Closure temperature and geospeedometry – a comparative review

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When investigating isotopic ages of metamorphic minerals as indicators of cooling history, the traditional expression 'blocking temperature' was replaced by 'closure temperature' (Dodson, 1973) because mineral-isotopic systems do not necessarily open during a thermal pulse at the same temperature at which they close during cooling. For an isotopic dating system the closure temperature T_c may be defined as the system's temperature at the time corresponding to its apparent age. With various simplifying assumptions T_c may be related to diffusion parameters and grain geometry. The kinetic model presented by Dodson (1973) has antecedents in thermometric interpretations by Gentner et al. (1954) of K-Ar and U-He measurements on sylvites, and in Néel's (1947) analysis of palaeomagnetic blocking temperature. It uses the exponential nature of the Arrhenius relationship to introduce the 'cooling time constant', τ_c, which is the time needed for the diffusion coefficient to diminish by a factor e. In physical terms, at the closure temperature the isothermal diffusion time (very short at high temperatures, very long at low) is comparable with the cooling time constant. Provided metamorphic recrystallisation occurs well above the closure temperature, and the surface concentration of the diffusing component is always zero, the analytic solution for diffusional closure in a grain of size a is:

$$\frac{E}{RT_c} = \ln\left(A\frac{\tau_c D_0}{a^2}\right) \qquad (1)$$

in which A is a numerical constant dependent upon the shape of the grain, and the other symbols have their usual meanings. Although τ_c depends on cooling rate, its logarithmic relationship to T_c means that closure temperature is rather insensitive to cooling rate, so that cooling histories can in principle be determined accurately from two or more isotopic dating systems with different closure temperatures.

Some retrogressive chemical exchange geothermometers can be described by the same equation, notably if a trace component such as ^{18}O exchanges with an infinite, well-mixed reservoir. Here T_c is in principle known from the observable concentrations of the diffusing component in the grain and in the reservoir, so that τ_c and therefore cooling rate can be calculated. However, the cooling rate depends exponentially upon T_c, which limits its accuracy.

A closure profile - that is, the concentration distribution of a diffusing component after a system has completely closed - can be interpreted by a similar equation (Dodson, 1986) *under similar restrictive conditions.* (In other words, the closure profile may be regarded as a closure temperature distribution across a mineral grain.) Solutions to the more difficult problem of retrograde diffusional exchange *without* such restrictions were presented by Lasaga et al. (1977), and Lasaga (1983), who coined the term 'geospeedometry' for the determination of cooling rates from such data. In essence Lasaga investigates closure profiles prependicular to a grain boundary between two minerals, across which diffusional exchange (e.g. between Fe and Mg) is taking place. In his extreme case retrogressive effects do not penetrate into the interior of either grain, because diffusion at the peak metamorphic temperature is very slow, and the closure temperature calculated by (1) is much higher than the recrystallisation temperature. The problem therefore reduces to prediction of closure profiles in boundary layers at the contact between two semi-infinite solids. Here, although local closure temperatures could in principle be defined on the basis of local concentrations, they would not have any obvious physical meaning, because they would depend upon a more or less arbitrary choice of reference concentration in the other phase.

Differences in terminology and choice of mathematical symbols have obscured common features of these different approaches to closure of cooling mineral systems. Their common ground is explored, and an attempt is made to evaluate some more recent developments in this area of geoscience.

References

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