid or pseudo-fluid by mineral reactions (including partial melting).

FLUIDS AND FAULTING

Partial Melting

Faulting during partial melting of eclogite (the high-pressure equivalent of basalt) under high stress has been investigated by Zhang et al. (2004). They deformed eclogite containing ~50% omphacite (Narich pyroxene) and ~50% garnet at a pressure of 3 GPa pressure and temperatures of 1000–1500K. The rock contained no hydrous phases, but the omphacite and garnet contained ~1,300 ppm and 0–300 ppm of dissolved H₂O, respectively. This material had a high strength at the lowest temperatures tested but was nevertheless ductile. At higher temperatures, approximately half the dissolved H₂O exsolved to grain boundaries, resulting in generation of <1 vol% melt as very thin films on essentially all garnet-pyroxene boundaries. The presence of melt on grain boundaries induced extensive microcracking parallel to σ_1 , leading to shear failure. However, by controlling the flow stress relative to the fracture stress by varying the strain rate, faulting could be turned on or off. The material within the fault zones of these specimens consisted of angular fragments of a wide range of sizes as well as glass blobs and films between particles (Figs. 1A, B). These results provided the first laboratory demonstration of a potential mechanism to explain earthquakes in hot subducting slabs.

Dehydration Embrittlement

The process of faulting during dehydration of hydrous phases under stress is well known. This process, dehydration embrittlement, was discovered in serpentine (e.g., Raleigh and Paterson 1965; Raleigh 1967) and also studied in gypsum (e.g., Ko et al. 1997; Wong et al. 1997). Early deformation studies were conducted at pressures less than 1 GPa (although higher pressure dehydration studies without stress control have reported acoustic emissions that might imply faulting; Mead and Jeanloz 1991; Dobson et al. 2002).

Dehydration embrittlement was immediately recognized as a potential trigger for deep earthquakes (see review by Green and Houston 1995), but more recently a problem developed with this concept. Rock mechanics theory predicts that a dehydration reaction with $V_{\text{products}} - V_{\text{reactants}} (\Delta V_{\text{reaction}}) < 0$ should not support a shearing instability

(Wong et al. 1997; Dobson et al. 2002; Green and Marone 2002). During the last decade, it was discovered that for serpentine, chlorite, and other relevant hydrous minerals, $\Delta V_{\text{reaction}}$ becomes negative at relatively low pressures (Ulmer and Trommsdorff 1995, 1999); in particular, for antigorite serpentine this occurs at ~ 2.2 GPa. Thus, if the predictions of rock mechanics theory are correct, the only mechanism known to be viable for initiation of earthquakes in the upper 300 km of Earth's mantle (dehydration embrittlement) would operate only to approximately 100 km.

fault segments in which the sense of stepping of the faults was such that the region between them was in compression (**Fig. 1d, e**). In contrast, a fluid phase separated from the solid products and caused extensive microcracking parallel to σ_1 ; these microcracks could be seen where they occurred in large relict olivine crystals (**Fig. 1f**). The fact that many partially healed microcracks contained fluid inclusion trails demonstrated that the microcracks had initially been filled with fluid.

Transformation-Induced Faulting

This faulting mechanism involves production of crack-shaped micro-lenses (**Fig. 2a**) of a nanocrystalline solid that behaves like a low-viscosity fluid. The interaction of the lenses with each other leads to failure in a way very similar to that of fluid-filled microcracks. Thus, the basic physics underlying the phenomenon (lens formation) is fundamentally different from brittle shear fracture, but the intermediate-scale physics (lens interaction through the elastic strain fields at their tips) appears to be the same (see summaries in Green and Houston 1995; Green 1994). This mechanism was discovered in experiments at pressures of 1–2 GPa in which metastable polycrystalline Mg_2GeO_4 (olivine structure) was deformed in the stability field of its high-pressure polymorph (spinel structure) (Green and Burnley 1989; Burnley et al. 1991), and the mechanism was

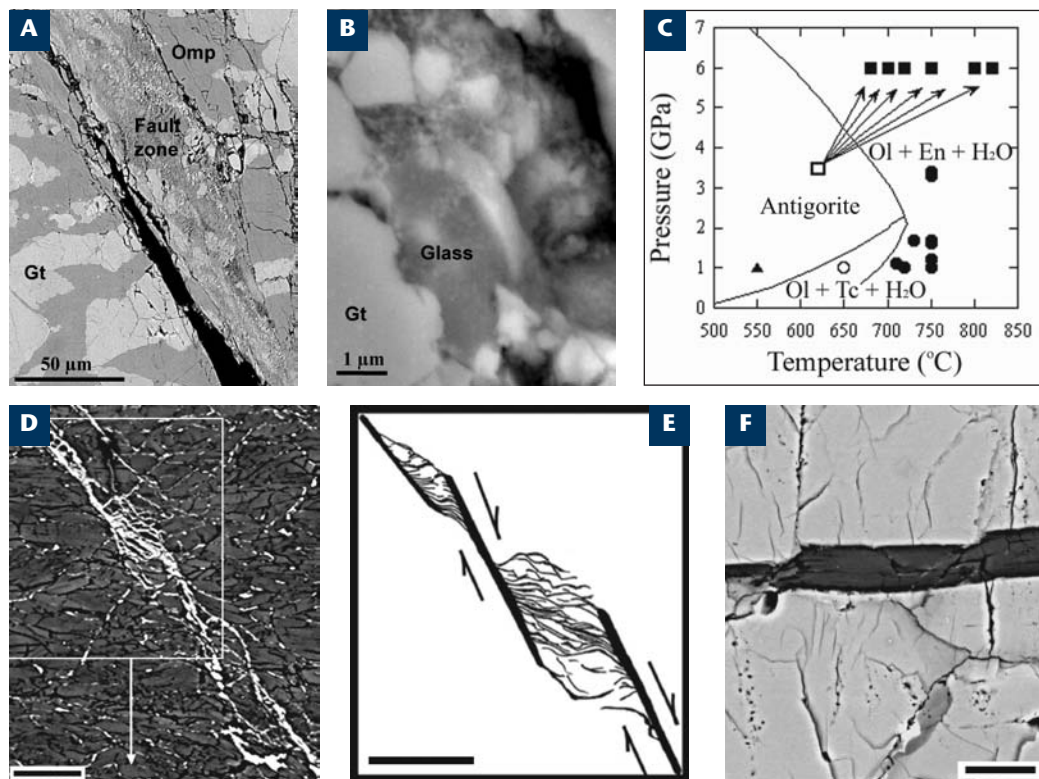


FIGURE 1 Dehydration Faulting. Back-scattered electron images of a fault zone in eclogite **A**, and detail of fault gouge **B**. Gt = garnet; Omp = omphacite (modified after Zhang et al. 2004). **C**. Phase relations for antigorite (Ulmer and Trommsdorff 1995) and experimental conditions after Jung et al. 2004. Ol = olivine; En = enstatite; Tc = talc. Open symbols represent conditions where specimens were annealed but not deformed; circles are conditions of experiments conducted in a modified Griggs apparatus; squares denote final conditions of experiments pressurized along arrow paths in a multi-anvil device; triangle represents specimen stressed to the breaking point without dehydration. **D**. Scanning electron micrograph in back-scatter mode showing a fault system generated at 6 GPa. Dark phase is antigorite; bright material is solid reaction products. **E**. Sketch clarifying features in **D**. **F**. Optical micrograph of relict olivine (white) and a single antigorite crystal (black) accompanied by numerous microcracks and fluid inclusion arrays aligned parallel to σ_1 . Scale bars of **D** to **F** = 20 μm .

To evaluate whether this shearing instability is quenched if $\Delta V_{\text{reaction}}$ is negative, Jung et al. (2004a) conducted a study of antigorite dehydration under stress at 1–6 GPa (**Fig. 1c**). Faulting was found to occur under all dehydration conditions, independent of the sign of $\Delta V_{\text{reaction}}$, and the microstructures of the deformed specimens were the same under all conditions. The solid dehydration products (primarily olivine) were found preferentially within and immediately adjacent to faults, where they formed extremely fine-grained micro-lenses normal to σ_1 . These lenses were particularly abundant within regions between *en echelon*

confirmed in similar experiments on mantle olivine, $(\text{Mg,Fe})_2\text{SiO}_4$, at 14 GPa in the wadsleyite stability field (Green et al. 1990). Additional studies demonstrated that the mechanism produces acoustic emissions during faulting (Green et al. 1992). A similar mechanism operates in ice Ih deformed in the ice II stability field (Kirby et al. 1991). In these experiments, the stable phase (spinel) was more dense than the metastable phase (olivine). The resulting volume loss resulted in contraction micro-lenses that spontaneously oriented themselves *perpendicular* to maximum compression. However, subsequent investigation of the phenomenon in a different system showed that if the stable phase is less dense than the metastable phase ($\Delta V_{\text{reaction}} > 0$), the resulting expansion micro-lenses spontaneously orient themselves *parallel* to maximum compression (Green and Zhou 1996). In both cases, the contents of the micro-lenses are nanocrystalline and the lenses self-organize, leading to shear failure in which the nanocrystalline contents of the lenses is incorporated into the fault zone as a lubricant. Analysis of the shape and behavior of the expansion micro-lenses shows them to be completely analogous to fluid-filled “tensile” microcracks (referred to as Mode I cracks in fracture mechanics because the displacements associated with formation of the crack are perpendicular to the plane of the crack). By further analogy, the compression micro-

lenses become Mode I microanticracks (Fletcher and Pollard 1981; Green and Burnley 1989; Burnley et al. 1991; Green and Houston 1995).

The instability is restricted to exothermic polymorphic phase transformations with a significant ΔV of reaction. The micro-lenses of solid reaction products referred to in the section on dehydration embrittlement display many similarities to the anticracks described here and may have the same origin and significance.

The faulting instability is limited to conditions under which the nanocrystalline lenses of the stable phase develop, and this requires temperature/pressure conditions under

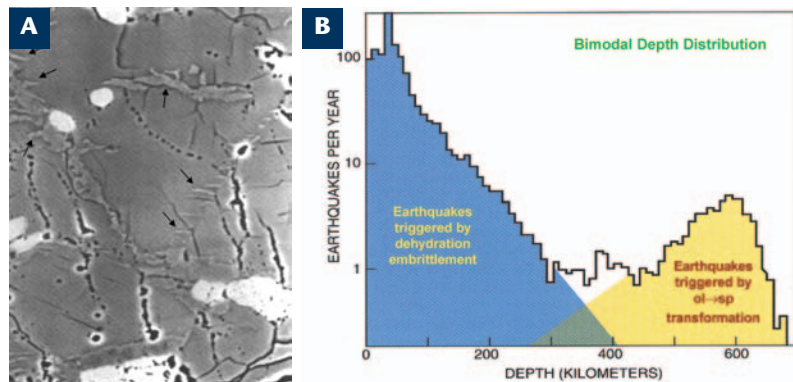


FIGURE 2 Transformation-induced faulting **A.** Spinel-containing anticracks growing on grain boundaries of Mg_2GeO_4 olivine (arrows) (modified after Green 1994). **B.** Earthquake frequency as a function of depth (modified after Frohlich 1989).

which the kinetics of nucleation of that phase are sluggish; the temperature must be sufficiently low that the nucleation rate is controlled by the temperature, not by the ΔG of reaction. Paradoxically, although the mechanism can operate only under conditions where nucleation is at first difficult, the nanocrystalline lenses are created by rapid nucleation. The explanation for rapid nucleation under conditions of initially sluggish nucleation is a combination of local temperature rise due to the exothermic reaction and the large ΔV of reaction that creates large stress concentrations around a nucleus. As a consequence, nucleation of additional crystals occurs adjacent to the first. The combination of these thermal and volumetric effects creates a positive feedback cycle and results in runaway nucleation. Under a nonhydrostatic stress, the developing packets of new phase adopt a crack-like morphology and align themselves so as to maximize the work done by the macroscopic stress field. The result is that if the ΔV of reaction is positive, the lenses align themselves parallel to maximum compression as if they were fluid-filled Mode I microcracks (Green and Zhou 1996), and if the ΔV is negative (as it is for olivine \rightarrow spinel), they align themselves normal to maximum compression and become Mode I microanticracks (Green and Burnley 1989; Green and Houston 1995). In either case, the Mode I features interact through the elastic strain fields at their tips, leading to self-organization into incipient shear failure, just as normal Mode I tensile fractures self-organize to produce faulting in brittle materials. In the case of filled Mode I features (whether with a true fluid or a pseudo-fluid), the low-viscosity filling material of the micro-lenses is spilled into the developing fault zone, thereby supplying a lubricant as part and parcel of fault development. As the fault grows, a process zone develops at its tip (just as in brittle failure), but again production of lubricant is a natural part of the process. As used here, self-

organization means simply that the micro-lenses interact with each other through their elastic strain fields; when the local density becomes sufficient, the material can no longer support the applied macroscopic stress and a shear fracture is born, in this case lubricated by the nanocrystalline contents of the coalescing micro-lenses.

This faulting mechanism provides a natural explanation for the increased frequency of earthquakes in the mantle transition zone (**Fig. 2b**). This mechanism also explains the abrupt termination of earthquakes at the base of the transition zone because reaction across the upper mantle – lower mantle boundary is endothermic and requires phase separation (to magnesium silicate perovskite + magnesio-wüstite). However, this mechanism requires the presence of metastable olivine to trigger an earthquake; hence it requires sufficiently cold subduction to inhibit the reaction to wadsleyite or ringwoodite in the central portion of a subducting slab. As a consequence, serious doubts have been raised about the ability of this theory to explain very large, very deep earthquakes such as the 1994 Bolivia earthquake (Silver et al. 1995; Kanamori et al. 1998; Mosenfelder et al. 2001). On the other hand, recent seismic results from beneath the southwestern Pacific Ocean suggest that there may be significant amounts of metastable olivine preserved in and behind the Tonga subduction zone (Brudzinski and Chen 2003; Chen and Brudzinski 2001, 2003; Green 2001, 2003; Tibi et al. 2003). This possibility raises the question

as to whether subduction zones may be colder than depicted in current computer models or whether the kinetics of the olivine \rightarrow spinel transformation may be more sluggish than currently believed. At present this problem is unresolved.

Summary of Fluids and Faulting

Although each of the three mechanisms of fluid-induced faulting discussed above has distinctive characteristics, they all involve production of a fluid with a viscosity much lower than that of the solid precursor, and they all are self-organizing under stress as a consequence of the changes of volume between the reactants and the products. In the first two mechanisms, the fluid is a natural consequence of dehydration; in the third, the fluid characteristics are acquired due to the exothermic nature of the reaction and resulting thermal runaway of the nucleation rate.

FLUIDS AND FLOW

Water-Weakening

Small amounts of dissolved H_2O can profoundly reduce the plastic flow strength of many silicates and oxides; this process is referred to as water- or hydrolytic-weakening. Quartz and olivine may be taken as representative of the Earth's crust and mantle, respectively. Therefore, we will focus on the effect of water on the rheology of these two minerals.

Quartz

Water-weakening of quartz has been extensively studied during experimental deformation (e.g. Griggs and Blacic 1965; Griggs 1967; Kronenberg et al. 1986; Ord and Hobbs 1986; Tullis and Yund 1989). The best experimental flow laws for quartz are those of Luan and Paterson (1992) and Gleason and Tullis (1995); they have been effectively combined and modified slightly by Hirth et al. (2001) based on natural observations. The exact mechanism of water-weakening remains poorly understood (e.g. Paterson 1989; Post and Tullis 1998; Rutter and Brodie 2004).

Olivine

The early studies of water-weakening of olivine (Carter and Avé Lallemant 1970; Blacic 1972), although undoubtedly correct qualitatively, were hampered by imprecise stress measurement. Subsequently, experiments using a more precise and accurate gas-medium “Paterson” apparatus (Chopra and Paterson 1981, 1984; Mackwell et al. 1985; Karato et al. 1986) quantified the water-weakening effect. An extensive literature has developed in recent years (see review by Kohlstedt et al. 1995).

Most recently, Mei and Kohlstedt (2000a, 2000b) deformed olivine aggregates in both the dislocation and diffusion creep regimes and found that creep strength under wet conditions decreases with pressure at $P \leq 0.5$ GPa. However, Karato and Jung (2003) found that after the initial decrease, the strength becomes pressure insensitive at 1–2 GPa (**Fig. 3**). Bai and Green (1998) previously had determined pressure independence of creep strength in wet Mn_2GeO_4 olivine at $P = 1\text{--}3$ GPa. This phenomenon was interpreted in both studies as due to a competition between strengthening due to the pressure effect on creep (activation volume) and weakening due to the increase of water fugacity with pressure.

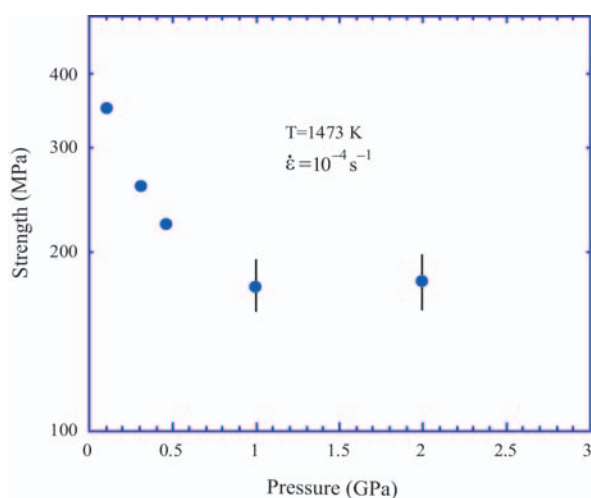


FIGURE 3 Effect of water on creep strength of olivine under wet conditions. Experimental data are normalized to a strain rate of $10^{-4}/\text{s}$ and temperature of 1473K (after Karato and Jung 2003).

Effects of Water on Slip Systems

Dissolved water is known to change the relative ease of slip systems in both quartz and olivine. A slip system is defined by the plane on which a dislocation loop expands (slip plane) and the direction in which the crystal lattice is offset by passage of the dislocation (slip direction). For example, slip system (010)[100] indicates that dislocation loops expand on (010) planes and that the direction of offset within the loop is [100]. In the dislocation creep regime, the relative ease of different slip systems controls the rotations that crystals experience during plastic deformation and the lattice preferred orientation (LPO) that results from those rotations. In the approximately simple shear deformations common in many geological contexts, a crystal can be mostly deformed by the easiest slip system; hence this system will also control the resulting LPO. Development of an LPO creates elastic anisotropy in the material, resulting in anisotropy of seismic wave propagation in Earth. Such patterns of seismic anisotropy can be determined by seismic studies and can be important in the interpretation of flow patterns.

Quartz

Blacic (1975) found that slip systems in quartz change with both temperature and water content: basal slip is easier at low temperature and low water content, whereas prismatic slip is easier at high temperature and high water content. In quartz, this effect has not yet proven to be important for the interpretation of natural rocks, but the discovery shows that an increase in dissolved water in a mineral, like a change in temperature, can have significant effects on the relative ease of slip systems in a mineral and therefore could control the resulting LPO.

Olivine

In olivine also, the easiest slip system varies with temperature and stress (e.g., Raleigh 1968; Carter and Avé Lallemant 1970; Durham and Goetze 1977; Zeuch and Green 1984). In addition, Mackwell et al. (1985) showed that the addition of small amounts of water (<300 ppm H/Si) at 0.3 GPa enhanced plastic deformation on the (010)[001] slip system more than on the (010)[100] system. Nevertheless, even high-strain experiments at these low pressures found no effect of water on preferred orientation (e.g., Zhang et al. 2000).

Realizing that high solubility of water in olivine is possible only at high pressure (Kohlstedt et al. 1996), Jung and Karato (2001a) deformed olivine by simple shear under wet conditions at 0.5–2 GPa and elevated temperature. They found the pattern of LPO to vary with water content and stress (**Fig. 4A**). Types A and D LPO are dominant at low water fugacity and have been known for a long time. Type A is commonly observed in rocks from the oceanic lithosphere (e.g. Nicolas and Christensen 1987) and is responsible for the seismic anisotropy imprinted during its formation. Until recently, interpretation of seismic anisotropy to understand flow patterns in the upper mantle have used this LPO exclusively (e.g. Nicolas and Christensen 1987). The new LPOs resulting from deforming olivine under high water fugacity (**Fig. 4B**), if present in the mantle, would also have a significant effect on seismic anisotropy. Several natural rocks showing the LPOs produced at high water contents have been reported. As a consequence, it is potentially possible to look for water in the mantle using seismic anisotropy (e.g., Karato 2003; Jung and Green 2004).

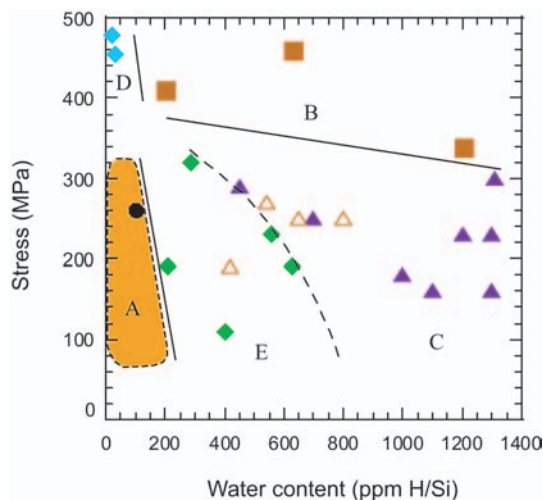


FIGURE 4A Effect of water on dominant slip system of olivine. Several types of LPO are shown as a function of water content and stress. LPO patterns imply the following slip systems **A**: (010)[100]; **B**: (010)[001]; **C**: (100)[001]; **D**: {0k}[100]; **E**: (001)[100]; open triangle: mixture of types C and E (after Jung et al. 2004b).

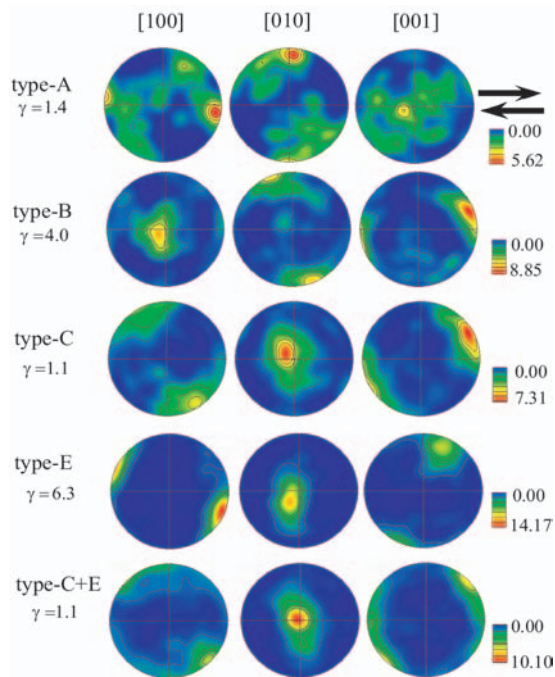


FIGURE 4B Typical pole figures showing effect of water and stress on the LPO of olivine (after Jung et al. 2004b). The E-W direction corresponds to the shear direction. The N-S direction corresponds to the shear plane normal. Color coding refers to the density of data points. Fabric types as in 4a.

Effect of Water on Dynamically Recrystallized Grain Size

Deformation at high temperature in the dislocation creep regime results in dynamic recrystallization. Under such conditions, recrystallization leads to a steady-state grain size that depends on the stress; hence grain size can be used to infer the stress under which natural rocks have been deformed.

Quartz

Experimental deformation of quartzite results in significant dynamic recrystallization (e.g. Hirth and Tullis 1992). Early work on experimental deformation of quartz aggregates (e.g., Green et al. 1970) showed that recrystallization of quartz under wet conditions leads to increased grain-boundary migration rates and larger grain sizes at a given temperature and strain rate. Nevertheless, quantitative determination of the difference in grain size, if any, for a given stress in quartz is still lacking. The relationship between recrystallized grain size and stress for dry quartz has been studied (e.g., Kohlstedt and Weathers 1980; Stipp and Tullis 2003), but data are not yet available under wet (water-saturated) conditions.

Olivine

Work at low pressures yielded insufficient solubility of H₂O in olivine to produce a measurable effect on the recrystallized grain size of olivine. Recently, however, by deforming specimens with added water at 2 GPa, conditions under which the fugacity of H₂O is sufficiently elevated to yield a measurable effect, Jung and Karato (2001b) found that recrystallization of olivine was significantly enhanced under wet conditions. When the water content of olivine exceeds ~800 ppm H/Si, the size of recrystallized grains is about 2–3 times larger than that under dry conditions under the same stress (**Fig. 5**).

Effect of Melt on the Deformation of Partially Molten Rocks

The effect of partial melting on the mechanical properties of rocks has been most extensively investigated in the peridotite system. Under hydrostatic stress, partial melt in this system does not effectively wet grain boundaries, and small amounts of melt therefore accumulate along triple junctions (Waff and Bulau 1979; Cooper and Kohlstedt 1984; Faul 1997), although surface-energy anisotropy results in some low-index grain boundaries being wetted (Jung and Waff 1998). The existence of melt reduces viscosity with increasing melt fraction at low strains, but the reduction of viscosity is less than about an order of magnitude in both dislocation and diffusion creep regimes if the melt fraction is less than ~5%. With increasing strain, however, melt leaves the triple junctions and spreads across grain boundaries (Jin et al. 1994; Bai et al. 1997); at still larger strains, the melt concentrates into parallel layers, thereby enhancing flow rates and resulting in chemical differentiation (e.g., Zimmerman et al. 1999; Holtzman et al. 2003). Using realtime observations in a deforming rock analog (norcamphor-benzamide), Rosenberg and colleagues have delineated the connection between these two regimes as strain progresses (Rosenberg and Riller 2000; Rosenberg and Handy 2000, 2001). Similar effects on the flow of salts with brine inclusions was shown in the 1980s (Urai 1983, 1985; Urai et al. 1986), emphasizing the generality of this kinetic effect.

Geophysical Implications

Faulting at depth in the Earth is enabled by creation of small amounts of a low-viscosity “fluid” under moderate or high stresses. Three self-organizing mechanisms have been described. Whether these mechanisms are sufficient to explain all deep earthquakes (singly or in combination) remains a question, but certainly, the production of a fluid is required. Importantly, the question concerning the viability of dehydration embrittlement under conditions of negative volume change during dehydration has been clearly answered; the sign of $\Delta V_{\text{reaction}}$ has no effect on triggering of faulting. Abundant Mode-I microcracks produced

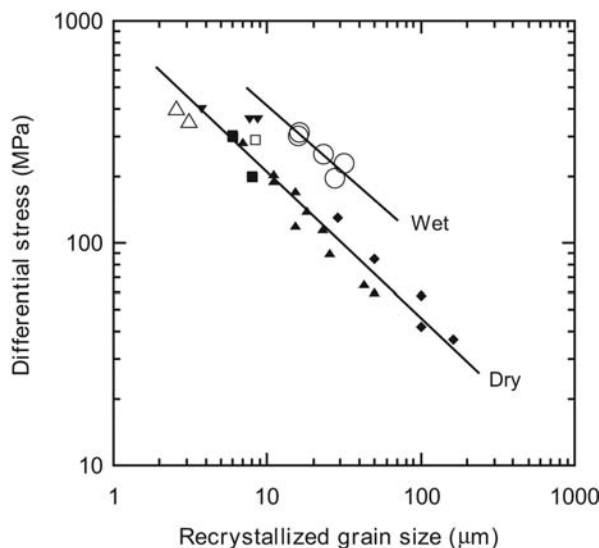


FIGURE 5 Effect of water on dynamically recrystallized grain size (after Jung and Karato 2001b). Open circles: wet condition (water content ≥ 800 ppm H/Si). Open triangle: dry condition. Open square: a sample with moderate water content (450 ppm H/Si). Filled triangle: water-added but still dry condition at the pressure of 300 MPa with water content < 200 ppm H/Si. Filled inverse-triangle: dry condition. Filled diamond: dry condition.

by dehydration of hydrous minerals under stress also may significantly reduce seismic wave velocity in subduction zones (Jung and Green 2004). The question naturally arises as to whether a fluid must be actively produced to trigger faulting or whether, once produced, a fluid of any density could trigger faulting by the pore-pressure effect. In principle, one might expect that, after decay of local stresses around newly generated pore fluids, the presence of fluid is all that is necessary. However, the patterns of faulting in subduction zones are so readily interpreted as sites of fluid (or pseudo-fluid) generation that it may be that fluids at depth dissipate rather rapidly after their generation, rendering them effective in triggering faulting only during or very shortly after their generation within the subducting plate (e.g., earthquakes do not occur in the deep mantle wedge where fluids must

be traversing the wedge on their way to triggering melting that feeds arc volcanoes).

Due to intracrystalline weakening by small amounts (hundreds to thousands of ppm) of H₂O, viscosity in the crust and upper mantle potentially can be lowered by several orders of magnitude depending on water fugacity. The existence of melt at low stresses also reduces viscosity, but by less than an order of magnitude if the melt fraction is less than a few percent. However, even with small amounts of melt, with increasing strain, melt and crystals partially segregate, with enhanced strain rate in the melt-rich zones and additional decrease in effective viscosity. Such strain partitioning can lead to differentiation, melt extraction, and finally volcanism. Dissolved water changes the dominant slip systems of olivine and quartz, resulting in changes in lattice preferred orienta-

tion and thereby potentially changing seismic wave velocity and anisotropy in the crust and upper mantle. Water also enhances dynamic recrystallization and grain boundary migration, with implications for paleostress estimates from natural rocks. Because the steady-state grain size at a given stress is larger for wet rocks than dry rocks, one must attempt to determine whether water-weakening was active during natural deformation before one can infer the paleostress from experimental calibrations.

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