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Influence of deformation and fluids on Ar retention in white mica: Dating the Dover Fault, Newfoundland Appalachians

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A B S T R A C T

White mica $^{40}Ar/^{39}Ar$ analyses may provide useful constraints on the timing of tectonic processes, but complex geological and thermal histories can perturb Ar systematics in a variety of ways. Ductile shear zones represent excellent case studies for exploring the link(s) between dynamic re-/neo-crystallization of white mica and coeval enhanced fluid flow, and their effect on $^{40}Ar/^{39}Ar$ dates. White mica $^{40}Ar/^{39}Ar$ dates were collected from compositionally similar granites that record different episodes of deformation with proximity to the Dover Fault, a terrane-bounding strike-slip shear zone in the Appalachian orogen, Newfoundland, Canada. $^{40}Ar/^{39}Ar$ data were collected ***in situ*** by laser ablation and by step heating single crystals. Results were compared to each other and against complementary U–Pb zircon and monazite, and K-Ar fault gouge analysis.

Although step-heat $^{40}Ar/^{39}Ar$ is a widely applied method in orogenic settings, this dataset shows that relatively flat step-heat $^{40}Ar/^{39}Ar$ spectra are in contradiction with wide spreads in *in-situ* $^{40}Ar/^{39}Ar$ dates from the same samples, and that plateau dates in some cases yielded mixed dates of equivocal geological significance. This result indicates that the step-wise release of Ar from white mica likely homogenizes and obscures spatially-controlled Ar isotope reservoirs in white mica from sheared rocks. In contrast, *in situ* laser ablation $^{40}Ar/^{39}Ar$ analysis preserves the spatial resolution of ^{40}Ar reservoirs that have been variably reset by deformation and fluid interaction. This study therefore suggests that laser ablation is the best method for dating the timing of deformation recorded by white mica. Final interpretation of results should be guided by microstructural analysis, estimation of deformation temperature, chemical characterization of white mica, and complementary chronometers.

Overall the dataset shows that granitic protoliths were emplaced between 430 and 422 Ma (U–Pb zircon). High strain deformation along the Wing Pond Shear Zone occurred between ca. 422–405 Ma (U–Pb monazite and $^{40}Ar/^{39}Ar$). Subsequent patchy Ar loss in white mica occurred locally during low T shear (<400 C), and via post-deformation fluid interactions. Low-temperature reactivation of the Dover Fault, a narrow segment of the Wing Pond shear zone, occurred at ca. 385 Ma ($^{40}Ar/^{39}Ar$). K-Ar dating of authigenic illite in fault gouge from the broadly co-linear brittle Hermitage Bay Fault indicates that slip along the terrane boundary persisted until at least the Mississippian.

1. Introduction

The $^{40}Ar/^{39}Ar$ step heating method applied to white mica is a common and valuable tool for studying metamorphic rocks (e.g. Bröcker et al., 2013; Forster and Lister, 2014; McWilliams et al., 2013). The method of progressively releasing Ar from white mica crystals has been proposed to mimic diffusion of Ar in nature. The age patterns reflected by Ar release spectra are often interpreted as corresponding to Ar distribution in the crystal(s) such that the thermal history of the grain(s) can be recovered (e.g. Harrison et al., 2009; Kula and Spell, 2012). However, metamorphosed and deformed rocks often record complex geological and thermal histories. The thermal history may be in competition with other physical processes that influence final Ar distributions in white mica grains and consequently, step-heat release spectra can be difficult to interpret or can yield equivocal results. For example, “inherited” Ar, relating to ^{40}Ar formed at an earlier time than the episode being dated, may persist in white mica if insufficient time was spent at temperatures that promote fast diffusion (in practice, well above its Ar closure temperature; Monié, 1990; Mottram et al., 2015; Viete et al., 2011). Moreover, white mica can grow during protracted low temperature metamorphism, at conditions for which thermal

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diffusion of Ar is inefficient (Reuter and Dallmeyer, 1989). Deformation can promote mica recrystallization or neocrystallization (Mulch and Cosca, 2004; Mulch et al., 2005; Sherlock et al., 2003), and can alter the effective white mica Ar diffusion distance (Cosca et al., 2011; Kramar et al., 2001). Finally, fluid infiltration, or lack thereof, can impact ^{40}Ar content in white mica, through the introduction of extraneous Ar, inefficient removal of radiogenic Ar, or by promoting mineral alteration (e.g. Warren et al., 2012a; review in Kelley, 2002). *In situ* and single grain fusion techniques can reveal complexities in the ^{40}Ar composition of white mica resulting from these processes that are otherwise obscured or homogenized in step heating experiments.

Ductile shear zones represent excellent case studies for exploring the link between dynamic re−/neo-crystallization of white mica and coeval enhanced fluid flow at a variety of temperatures. In this study we investigate the influence of deformation and fluids on Ar behavior in white mica from compositionally similar granites with different deformation patterns relating to the Dover Fault, a terrane-bounding strike-slip shear zone in the Appalachian orogen of Newfoundland, Canada. Detailed age information extracted from spatially-controlled *in-situ* ^{40}Ar/^{39}Ar analyses is compared to step-heat spectra obtained from single crystals separated from the same samples. ^{40}Ar/^{39}Ar data are bracketed by complementary U–Pb zircon and monazite age data, which record the timing of (re-)crystallization of those accessory phases. Brittle fault movement that formed a well-developed gouge within the Hermitage Bay Fault zone is constrained by dating of authigenic illite using the conventional K-Ar method (see Zwingmann and Mancktelow, 2004; Zwingmann et al., 2010) and confines the timing on the latest active retrograde deformation event along the terrane boundary. These data together demonstrate the value of high spatial resolution ^{40}Ar/^{39}Ar age data in elucidating the thermal and deformational histories of deformed and metamorphosed rocks. Furthermore, our data permit a time reconstruction of the deformation history of the Ganderian margin during the Salinic, Acadian and Neoacadian orogenies by direct dating of fault rocks.

2. Geological framework

The Appalachian–Caledonian orogenic system exposed in eastern North America, eastern Greenland, Scandinavia and central Europe records the Paleozoic, progressive closures of the Iapetus, Tornquist and Rheic oceans, and associated episodic accretionary events that culminated in the formation of the Pangaea supercontinent (van Staal et al., 1998, 2009). Within the eastern Canada Appalachians, accretion of the Dashwoods, Ganderia, Avalonia and Meguma terranes (and associated arcs, back-arcs and oceanic fragments) was accompanied by progressively eastward shifts (in present day coordinates) of orogenic deformation, metamorphism and magmatism, identified as the Taconic (495–450 Ma), Salinic (445–422 Ma), Acadian (421–400 Ma) and Neoacadian (400–350 Ma) orogenies, respectively (van Staal and Barr, 2012; van Staal et al., 2009). Amalgamation of the Newfoundland Appalachians was completed by the arrival of the Avalonia microcontinent against the eastern trailing margin of Ganderia. The accretionary nature of the Appalachian orogen is such that orogenic events are polyphase (shown by e.g., overprinting relationships), and diachronous (e.g., closure at one margin may have been coeval with initial collision elsewhere). Thus, the precise time–space relationships of the distinct orogenies are complex. For example, the western leading edge of Ganderia was still undergoing the late stages of the Salinic orogeny at the time of the onset of Acadian-related arc magmatism and deformation at its eastern trailing edge (van Staal et al., 2009, 2014).

The Ganderia microcontinent consists of Late Neoproterozoic–Ordovician arc and associated clastic metasedimentary rocks, whereas Avalonia comprises sub-greenschist facies Neoproterozoic volcanic, plutonic and sedimentary rocks overlain by Cambrian–Ordovician platform cover sequences (Hibbard et al., 2006; van Staal and Barr, 2012; van Staal et al., 2009). Though both microcontinents share Gondwanan affinity and Neoproterozoic basement, their distinct early Paleozoic geological records indicate that they were independent terranes prior to their amalgamation during the Acadian orogeny (e.g. Murphy et al., 2002; van Staal et al., 1996).

The docking of lower plate Avalonia against upper plate Ganderia occurred along a NE-striking sinistral-oblique transpressional margin; in Newfoundland, the Ganderia–Avalonia suture coincides with the Dover Fault (Fig. 1; Blackwood and Blackwood and Kennedy, 1975; Dallmeyer et al., 1981; Holdsworth, 1994) and is correlated at depth with a geophysically-defined crustal-scale structure that offsets the Moho (Keen et al., 1986; Marillier et al., 1989; Stockmal et al., 1990). Sinistral shear is recorded in a ~20 km wide NE-striking zone of ductile shear that parallels the Dover Fault and the Wing Pond shear zone (Fig. 1; Holdsworth, 1994). Earliest sinistral shear was at least partly coeval with Silurian development of an eastward-increasing metamorphic field gradient within Ganderian rocks that reached sillimanite-grade at the terrane margin and was accompanied by anatexis and widespread syn-tectonic pluton emplacement (D'Lemos et al., 1997; Holdsworth, 1994). A subsequent narrow dextral ductile to brittle-ductile shear zone, the Dover Fault, formed under lower greenschist-facies conditions, locally overprinting the Silurian Wing Pond shear zone (D'Lemos et al., 1997; Holdsworth, 1994). The post-tectonic Ackley granite stitches the Dover Fault and provides a minimum age for displacement along the terrane boundary of 377 ± 4 Ma (Fig. 1; Kellett et al., 2014).

Whereas the general and relative timing of the Wing Pond and Dover Fault shear zones are established from magmatic rocks that exhibit syn-tectonic and cross-cutting relationships (Holdsworth, 1994), direct dating of different movement histories recorded by the mylonites has not previously been attempted. Although the docking of Avalonia against Ganderia is genetically associated to the Acadian orogeny, the Silurian–Devonian deformation and metamorphism history of the eastern Ganderian margin and particularly the Wing Pond and Dover Fault shear zones may record components of Salinic, Acadian *and/or* Neoacadian events (e.g. Dunning et al., 1990; Holdsworth, 1994; Schofield and D'Lemos, 2000; van Staal, 1994; van Staal et al., 2009). Thus better timing constraints on sinistral and dextral shear episodes are imperative for elucidating the tectonic response of this plate boundary to the different accretionary events.

3. Sample descriptions and microstructural characterization

Samples were collected from four granites that were syn-tectonically emplaced at the trailing edge of the Ganderia microcontinent, as well as fault gouge from the Hermitage Bay Fault, the interpreted southern extension of the Dover Fault (Fig. 1). Each sample represents a different structural setting, in order to examine the Ar systematics within different deformation regimes in the region of the Dover Fault (Fig. 2E). Sample locations are given in Table 1 and on Fig. 1. White mica back-scattered electron (BSE) and chemical maps (Al, K, Ca, Fe and Si) were obtained and quantitative compositions calculated from electron microprobe analyses (summarized in Table 2, methods in supplementary data, full results in Table A1, Figs. A1–A4).

We also conducted a microstructural investigation of samples VL-12-NF-08, 12-KNA-002, 12-KNA-005 and 12-KNA-006, including quartz *c*-axis crystallographic fabric analysis, to constrain deformation conditions for the white mica. Thin sections of the samples collected were cut parallel the macroscopic stretching lineation and perpendicular to the dominant foliation (where present). Quartz *c*-axis orientations were determined using a Russell-Head Instruments G60 Automated Fabric Analyser. Quartz *c*-axis data from previous versions of the instrument, which have similar optical systems to the G60 used in this study, are indistinguishable from data generated using electron back-scatter diffraction methods (Peternell et al., 2010; Wilson et al., 2007).