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Partial cordierite breakdown during post-seismic recovery: the significance of plastic deformation for cation diffusion and metamorphic equilibrium

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Brittle intra-crystal fracturing occurred during a microseismic event in migmatites of the Ordovician Sierras Pampeanas (NW Argentina), forming micro-shear zones and brittle fragments in cordierite. The seismic event occurred at amphibolite facies P-T conditions under high strain rates ($\geq 10^{-7}$ s^{-1}). During post-seismic recovery and coarsening of crystal fragments, primary cordierite (X_{Mg}=0.65) underwent partial breakdown along the deformation zone, forming a secondary mineral assemblage in an alteration zone along grain boundaries of coarsened crystal fragments. The secondary assemblage is restricted to the recovery zone. The breakdown of primary cordierite (Crd_P) is accompanied by the formation of secondary sillimanite, magnetite, staurolite (X_{Mg}=0.24, ~0.5 wt% ZnO), quartz, and secondary cordierite (Crd_S; X_{Mg}=0.70-0.80). Crd_S, volumetrically the most important secondary phase, forms by diffusion of Mg and Fe, altering Crd_P by Fe loss and uptake of Mg. All other secondary phases form by nucleation. Two simultaneous cordierite breakdown reactions have been balanced using CSpace 1.01:

100 Crd_P (X_{Mg} 0.65) = 21.8 Sil +12.8 Mag + 33.5 Qtz + 5.6 H_2O + 89.1 Crd_S (X_{Mg} 0.75)

100 Crd_P (X_{Mg}0.65) = 8.1 Mag + 53.6 Qtz + 4.5 H_2O + 8.1 St (X_{Mg}0.24) + 83.3 Crd_S (X_{Mg} 0.75)

The bulk chemical major element composition of the alteration zone is nearly identical to the composition of primary cordierite, suggesting that elemental exchange between the alteration zone and the cordierite matrix is limited. However, minor fluid influx, supplying Zn, K, Si, and O is indicated by the composition of staurolite, minor formation of biotite and quartz, and by the oxidation of Fe^{2+} within the alteration zone. The modal composition of the alteration zone has been determined by point counting, which yields similar results like CSpace results (converted into vol%), and MODAN calculations, which calculates modes based on the average alteration zone composition, and the compositions of secondary phases. The average modal composition of the alteration zone is:

2.3 Sil + 2.0 Mag + 4.3 Qtz + 3.9 St+ 87.5 Crd_S (vol%)

Thermodynamic modelling of primary cordierite breakdown using Theriak Domino shows that the observed breakdown is possible only in a small $P-T$window around P=450 MPa and T=555 ˚C, which is in good agreement with the retrograde $P-T$ path of the Sierra de Quilmes migmatites. Modes calculated using Theriak Domino are similar to results using descriptive methods (point counting), or methods based on chemistry and petrography (MODAN, CSpace). Since modes predicted on the assumption of petrological equilibrium are close to the observed modes, the breakdown reaction seen in the alteration zone most likely represents conditions of, or close to, thermodynamic equilibrium.

The formation of the secondary mineral assemblage in the alteration zone depends upon the efficient supply of cations, essentially Si, Al, Fe and Mg. The bulk composition of new secondary minerals (Qtz, St, Mag, Sil) is enriched in Fe compared to Crd_P, whereas Crd_S is Fe depleted. The provision of Si and Al required for Sil, Qtz, and St can be assigned to partial cordierite breakdown. The excess Fe needed for Mag and St, and the removal of surplus Mg from Crd_P breakdown, depends on Fe-Mg diffusion within Crd_S. Since Crd_S forms exclusively in the post-seismic recovery zone, we interpret dislocation creep, and hence cation diffusion related to plastic deformation, as the key process for the formation of reaction products reflecting thermodynamic equilibrium.