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Parent zonation in thermochronometers - resolving complexity revealed by ID-TIMS U-Pb dates and implications for the application of decay-based thermochronometers

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High temperature (>350°C) U-Pb thermochronometers primarily use accessory minerals such as apatite, titanite and rutile, and assume that daughter isotopes are lost by thermally activated volume diffusion while the parent remains immobile. Studies exploiting such behaviour have been successfully used to reconstruct thermal histories spanning several hundred million years (e.g. Cochrane et al., 2014). However, outliers in date (ID-TIMS) vs diffusion length space are frequently observed, and grains are frequently found to be either too young or too old for expected thermal history solutions using the diffusion data of Cherniak et al. (2010). These deviations of single grain apatite U-Pb dates from expected behaviour could be caused by a combination of i) metamorphic (over-)growth, ii) fluid-aided Pb mobilisation during alteration/recrystallization, iii) parent isotope zonation, iv) metamictisation, and v) changes in diffusion length with time (e.g. fracturing). We present a large data set from the northern Andes of South America, where we compare apatite U-Pb ID-TIMS-(TEA) data with LA-ICP-MS element maps and in-situ apatite U-Pb LA-(MC)-ICP-MS dates. These are combined with U-Pb zircon and $^{40}Ar/^{39}Ar$ (muscovite) data to attempt to distinguish between thermally activated volume diffusion and secondary overgrowth/recrystallization. We demonstrate that in young (e.g. Phanerozoic) apatites that have not recrystallized or experienced metasomatic overgrowths, U-Pb dates are dominantly controlled by volume diffusion and intra-crystal uranium zonation. This implies that ID-TIMS analyses of apatites with zoned parent isotope distributions will not usually recover accurate thermal history solutions, and an in-situ dating method is required. Recovering the uranium distribution during in-situ analysis provides a means to account for parent zonation, substantially increasing the accuracy of the modelled t-T-paths. We present in-situ data from apatites where scatter in date v diffusion length scale is observed and compare t-T-paths from single grain and in-situ modelling. Modelling of in-situ data will further show if all apatites from a single hand specimen record the same thermal history using Cherniak et al. (2010) diffusion data, or if the Pb-in-apatite diffusion parameters are a function of composition. U zonation is ubiquitous in the studied rocks (Triassic apatites extracted from peraluminous leucosomes), implying that these conclusions may also apply to lower temperature thermochronometers that are based on uranium decay, such as (U-Th)/He dating.