Intergranular fluid distributions in rocks at a nanometer scale

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Intergranular fluid distributions in fluid-bearing rocks have essential roles for fluid migration and rheology of the rocks. Numerous studies of measurements of dihedral angles between fluids and grains have been done for synthetic aggregates (e.g., quartz, olivine, feldspar). Although the dihedral angles between fluid-solid has often been considered as more than 0 degree, sometimes the existence of thin (~1 nm) fluid film has been estimated (e.g. De Kloe et al. 2000). Structural analysis with sub-nanometer to micron size is possible by TEM; therefore, the method allows a fine structural analysis such as determining the presence of the thin fluid film at grain boundaries. Hiraga et al. (2001) found a fluid morphology controlled by interfacial energies at intergranular regions resulting in appearance of well-defined dihedral angles between aqueous fluid and grains in natural rocks. Their high-resolution TEM observations demonstrate that pore-free regions at grain boundaries are tight even at a nanometer scale, showing the absence of the aqueous fluid film in the rocks.

Studies of grain boundaries in partially molten ultramafic rocks have led to two conflicting conclusions: nanometer-thick melt films wet grain boundaries (Drury and Fitz Gerald 1996; De Kloe et al. 2000) versus essentially all grain boundaries are melt-free (Vaughan et al. 1982; Kohlstedt 1990). If a thin melt film exists along the grain boundaries, the rock should be weakened significantly, therefore, the confirmation of the presence of the film is critical to control the rheology of the partially molten rocks. Hiraga et al. (2002) found characters of grain boundaries in quenched partially molten peridotites as: (i) Although a small fraction of grains are separated by relatively thick (~10 micron) layers of melt, lattice fringe imaging by high-resolution TEM reveals that most of the remaining boundaries do not contain a thin amorphous phase. (ii) Due to the anisotropy of the olivine-melt interfacial energy, melt often extends 1 to 2 micron from a triple junction into an adjoining grain boundary before the boundary becomes tight, giving an effective dihedral angle of only ~2 degree. (ii) The chemistry of olivine-olivine grain boundaries was analyzed by nano-beam analytical scanning TEM with a probe size of less than 2 nm. The result tells that Ca, Al and Ti segregate to grain boundaries forming enriched regions of less than 5 nm wide. Si is not enriched at the grain boundaries and the same type of chemical anomaly is found in subsolidus system (Hiraga et al. in press). These facts show the absence of the melt films, however, elemental segregation occurs to olivine grain boundaries. Creep experiments on the partially molten rocks analyzed in this study reveal little weakening even at melt contents up to 4 vol%, consistent with our observations of melt-free grain boundaries.