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Re-evaluating the closure temperature concept in metamorphic rocks: when does $^{40}Ar/^{39}Ar$ dating constrain exhumation?

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The determination of metamorphic cooling/exhumation rates using the apparent $^{40}Ar/^{39}Ar$ age of muscovite, important for underpinning tectonic models, is based on several simplifying assumptions including the concept of the Dodson closure temperature. These assumptions are shown to be invalid in a significant number of metamorphic scenarios where Ar diffusion is hindered, for example under certain pressure-temperature (PT) conditions, or when removal of Ar from the rock volume is inefficient due to low fluid contents and low permeability. Using numerical diffusion models which include a recently reported significant pressure dependence of Ar diffusion in muscovite, we systematically interrogate all the assumptions associated with $^{40}Ar/^{39}Ar$ dating. A simple graphic method for evaluating the PT regions in which $^{40}Ar/^{39}Ar$ dates could meaningfully constrain the timing of exhumation in an open system is presented. The link between apparent $^{40}Ar/^{39}Ar$ age and traditional "Dodson closure temperature" is found to be valid only when muscovite crystallizes under, or subsequently reaches, high temperature and relatively low pressure conditions in an open system. We show that open system behavior may be most reliably verified by comparing theoretical and measured $^{40}Ar/^{39}Ar$ age profiles across muscovite grains. We suggest that the most robust method for determining whether metamorphic muscovite $^{40}Ar/^{39}Ar$ ages relate to the timing of exhumation involves: (1) the determination of the pressure, temperature and time (PTt) conditions of muscovite crystallization, (2) the collection of high-precision and high spatial resolution $^{40}Ar/^{39}Ar$ profiles across muscovite and (3) the comparison between analytical data and numerical diffusion models. The results and discussion presented here for muscovite are equally applicable to other metamorphic minerals commonly dated using the $^{40}Ar/^{39}Ar$ system.