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Age discordance and mineralogy

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Abstract

Observations of discordant ages, meaning that an age given by one mineral geochronometer is different from the age given by another geochronometer from the same rock, began in the early days of geochronology. In the late 1950s and 1960s, discordant U-Pb zircon ages were unquestioningly attributed to Pb diffusion at high temperature. Later, the mineralogical properties and the petrogenesis of the zircon crystals being dated was recognized as a key factor in obtaining concordant U-Pb ages. Advances in analytical methods allowed the analysis of smaller and smaller zircon multigrain fractions, then the analysis of individual grains, and even pieces of grains, with higher degrees of concordancy. Further advances allowed a higher analytical precision, a clearer perception of accuracy, and a better statistical resolution of age discordance. As for understanding the cause(s) of discordance, belief revision followed the coupling of imaging, cathodoluminescence (CL), and backscattered electrons (BSE), to in situ dating by secondary ion mass spectrometry (SIMS) or by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Discordant zircon and other accessory minerals (e.g., monazite, apatite, etc.) often consist of young rims accreted onto/into older cores. Age gradients are sharp, and no Pb diffusion gradients are observed. As U-Pb discordance in crystalline, non-radiation damaged grains is caused by diachronous, heterochemical mineral generations, interpretations of mineral ages, based on the exclusive role of diffusion, are superseded, and closure temperatures of zircon and monazite are irrelevant in geological reality.

Other isotopic systems (Rb-Sr, K-Ar) were believed, since the 1960s, to be similarly controlled by the diffusivity of radiogenic daughters. When zircon and monazite discordance were recognized as zone accretion/reaction with sharp boundaries that showed little or no high-temperature diffusive re-equilibration, the other chronometric systems were left behind, and interpretations of mineral ages based on the exclusive role of diffusion survived.

The evidence from textural-petrologic imaging (CL, BSE) and element mapping by electron probe microanalyzer (EPMA) or high spatial resolution SIMS or LA-ICP-MS provides the decisive constraints. All microcline and mica geochronometers that have been characterized in detail document patchy textures and evidence for mineral replacement reactions. It is important not to confuse causes and effects; heterochemical microstructures are not the *cause* of Ar and Sr loss; rather, they *follow* it. Ar and Sr loss by dissolution of the older mineral generation occurs first, heterochemical textures form later, when the replacive assemblage recrystallizes. Heterochemical mineral generations are identified and dated by their Ca/Cl/K systematics in ^{39}Ar-^{40}Ar. Replacive reactions adding or removing Cl, such as, e.g., sericite overgrowths on K-feldspar, retrograde muscovite intergrowths with phengite, etc. are detected by Cl/K vs. Ar/K isotope correlation diagrams. Ca-poor reaction products, such as, e.g., young biotite intergrown with older amphibole, adularia replacing microcline, etc., can be easily identified by Ca/K vs. Ar/K diagrams supported by EPMA analyses. Mixed mineral generations are observed to be the cause of discordant, staircase-shaped age spectra, while step-heating of crystals with age gradients produces concordant plateaus. Age gradients are therefore unrelated to staircase age spectra.

There is a profound analogy between the U-Pb, Rb-Sr, and K-Ar systems. Pb and Ar diffusion rates are both much slower than mineral replacement rates for all $T < 750$ °C. Patchy retrogression textures are always associated with heterochemical signatures (U/Th ratios, REE patterns, Ca/Cl/K ratios). As a rule, single-generation minerals with low amounts of radiation damage give concordant ages, whereas discordance is caused by mixtures of heterochemical, resolvably diachronous, mineral generations in petrologic disequilibrium. This can also include (sub-)grains that have accumulated significant amounts of radiation damage. For accurate geochronology the petrologic characterization with the appropriate technique(s) of the minerals to be dated, and the petrologic context at large, are as essential as the mass spectrometric analyses.

Keywords: Geochronology, U-Pb dating, Rb-Sr dating, K-Ar dating, mineral zoning, ^{39}Ar-^{40}Ar age spectra, U-Pb concordia

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