Study of Microstructure and Mechanism of Olivine-Spinel Phase Transformation in Fayalite

P. Raterron, J. Chen (SUNY, Stony Brook)

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Introduction: The olivine (α) transformations into wadsleyite (β) and ringwoodite (spinel γ) are good candidates for promoting deep focus earthquakes at low to moderate temperature in subducting slabs. These transformations have been intensively studied over the past two decades by investigating transformed olivine in meteoritic material, or by carrying out high-pressure experiments. Except for a few studies (e.g. Furnish and Basset, 1983), experiments were mostly done at moderate to high temperature (T>800˚C) in pseudo-hydrostatic environment, and the results were obtained post-mortem ("cook and look" method). Two mechanisms have been proposed for the olivine α-γ transformation: a shear induced mechanism (see Madon and Poirier, 1983), which consists of a martensitic-like transformation induced by high shear stresses, and a nucleation and growth process operating mostly at high-temperature (e.g. Burnley and Green, 1989; Kershhofer et al., 1998).

Methods and Materials: In order to investigate the effect of stress on the olivine α-γ transformation at low temperature, six samples of fayalite (Fa100) were annealed in DIA-type cubic-anvil high-pressure apparatuses. The Fa100 olivine end-member was chosen because it transforms directly into γ -spinel (no β-phase) and does not undergo compositional changes during the transformation. The Fa100 transformation also occurs in a range of pressure accessible to our experimental devices. The cell pressure, the stress in the samples, as well as the phases in presence (α and/or γ) were monitored in situ using the synchrotron x-rays generated at the NSLS facility. The starting materials consisted of synthetic fayalite powders. All samples thus exhibited high deviatoric stresses (typically 2.5 GPa) after cold compression. In order to release the "loading" stress, three of the six samples were pre-annealed in the fayalite stability before undergoing the α-γ transformation at higher pressure. All the specimens (stressed and unstressed) were eventually annealed in the γ stability field.

Results: One stressed and one unstressed specimens were annealed until completion of the α-γ transformation. For both these samples, the transformation was monitored using a monochromatic X-ray beam. X-ray data reveal that the stressed sample transformed at lower temperature (from 450˚C) than the unstressed sample which transformed at T>600˚C. X-ray structure refinement also reveals that in both samples the spinel oxygen sub-lattice was set-up before the spinel cationic sub-lattice. This observation suggests that in both cases the α-γ transformation was stress induced. The four other samples were quenched while the transformation was still going on. Transmission electron microscopy (TEM) of the partly-transformed stressed samples shows transformed areas consisting of nanometric spinel grains which tend to recrystallize into micrometric grains at temperature as low as 450˚ C. Optical microscopy and TEM investigation of the partly-transformed unstressed samples reveal spinel areas consisting of defective micrometric grains; these transformed areas have spherical shapes and seem to propagate throughout the material as a runaway process. These latter observations strongly suggest that, at low temperature, a snowball-like process promotes shear-induced transformation in the unstressed sample.

Conclusions: We believe that the driving force for this snowball-like process is the high deviatoric stress induced by the transformation itself (resulting from the associated volume reduction) in the vicinity of the transformed areas. If such snowball-like mechanism operates in natural olivine, one may expect the olivine--spinel transformation in cold subducting slabs to be stress induced and quickly completed after spinel nucleation.

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References: Burnley and Green (1989) Nature, 338, 753-756; Furnish and Bassett (1983), J. Geophys. Res., 88,10333-10341; Kershhoffer et al. (1998) Mineralogical Mag., 62, 617-638; Madon and Poirier (1983) Phys. Earth and Planet. Int, 33, 31-44