Frictional Melting and Deformation in the Upper Mantle: Constraints from Cr-Al Spinel in Ultramafic Psuedotachylyte from Balmuccia

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Ultramafic pseudotachylyte is thought to represent a remnant of earthquake rupture in the upper mantle, and potentially provides useful information for better understanding rupture mechanism of deep earthquakes (Karato, 2003). Jin et al. (1998) examined microstructure of olivine in and near the host peridotite of a pseudotachylyte vein, and discussed the evolution of deformation before the seismic rupture. The presence of glass in the ultramafic pseudotachylyte provide definite evidence for frictional melting (Obata and Karato, 1995; Anderson and Austrheim, 2006), but it also implies very low ambient temperature not to induce extensive crystallization or devitrification, which casts doubt that the rupture event really took place in the upper mantle conditions. At temperatures of the upper mantle usually higher than ~700^{o}C, complete crystallization of glass or melt is inevitable during or after the cooling event. An exceptional case was reported by Ueda et al. (2006 JPGU Meeting), who found a thin ultramylonite in Balmuccia peridotite (Italy), exhibiting pseudotachylyte-like morphologies, such as injection veins branching out from a fault vein, but consisting completely of minerals without any glassy material or obvious quench textures. Obata et al. (2007 JPGU Meeting) further argued that it was pseudotachylyte recrystallized at 700-800^{o}C in the spinel peridotite facies, and discussed the role of H2O-CO2 fluid played in the ductile-to-brittle transition leading a seismic rupture and frictional melting. However, these studies failed to provide conclusive evidence for melting or estimation of degree of melting, and the deformation history before and after the frictional melting has not been fully clarified yet. We have observed Cr-Al spinel in and bordering the holocrystalline pseudotachylyte with FE-SEM attached with EDS and EBSD, and obtained unequivocal evidence for melting and drastic transition of deformation phases through the formation and freezing of the pseudotachylyte veins.

Cr-Al spinel occurs in all micro-lithologies in and fringing the pseudotachylyte veins. Spinel shows enormous diversity in terms of morphology, Cr-Al zoning, and internal structure depending on its mode of occurrence. Clear evidence for melting comes from tiny spinel grains occurring in the injection veins. They are mostly elongate parallel to the adjacent foliation defined by pyroxenes and olivine and smaller than 20 microns across. It has a thin rim (smaller than 2 microns) composed of fine (smaller than 1 micron) intergrowth of clinopyroxene and spinel showing radial alignment. Spinel in the intergrowth is richer in Cr than the internal part. There is a tendency that the crystal size of intergrowth decreases with a decrease in the rim thickness. The internal part of spinel consists of several subgrains with similar crystallographic orientation with each other. The crystallographic orientation of spinel in the rim is nearly the same as that of the directly contacting subgrain. An isolated fine intergrowth without internal part and an intergrowth being barely torn off from the internal part are also observed. These textural and compositional features clearly indicate that Cr-Al spinel underwent partial dissolution by a short heating event accompanied by deformation in partially molten state. The subgrain size of internal part of spinel is a few microns, which indicates that spinel had deformed under very high stress (larger than ~400 MPa, which is estimate for olivine with the minimum grain size of ~5 microns after Jin et al., (1998)) before the frictional melting. The present study demonstrates that the shear heating instability can be a mechanism of deep earthquake at mantle condition as high as 700-800^{o}C and ~1.0 GPa following localization of ductile deformation induced by extremely high stress.