Isotopic closure

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For over 3 decades, field geologists have been using a very simple concept, that of 'closure temperature' to characterize isotope exchange between dated minerals and their surroundings. Jäger (1967) formulated the 'closure temperature' working hypothesis, which was soon found to be such a convenient tool that it escaped critical assessment. It gradually became the foundation of a complex edifice, in which the isotope exchange of every known mineral was assigned a 'closure temperature' ultimately calibrated on the micas of the Central Alpine gneisses. This edifice is very rigid, in the sense that it is impossible to change either assumptions or calibrations without producing a chain of inconsistencies.

However, the 'closure temperature' concept is an oversimplification of present-day understanding both of mineralogy (Parsons and Brown, 1984) and petrology (Kerrick, 1994).

Re-examining the original data-base of 60 white mica and 90 biotite ages of Jäger (1967), it becomes obvious that the concentric regularity of 'cooling ages' is less clear-cut than Jäger's interpretation; in particular, the role of mineral alteration reactions, documented by Arnold and Jäger (1965), was ignored. Furthermore, extrapolating the Jäger calibration to high-temperature minerals such as titanites, monazites or garnets implies diffusivity estimates that are seriously inconsistent with recent laboratory diffusion experiments based on direct depth profiling of tracer isotopes (e.g. Cherniak, 1995). However, this unsatisfactory situation has never been placed into a broader context, in which the three large literature data-sets of high-resolution mineralogical analyses, closely spaced sample collection in the field, and physical modelling of real atoms in real lattices are combined into a self-consistent perspective.

The Pb diffusivity experiments make it clear that volume diffusion is an extremely slow process. This accounts for the growing number of reports that in dry natural examples the Pb isotopic record is hardly if at all modified after crystallization.

The apparent paradox of zircons, whose Pb survives magmatic temperatures but succumbs to greenschist overprint, strongly supports the more realistic paradigm that it is not thermally induced diffusion that produces the largest isotopic transport, but rather fluid circulation, even though the temperature was lower by 700 K.

The suggestion that fluids enhance mineral recrystallization is not new to mineralogists, but its importance for isotopic systems has always been dismissed as 'alteration'. Only recent HRTEM work has been able to document that all minerals, even the apparently ideal ones, share a pattern of retrograde alteration.

Another insight that was not available at the time of Jäger's calibration of white mica 'thermochronology' was the preservation of mineralogical relics in the polymetamorphic gneisses on which 'closure temperatures' had been defined. The fact that white mica ages in Jäger's (1967) gneisses are always older than Alpine U/Pb minerals (titanites, monazites, garnets, zircons) is proof that pre-Alpine phengitic relics substantially pollute the isotopic record of Alpine muscovites. Indeed, Hammerschmidt and Frank (1991) obtained both ^{39}Ar/^{40}Ar age spectra and electron microprobe traverses on micas from gneisses in the Central Alps; their data show a correlation between degree of mineralogical inheritance and isotopic inheritance, i.e. between Si p.f.u. and age spectrum discordance.

Discriminating heterochemical relict phases on a purely isotopic basis (in case no competent petrographer is at hand) is made possible by stepwise release techniques such as Pb/Pb stepwise leaching (Frei *et al*, 1997) and ^{39}Ar/^{40}Ar (stepwise heating and laser profiling). The evidence from ongoing work is that mineralogical relics, as a rule, guarantee isotopic inheritance.

In summary, the isotopic exchange in minerals is controlled by fluid availability to promote recrystallization. Temperature plays a subordinate role in so far as the extremely low true volume diffusion is almost always overrun by fluid-assisted isotope transport.

If petrology provides P and T, but geochronology provides t and a_{H_2O}, how can the two ever be linked? The uncomfortable answer is that there is no ready-made shortcut, as the interplay between a very low volume diffusion and a very high fluid-assisted isotope exchange needs to be assessed for each sample individually with the help of petrography.

References

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