Role of dynamic grain boundary wetting in fluid circulation beneath volcanic arcs

Saswata Hier-Majumder¹ and David L. Kohlstedt²

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1 Introduction

The mantle wedge above a subducting slab is a region of active volatile transport. High water contents of arc lavas and glass inclusions in olivine xenocrysts hosted in arc magmas indicate a volatile-rich source region [Roggensack et al., 1997]. Progressive cross-arc decline of fluid-mobile elements indicates shallow level circulation of a slab-derived aqueous fluid within the mantle wedge [Ryan et al., 1995]. The fluid induces melting of the mantle peridotite as it reaches the solidus of wet mantle peridotite [Tatsumi and Kogiso, 1997]. Therefore, the location of the magma source region and, consequently, the volcanic front, is determined by both the thermal structure of the mantle wedge and the trajectory of the slab-derived fluid [Mibe et al., 1999].

One possible mechanism for transport of the slab-derived aqueous fluid in the mantle wedge is porous flow along a network of interconnected pores driven by a pressure gradient. Under a hydrostatic state of stress, formation of such an interconnected network needs to meet at least one of two requirements [Von Bargen and Waff, 1986]. First, the dihedral angle at the solid-solid-fluid junction must be <60° so that most of the pore-fluid can concentrate in tubules along grain edges. Second, if the dihedral angle is >60°, the volume fraction of pore-fluids must be larger than the critical volume fraction required to interconnect pockets of pore-fluid isolated in four grain corners. The possibility of formation of an interconnected pore-fluid network in the mantle wedge has been tested by measuring the dihedral angles in water-saturated olivine aggregates annealed under hydrostatic conditions over a range of temperature and pressures [Watson and Brenan, 1987; Mibe et al., 1998, 1999]. The results indicate that formation of an interconnected network is not possible in certain regions of the mantle wedge due to the large dihedral angle subtended by the small volume fraction of available pore-fluid.

However, the mantle wedge is a dynamic region, undergoing intense deformation. The associated non-hydrostatic state of stress can drastically influence the geometry of the pore-fluid network and thus the permeability. In the extreme, deformation can cause fracturing of the matrix, thus altering the permeability of the rock [Davies, 1999]. However, at the elevated temperature and pressure of Earth’s mantle, solid state creep rather than brittle fracturing is likely to be the dominant deformation mechanism. Deformation experiments on Fe-FeS-olivine aggregates and MORB-olivine aggregates reveal that an applied stress can both create a pore-network and modify the geometry of a preexisting network [Kohlstedt and Zimmerman, 1996; Zimmerman et al., 1999; Holzmann et al., 2003; Scott, 2000; Bruhn et al., 2000; Hustoft and Kohlstedt, 2006]. Such a transition in the geometry of the pore-fluid network is caused by expulsion of isolated pore-fluid pockets into grain boundaries, driven by stress singularities near the pore-fluid pocket, a process known as dynamic grain boundary wetting [Hier-Majumder et al., 2004]. Therefore, to characterize the porous flow of aqueous fluid in the mantle wedge, it is necessary to investigate the influence of deformation on the extent of grain boundary wetting both for isolated pockets of aqueous fluids and for a preexisting pore-fluid network with a random geometry. In this study, we report the first experimental investigation of the role of deformation-induced grain boundary wetting on porous flow of aqueous fluid in the mantle wedge.

2 Experimental Details

We experimentally investigated the influence of deformation on the geometry of the pore-fluid network in two types of silicate-water aggregates with different initial pore-fluid distributions. The first assemblage was an olivine-water aggregate synthesized by hot-pressing fine-grained (~10 µm) powder of San Carlos olivine with 1–3 vol% added free water at a temperature of 1523 K and a pressure of 300 MPa. The bright-field transmission electron microscope (TEM) image in Figure 1a illustrates the rounded corners and an average dihedral angle of 76° ± 26°.
indicating that the fluid was distributed mostly in isolated pockets at four grain corners. The second assemblage was a clinopyroxene-water aggregate fabricated by hot-pressing ground, fine-grained (~6 μm) powder of Sleaford Bay clinopyroxenite with added 1–3 vol% free water at 1523 K and 300 MPa. The natural clinopyroxenite contained <1 vol% apatite and quartz that melted in the presence of water during the run, generating a highly siliceous, water-rich fluid. This fluid was observed as glass-filled pockets in the quenched aggregates [Hier-Majumder et al., 2005]. Such a pocket is displayed in the bright-field TEM image in Figure 1b. The shape and an average dihedral angle of 54° ± 19° of the pockets indicate that most of the fluid resided in an isotropic network of interconnected tubules along triple grain junctions.

Constant load as well as displacement rate stepping deformation tests were performed on the hot-pressed samples in a simple shear geometry in a gas-medium creep rig. Thin discs, 500–900 μm in thickness, were cut from the hot-pressed samples and shaped into ellipses with major axes ~8 mm and minor axes ~6 mm. Each ellipse was then cut in half along the minor axis. Both halves of an ellipse and a 125 μm thick Ni foil were then placed between two ThO2 – W pistons. The pistons and the sample were placed inside a Ni sleeve. The two ThO2 – W pistons were cut at 45°, such that the plane of maximum shear stress was parallel to sample, when a load was applied along the cylindrical axis of the pistons. The load during the deformation tests was monitored by an internal load cell. The displacement was measured using a linearly variable differential transformer. For the constant load experiments, a fixed load was applied to the pistons, whereas for the constant displacement rate tests, the load was applied by an actuator moving at a fixed displacement rate. We applied shear stresses between 100 and 200 MPa to deform the olivine-water aggregates and between 10 and 100 MPa to deform the clinopyroxene-water aggregates. Some clinopyroxene-water aggregates were deformed in displacement rate stepping experiments. In these experiments, we deformed the samples between strain rates of 10⁻⁵ and 10⁻³ s⁻¹. In this study, we report the results from 5 shear deformation experiments on olivine-water aggregates and 4 on clinopyroxene-water aggregates, each containing 5–10 load or displacement rate steps. The temperature and pressure of the shear experiments were similar to those used in the hot-press.

Samples for microscopic observation were prepared from polished sections of the deformed aggregates, cut parallel to shear direction and perpendicular to the shear plane. The sections were polished using diamond lapping films of grit size down to 0.5 μm. Subsequently, the sections were chemically and mechanically polished in a colloidal silica suspension with a grain size 40 nm. Polished sections were observed with a JEOL 6500 field emission gun scanning electron microscope (FEG SEM) at the University of Minnesota and a Leo FEG SEM at the Bayerisches Geoinstitut, Bayreuth, Germany. Thin sections for optical microscopy were prepared by polishing both sides. Doubly polished thin sections of the samples were used to prepare foils for imaging in transmission electron microscope (TEM). The thin sections were milled into thin foils in a Gatan Duo Mill using Ar ions incident at angles between 10° and 15° at a voltage of 2 to 3 kV for 15–25 h. Subsequently the foils were ion polished to obtain a large electron transparent region in a Gatan Precision Ion Polishing System using Ar ions incident at an angle of 6°. TEM images were obtained using a Philips CM30 and an FEI Tecnai T12 FEG microscopes. Continuity of the observed surface microstructure (SEM, reflected optical microscopy) into the volume (TEM, transmitted optical microscopy) of the samples indicated the absence of damage or alteration to the surface due to sample preparation.

3. Results

Mechanical data from the deformation tests indicated that both aggregates deformed by power-law creep. The flow law for the olivine-water aggregates was characterized by a stress exponent of n = 3.5, a value typical of deformation in the dislocation creep regime. Moreover, electron backscattered diffraction (EBSD) analysis of the deformed olivine aggregates indicated the presence of a pronounced crystallographic fabric characteristic of dislocation glide on the (010)[100] slip system. The clinopyroxene-water aggregates crept with a stress exponent of n = 1, indicating that deformation took place by diffusion-controlled creep. No difference was observed in the mechanical behavior or the microstructure between the clinopyroxene-water aggregates deformed in the constant load tests and those deformed in displacement rate stepping tests. Both olivine-water and clinopyroxene-water aggregates were characterized by a shape preferred fabric of the grains.

In deformed olivine-water aggregates, the fluid phase segregated into planes rich in lens-shaped fluid inclusion along grain boundaries. Such fluid-rich planes are inclined at an average angle of ~16° to the shear direction, in a sense antithetic to the sense of the applied shear. The backscattered, orientation-contrast electron image in Figure 2a illustrates several such fluid inclusion-rich planes. The arrows in the figure indicate traces of individual planes of segregated fluid on the polished section. The length of individual planes varied from tens to hundreds of microns. In several samples, shear localization along the long fluid-rich planes was marked by kinks in the Ni shear strain marker. The smallest spacing between such planes was
The orientation of the fluid-rich planes was independent of the total shear strain. The bright-field TEM image in Figure 2b shows an enlarged view of two lens-shaped pockets along a plane similar to those imaged in Figure 2a.

The fluid phase in the deformed water-saturated clinopyroxene aggregates segregated along planes consisting of wetted grain boundaries connecting pockets at grain corners. The orientation of these planes was similar to that in the olivine-water aggregates. The atomic contrast cathodoluminescence SEM image in Figure 3a highlights the presence of several fluid-rich planes inclined in a sense opposite to the thick bright Ni strain marker. Slip along the largest fluid-rich plane induces shear localization, manifested as a kink in the strain marker. The bright-field TEM image in Figure 3b illustrates two pockets joined by a grain boundary glass film (~100 nm thick). The solid arrows in this figure mark the glass film along the wetted grain boundaries. The average length of the fluid-rich planes in the clinopyroxene aggregates are similar to those in the water-saturated olivine aggregates. The orientation of the fluid-rich planes are independent of the total shear strain, similar to the water-saturated olivine aggregates.

4. Discussions

The experimental observations can be directly scaled to natural conditions by constraining the value of the capillary number $Ca = \sigma d/\gamma$, where $\sigma$, $d$, and $\gamma$ are the stress, grain size, and the surface tension, respectively. The balance between stress and the interfacial tension is controlled by $Ca$ [Leal, 1992]. Deformation-induced microstructures produced in the laboratory experiments at stresses ~100 MPa and grain sizes ~10 $\mu$m should be similar to those produced at earth-like stress levels of ~1 MPa and grain sizes of ~1 mm, for $\gamma = 1 J m^{-2}$.

Figure 2. Microstructure illustrating fluid segregation in deformed olivine-water aggregates. (a) Orientation contrast, backscattered SEM image of a sheared aggregate. The white and black arrows mark fluid-rich planes along grain boundaries. The shear direction is indicated by two large black arrows on the top. (b) Bright-field TEM image of fluid pockets along grain boundaries.

Figure 3. Microstructure illustrating fluid segregation in deformed clinopyroxene-water aggregates. (a) Atomic contrast cathodoluminescence SEM image showing the alignment of the fluid-rich planes with respect to the bulk shear. The thick bright phase is the Ni strain marker, which was vertical prior to deformation. Notice the kink in the strain marker due to slip along the large fluid-rich plane marked by several thick, white arrows. The shear direction is indicated by two large black arrows on the top. (b) Bright-field TEM image of a similar aggregate illustrating the presence of a ~100 nm thick fluid film (marked by arrows) connecting two fluid pockets. The circular line in the pocket on the left encloses a hole created during ion-milling of the TEM sample.

Figure 4. (a) Plot of isopleth for a dihedral angle of 60° with amphibole-breakdown [Schmidt and Poli, 1998] and melting [Katz et al., 2003] curves. Data in the solid squares are calculated from the dihedral angle-temperature relation reported in Figure 3 (a) for pressures of 1, 3, and 5 GPa in reference [Mibe et al., 1999]. The linear fit is given by $T (°C) = 1150.5 – 84.5 P (GPa)$. The cartoons illustrate the pore-fluid geometry in deforming aggregates below and above the 60° isopleth. Only deformation-assisted porous flow can take place in the shaded region. The slab geotherm is obtained from our calculation of the thermal structure. (b) Map of fluid transport in the mantle wedge (upper-left half of the figure). Short, broken lines indicate unit permeability vector $k_n$ inclined at 16° to the direction of maximum shear due to slab drag. The flow field in the mantle wedge is indicated by the arrows. Water-saturated peridotite solidus and the 60° dihedral angle isopleth are overlaid as broken and solid curves. The colormap indicates the temperature distribution. Porous flow can take place in the region between the 60° isopleth and the slab surface only along deformation-induced fluid-rich planes.
[12] During deformation, pore-fluid segregates into long, continuous, shear-localizing planes as depicted in Figure 3a, establishing an anisotropic permeability structure. Lattice-Boltzmann calculations on the melt geometry of sheared olivine-MORB aggregates also indicate that the permeability $k_p$ parallel to melt-rich planes is an order of magnitude larger than the permeability component perpendicular to the fluid-rich planes, $k_n$ [Scott, 2000]. Formation of such high permeability planes in the creeping mantle wedge will enhance circulation of slab-derived fluid at depths shallower than those predicted from estimates of interconnectivity based on hydrostatic experiments.

[13] The mantle wedge flow field and thermal structure directly influence circulation of slab-derived fluid. To demonstrate this relation, we calculated an analytical solution for wedge flow [Batchelor, 1997], which we subsequently used to numerically solve the heat diffusion-advection equation for a 50 Ma old slab employing a 2D multigrid algorithm [Patankar, 1980; Press et al., 1992]. As illustrated in Figure 4a, the $60^\circ$ isopleth, the hydrostatic connectivity threshold, intersects the calculated slab surface temperature at a depth of $\sim 160$ km. Therefore, in the absence of deformation, amphibole-derived water will travel to a depth of 160 km, trapped as isolated pockets within the matrix until the dihedral angle is reduced to $< 60^\circ$ [Mibe et al., 1998, 1999]. However, our experimental results demonstrate that deformation of the matrix will cause the isolated fluid pockets to segregate into fluid-rich planes, thus transporting the water at much shallower depths.

[14] Deformation-assisted water transport in the mantle wedge has two important implications for subarc mass transport. First, slab-derived water can induce melting at shallow depths. The trajectory of water is illustrated in Figure 4b as short, broken lines, parallel to the unit principle permeability vector $k_p$, oriented at an angle of $16^\circ$ to the direction of maximum shear. The trajectory intersects the wet peridotite solids near 100 km, 60 km shallower than the predicted hydrostatic threshold as described in Figure 4a. Second, enhanced fluid circulation in the mantle wedge will result in a more efficient redistribution of fluid-mobile elements in the mantle wedge. A detailed chemical geo-dynamics study is necessary to determine the extent of chemical exchange between the fluid and the slab as well as the possibility of the existence of a subarc mantle reservoir for these elements.

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S. Hier-Majumder, Kline Geology Laboratory, Department of Geology and Geophysics, Yale University, 210 Whitney Ave., New Haven, CT 06511, USA. (saswata.hier-majumder@yale.edu)

D. L. Kohlstedt, Department of Geology and Geophysics, University of Minnesota-Twin Cities, 310 Pillsbury Drive SE, Minneapolis, MN 55455, USA. (dlkohl@umn.edu)