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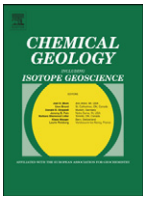

Argon redistribution during a metamorphic cycle: Consequences for determining cooling rates

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ABSTRACT

^{40}Ar/^{39}Ar thermochronology is commonly used to constrain the rates and times of cooling in exhumed metamorphic terranes, with ages usually linked to temperature via Dodson's closure temperature (T_C) formulation. Whilst many metamorphic ^{40}Ar/^{39}Ar data are consistent with the timing of crystallisation or cooling within a chronological framework defined by other, higher temperature, chronometers, other ^{40}Ar/^{39}Ar data are more difficult to interpret. We report white mica and biotite single grain fusion and laser ablation ^{40}Ar/^{39}Ar ages from felsic gneisses from the Western Gneiss Region, Norway. The rocks record isothermal decompression from peak eclogite-facies conditions (white mica stable) to amphibolite-facies conditions (biotite stable) at c. 700 °C. White mica and biotite yield dispersed single grain fusion dates from 416 to 373 Ma and 437 to 360 Ma respectively. In-situ laser ablation analyses provide a similar range, with white mica spot ages ranging from 424 to 370 Ma and biotite spot ages ranging from 437 to 370 Ma. The dates span the duration of the metamorphic cycle suggested by previous studies, and cannot be reconciled with the results of simple models of Ar loss by diffusion during cooling. Samples that show evidence for different physical processes, such as the chemical breakdown of white mica, partial melting, and fluid ingress, generated different age populations to samples that did not experience or record obvious petrological evidence for these processes. Samples that record significant recrystallization and deformation yielded younger white mica (but older biotite) single grain fusion ages than more pristine samples. Amphibolite-facies gneisses that preserve evidence for significant partial melting generated younger biotite ages than samples that recorded evidence for significant hydration. Our data support other reported observations that high-temperature metamorphic mica ^{40}Ar/^{39}Ar dates cannot be assumed to record the timing of cooling through a specific temperature window. Careful assessment of the petrographic context of the dated minerals and consideration of their post-crystallisation history may provide a more robust insight into whether ‘age’ links to ‘stage’ in a temporally meaningful way.

1. Introduction

Understanding the timing of when, and the rate at which, metamorphic terranes are exhumed through the Earth's mantle and crust is important for constraining geodynamic models of tectonic processes. ^{40}Ar/^{39}Ar mica thermochronology is typically employed to constrain exhumation and cooling rates, with age most commonly being linked to temperature via the Dodson closure temperature (T_C) formulation (Dodson, 1973). This solution to the diffusion equation is only applicable for geological applications under the following boundary conditions: (1) negligible initial lattice-hosted ^{40}Ar during crystallisation (i.e. a very low mineral:fluid partition coefficient), (2) Ar distribution within the mineral controlled only by thermally-activated volume diffusion that adheres to Fick's 2nd law of diffusion (modified for a source term), (3) an ‘open’ grain boundary network (i.e. the grain boundary effectively has a negligible concentration of Ar) during the temperature interval over which within-grain Ar diffusion is efficient and (4) initial crystallisation at a temperature at which within-grain Ar diffusion is efficient.

As geochronological data continues to be collected at ever-higher spatial resolution and analytical precision, it is becoming possible to test some, but not all, of the listed boundary conditions. This is important for determining the geological scenarios in which the Dodson T_C formulation is justifiably applicable vs. those situations where it is not. For example mineral thermobarometers provide estimates of

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metamorphic pressure-temperature conditions at different stages of the rock evolution, which, when coupled to experimental diffusion parameters, provide insight into whether a specific rock reached temperatures high enough for efficient diffusion in different minerals (c.f. Warren et al., 2012c). In-situ laser ablation profiles across grains of sufficient size can provide evidence for diffusion (e.g. Wartho and Kelley, 2003). Petrological modelling and a temporal framework based on independent higher-temperature chronometers coupled with diffusion modelling provide a solid platform for assessing open system behaviour and/or incorporation of initial ^{40}Ar during crystallisation.

Over the last few decades, a significant number of studies have shown that micas in high pressure (>15 kbar) metamorphic rocks appear to be particularly prone to yielding ^{40}Ar/^{39}Ar ages that are "too old" relative to other independently constrained 'events' along their *P-T* paths. For example, despite temperatures high enough for theoretically effective diffusion, ^{40}Ar/^{39}Ar data from high pressure micas commonly produce ages that are older than the timing of peak metamorphism from zircon U-Pb data, or relative to the petrographically-constrained timing of mica crystallisation, (Foland, 1979; Li et al., 1994; Arnaud and Kelley, 1995; Scaillet, 1996; Ruffet et al., 1997; Sherlock and Arnaud, 1999; Baxter et al., 2002; Warren et al., 2012a). Studies suggest that the incorporation of "excess" ^{40}Ar (^{40}Ar$_E$, decoupled from its parent ^{40}K) by diffusion from the grain boundary into the mineral lattice and/or lattice defects, or during deformation or (re)crystallisation may modify ^{40}Ar concentrations (Li et al., 1994; Ruffet et al., 1997; Pickles et al., 1997; Villa, 1998; Sherlock and Kelley, 2002; Wartho and Kelley, 2003; Di Vincenzo, 2004; Warren et al., 2011). Other studies suggest that non-zero grain boundary conditions were experienced during or after crystallisation: high Ar concentrations in the grain boundary would hinder efficient diffusive loss of Ar, and lead to inherited ages that are older than predicted by the Dodson T$_C$ formulation, but younger than the timing of mineral crystallisation (c.f. Baxter et al., 2002). Recent experimental data additionally suggest that Ar diffusion in white mica is pressure- as well as temperature-dependent (Harrison et al., 2009), suggesting higher Ar retention than previously suspected at metamorphic pressures >10 kbar.

^{40}Ar/^{39}Ar data may therefore relate to the timing of mineral crystallisation, the timing of cooling through a specific temperature or temperature interval (specifically whether they adhere to the Dodson T$_C$ formulation), or may be geologically meaningless. Determining between these options is important for quantifying rates and timescales of tectonic processes. Here we track the incorporation, release, and transport of Ar within and between different minerals during a metamorphic cycle, and especially during the exhumation-related, retrograde metamorphic reactions. The study of such processes informs the assessment of the main mechanism(s) for redistributing Ar within minerals, and provides example cases for which ^{40}Ar/^{39}Ar may or may not be reliably linked to temperature via the Dodson T$_C$ formulation.

Mid- to lower-crustal felsic gneisses exposed in the Western Gneiss Region (WGR), western Norway provide an excellent natural laboratory for determining Ar behaviour during a burial-exhumation cycle because the gneisses are broadly similar in composition but preserve different stages of the metamorphic evolution. The WGR experienced a high temperature evolution (~700 °C) for 10–15 Ma (Wain et al., 2000, Hacker, 2007, Spencer et al., 2013, Kylander-Clark & Kylander-Clark and Hacker, 2014) – long enough for diffusive processes to have been, in theory, efficient enough for all micas of the same grain size and composition to retain the same ^{40}Ar/^{39}Ar age (Warren et al., 2012b). Published white mica ^{40}Ar/^{39}Ar multi- and single-grain step heating ages from the Outer Nordfjord area range from 409 to 380 Ma and are interpreted as cooling ages (Root et al., 2005; Young et al., 2011). Published white mica and biotite ^{40}Ar/^{39}Ar multi- and single-grain step heating ages from the Outer Nordfjord area range from 389 to 374 Ma and 402 to 375 Ma, respectively, and interpreted as cooling ages (Lux, 1985; Berry et al., 1995; Hacker and Gans, 2005; Root et al., 2005; Walsh et al., 2007; Young et al., 2011; Walsh et al., 2013). More recent single grain fusion and in-situ laser ablation techniques have yielded highly variable white mica ^{40}Ar/^{39}Ar ages, both within and between grains in the same sample, as well as between different samples (Warren et al., 2012a). The range generated by the single grain fusion data was greater than the range expected from diffusive loss in different grain sizes. Furthermore, the spatial patterns that the in-situ data showed were inconsistent with diffusive loss on cooling.

Here we systematically document age populations from samples that show evidence for different physical processes including mineral breakdown/replacement, deformation, partial melting, and hydration, and compare them with age populations from samples that have not experienced or recorded evidence for these processes. Our data show that all samples generate a range of ^{40}Ar/^{39}Ar ages spanning at least 15 Ma. Samples that preserve evidence for significant recrystallization and deformation displayed younger white mica, but older biotite, single grain fusion age populations than more pristine samples. Amphibolite-facies gneisses preserving evidence for significant partial melting yield younger biotite

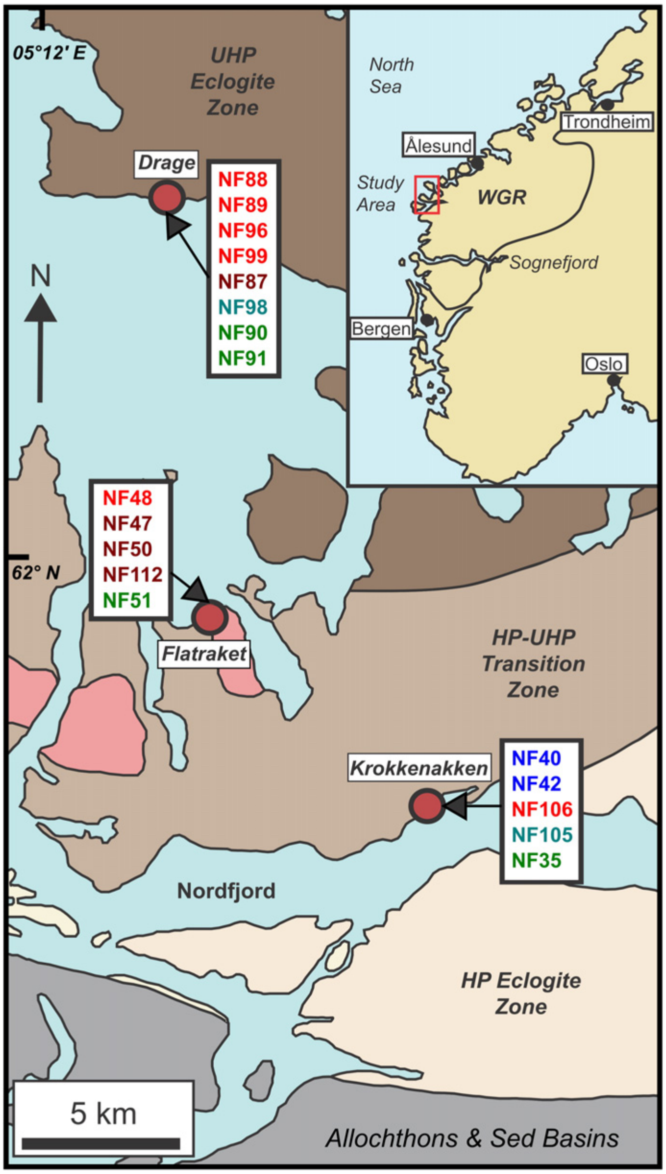

Fig. 1. A simplified geological map, modified after Wain (1997), of the Outer Nordfjord region of the Western Gneiss Region (WGR), Norway, showing the locations of the study sites and the sample numbers collected from each locality. The sample numbers are colour-coded to reflect the petrological groups defined in the text. Blue = Group 1a; Red = Group 1b; Brown = Group 1c; Teal = Group 2a; and Green = Group 2b. UHP = ultra-high pressure; HP = high pressure.