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Nano is the next big thing: Revealing geochemical processes with atom probe microscopy

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Characterizing compositional variations in minerals at the nanometre scale has the potential to yield fundamental insights into a range of geological processes associated with nucleation and mineral growth and the subsequent modification of mineral compositions by processes such as diffusion, deformation and recrystallization. However, there are few techniques that allow the quantitative measurement of low abundance trace elements and isotopes signatures at the nanometre scale. Atom probe microscopy is one such technique that has been widely used in the study of metals and, in the last decade, semiconductors. However, the development and application of atom probe microscopy to minerals is in its infancy and only a handful of published studies exist in the literature. Here, we provide an introduction to atom probe microscopy and its potential use in geological studies using two examples from both undeformed and deformed zircon ($ZrSiO_4$).

In the first example, we use atom probe microscopy to show that discordant data from the core of an undeformed 2.1 Ga zircon, metamorphosed at granulite facies conditions 150 Myr ago, contains distinct Pb reservoirs that represent both the crystallisation and metamorphic $^{207}Pb/^{206}Pb$ ages. Crystallisation ages are preserved within $\sim$10 nm diameter dislocation loops that formed during annealing of radiation-damaged zircon during the prograde path of the metamorphic event. The results highlight the potential for resolving the chronology of multiple, distinct Pb reservoirs within isotopically complex zircon and provide an explanation for varying amounts of discordance within individual zircon grains.

In the second example, we illustrate complex trace element distributions associated with near-instantaneous deformation of a shocked zircon during the $\sim$1.17 Ga Stac Fada bolide impact. Substitutional and interstitial ions show correlated segregation, indicating coupling between different mobility mechanisms associated with the rapid formation and migration of oxygen vacancies and dislocations into low energy configurations.

The results of these two studies show how quantification of elemental and isotopic variations at the nanoscale may reveal fundamental new insights into geochemical processes that underpin the interpretation of geochemical data collected at the microscale. Furthermore, these new data highlight the important role of crystal defects, even in undeformed zircon, in the chemical modification of zircon, and allow the interplay amongst radiation damage, recrystallization and deformation to be assessed.