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High-temperature Raman spectroscopy of quartz inclusions in garnet: a tool to investigate lower crustal rheology

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Earthquakes result from the brittle failure of rocks at depths and are primarily induced by far-field tectonic stresses. Despite this general understanding, the atomic-scale mechanisms triggering brittle failure in dry ductile crustal rocks remain elusive. Quartz, a widespread mineral in the lower crust, undergoes an instantaneous polymorphic transformation from the α to β phase under pressure and temperature conditions aligning with estimates for several lower-crustal paleo-earthquakes, recorded as pseudotachylytes. The α–β quartz transition is characterized by displacive reversibility. As α–quartz approaches the transition temperature (T_c = 847 K for a free quartz crystal at atmospheric pressure) under constant pressure, its volume increases nonlinearly without abrupt jumps. However, near the phase-transition temperature, the bulk modulus of quartz exhibits a notable drop from approximately 30 GPa to nearly zero, followed by an abrupt rise to over 70 GPa within 10 K temperature range (Lakshtanov et al., 2007).

Near the α–β transition, quartz inclusions within garnet hosts should develop substantial differential strain, thereby imposing strong differential stresses on the surrounding host crystal. We used in situ high-temperature Raman spectroscopy on quartz inclusions in garnet to monitor the structural deformation and atomic dynamics across the phase transition. The temperature-dependent behaviour of the phonon wavenumbers (ω) in quartz inclusions, particularly the hardening and disappearance of a minimum in ω(T) for A modes near 208 and 464 cm^{-1} (related to the α–β phase transition), along with the persistence of Raman activity at ~128 cm^{-1} and ~355 cm^{-1} above T_c, confirms the accumulation of abnormally high strain in confined quartz grains near the anticipated phase transition. The stored elastic energy in the inclusion is subsequently released through the inclusion-host boundary into the host during the α–β transition. This release causes the garnet around the quartz inclusion to fracture or, in some instances, shatter due to the significant differential stresses forming within the inclusion at its transition. Notably, inclusions of apatite and zircon within the same garnets remain unchanged under the same conditions, thereby excluding the possibility of fracturing being caused by the host garnet itself.

Our experiments show that the α–β transition of a single quartz inclusion in garnet is sufficient to fracture the host phase in a laboratory environment. This process can be upscaled to quartz-

bearing rocks at lower crustal conditions and might provide the initial mechanical instabilities necessary to trigger ductile and/or brittle deformation in quartz-bearing rocks, eventually leading to earthquakes.

References

Lakshtanov, D.L., Sinogeikin, S.V., Bass, J.D., 2007. High-temperature phase transitions and elasticity of silica polymorphs. Physics and Chemistry of Minerals 34, 11-22.