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Grain-size effects on the closure temperature of white mica in a crustal-scale extensional shear zone — Implications of in-situ $^{40}Ar/^{39}Ar$ laser-ablation of white mica for dating shearing and cooling (Tauern Window, Eastern Alps)

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ABSTRACT

In-situ $^{40}Ar/^{39}Ar$ laser ablation dating of white-mica grains was performed on samples from the footwall of a crustal-scale extensional fault (Katschberg Normal Fault; KNF) that accommodated eastward orogen-parallel displacement of Alpine orogenic crust in the eastern part of the Tauern Window. This dating yields predominantly cooling ages ranging from 31 to 13 Myr, with most ages clustering between 21 and 17 Myr. Folded white micas that predate the main Katschberg foliation yield, within error, the same ages as white-mica grains that overgrow this foliation. However, the absolute ages of both generations are older at the base (20 Myr) where their grain size is larger (300–500 μm), than at the top and adjacent to the hangingwall (17 Myr) of this shear zone where grain size is smaller (<100–300 μm). This fining-upward trend of white-mica grain size within the KNF is associated with a reduction of the closure temperature from the base (~445 °C) to the top (<400 °C) and explains the counter-intuitive trend of downward-increasing age of cooling in the footwall. The new data show that rapid cooling within the KNF of the eastern Tauern Window started sometime before 21 Myr according to the $^{40}Ar/^{39}Ar$ white-mica cooling ages and between 25–21 Myr according to the new Rb/Sr white-mica ages, i.e., shortly after the attainment of the thermal peak in the Tauern Window at ~25 Myr ago. These new data, combined with literature data, support earlier cooling in the eastern part of then Tauern Window than in the western part by some 3–5 Myr.

1. Introduction

Determining the timing of cooling of deeply buried basement rocks is crucial for evaluating the age and rates of exhumation in orogens and for understanding the mechanisms of exhumation, e.g., the relative importance of tectonic unroofing and erosional denudation (e.g., Ring et al., 1999; Reiners and Brandon, 2006). In the Alps, two Oligo–Miocene thermal domes (Lepontine Dome, Tauern Window; "L" and "T" in inset of Fig. 1) overprint an early Cenozoic nappe stack whose units derive from the accreted European lower plate of the Alpine orogen. Conventional thermochronology paired with petrological studies over the past four decades has shown that exhumation of both domes largely occurred in Miocene time (e.g., Clark and Jäger, 1969; Wagner and Reimer, 1972; Selverstone, 1988; Grasemann and Mancktelow, 1993; Fügenschuh et al., 1997; Neubauer et al., 1999; Luth and Willingshofer, 2008; Campani et al., 2010; Fox, 2012). However, recent in-situ dating reveals that cooling in the Tauern Window was heterogeneous and related to a combination of folding, extensional faulting and erosion (Scharf et al., 2013a).

The Tauern Window comprises two main structural and metamorphic domes: the Western and Eastern Tauern domes (WTD, ETD; Fig. 1a). These expose post-nappe amphibolite-facies metamorphism in their cores and are flanked at either end by low-angle normal faults: the Brenner and Katschberg normal faults (BNF, KNF; Selverstone, 1988; Behrmann, 1988; Genser and Neubauer, 1989). Most authors relate the

Abbreviations: BNF, Brenner Normal Fault; ETD, Eastern Tauern Dome; KNF, Katschberg Normal Fault; WTD, Western Tauern Dome.

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exhumation of the basement nappes contained in these domes to the northward indentation of that part of the Adriatic Microplate located south of the Tauern Window and east of the Giudicarie Belt (Scharf et al., 2013a and references cited therein). This late-stage deformation in front of the indenter involved a combination of broadly coeval post-nappe folding, orogen-parallel extension and erosion (e.g., Ratschbacher et al., 1991; Fügenschuh et al., 1997; Rosenberg et al., 2007; Schmid et al., 2013). However, distinguishing the relative contribution of these mechanisms has proved elusive. Compilations of the available thermochronometric data indicate that rapid exhumation (~1 mm/yr) and cooling (≤40 °C/Myr; Foeken et al., 2007) began and ended earlier in the eastern part of the Tauern Window than in the western part (e.g., Luth and Willingshofer, 2008; Scharf et al., 2013a). At first sight this is at odds with analogue models of Adriatic Microplate indentation in the Eastern Alps that predict synchronous exhumation of units in the entire Tauern Window (Ratschbacher et al., 1991; Rosenberg et al., 2007).

The amount and quality of data in the Tauern Window are not uniform. Exhumation and cooling of the western Tauern Window are fairly well constrained by thermochronometry and thermal modelling (e.g., von Blanckenburg et al., 1989; Genser et al., 1996; Fügenschuh et al., 1997). In contrast there is a relative dearth of such work in the east where past efforts (e.g., Cliff et al., 1985; Droop, 1985; Dunkl et al., 2003) have not been complemented by thermal modelling.

This paper presents new $^{40}Ar/^{39}Ar$ laser-ablation ages from white-mica aggregates and new Rb/Sr white-mica ages from the footwall of the KNF. After a brief introduction to the geological setting and methods, the in-situ age data are presented in their microstructural and metamorphic contexts. It is shown that the ages obtained do not vary with growth generation in the same sample, but with average size of the grains in the KNF. This pronounced grain-size dependence of the new $^{40}Ar/^{39}Ar$ laser-ablation ages is used to track the cooling history of the eastern Tauern Window during activity of the KNF. It is argued that cooling migrates from the base of a low-angle normal fault (445 °C) towards the top, near the hangingwall (<400 °C). This cooling trend is best explained with the smaller grain-size of the white mica and, therefore lower closure temperature towards the top of the normal fault. Finally, a comparison of the cooling histories of the eastern and western parts of the Tauern Window discusses the implications for determining whether large-scale exhumation and cooling of orogenic crust was triggered during collision or later, during indentation of the Adriatic Microplate.

2. Geological setting

2.1. Tectonic overview

The nappe stack exposed in the Tauern Window formed during convergence and collision of the Adriatic and European plates in late Cretaceous to Cenozoic times (e.g., Trümpy, 1960; Frisch, 1979; Stampfli et al., 2001; Schmid et al., 2004; Handy et al., 2010). From top to bottom, this nappe stack comprises oceanic (Penninic units: Matreier Zone and Glockner Nappe System) and Europe-derived (Subpenninic units: Modereck and Venediger nappe systems) crustal units, some of which experienced high-pressure subduction metamorphism prior to nappe stacking (Kurz et al., 2008). These units were refolded, imbricated and partly exhumed in Oligo–Miocene time before undergoing final exhumation during coeval doming and orogen-parallel extrusion of the entire orogenic edifice towards the Pannonian Basin (e.g., Ratschbacher et al., 1991; Royden, 1993; Decker et al., 1994; Peresson and Decker, 1997; Frisch et al., 1998; Scharf et al., 2013a; Schmid et al., 2013). The Austroalpine units surrounding and overlying this nappe stack represent an earlier orogenic wedge that formed in late Cretaceous time (Eo-Alpine Orogeny Frank, 1987; Froitzheim et al., 1994, 2008; Handy et al., 2010). The base of this wedge that directly overlies the Penninic nappes shows latest Cretaceous to Cenozoic Rb/Sr and $^{40}Ar/^{39}Ar$ ages (Brewer, 1969; Hawkesworth, 1976; Liu et al., 2001) and is highly retrogressed. The ETD and WTD (Fig. 1a) expose Subpenninic basement units that experienced upper greenschist- to amphibolite-facies Barrovian-type thermal overprinting (the so-called "Tauernkristallisation"; Sander, 1911) at 30–28 Myr (Inger and Cliff, 1994; Thöni, 1999; Kurz et al., 2008). This thermal event may have lasted until 25 Myr according to new Sm/Nd ages of garnets from the WTD (Pollington and Baxter, 2010) and ETD (Favaro et al., 2015), and it overprinted a duplex system within the Europe-derived basement rocks (Venediger Duplex; Lammerer and Weger, 1998; Scharf et al., 2013a; Schmid et al., 2013).

Subsequent to this thermal overprint both Tauern domes were sheared, especially near their margins, i.e., adjacent to the overlying Austroalpine units, during final unroofing and exhumation in latest Oligocene to early Miocene time (e.g., Fügenschuh et al., 1997; Scharf et al., 2013a; Schmid et al., 2013). The Southern Alps, located south of the Periadriatic Fault and east of the Giudicarie Belt (PF and GB; Fig. 1a), were unaffected by Alpine metamorphism and represent the Adriatic Microplate Indenter in map view (Rosenberg et al., 2007). The leading edge of this indenter also included Austroalpine units north of the Periadriatic Fault and south of the Tauern Window that show little or no ductile overprint and behaved as rigid blocks during indentation (Scharf et al., 2013a).

The KNF as first described by Genser and Neubauer (1989) is a 5 to 10 km thick mylonite belt which is overprinted by cataclasites developed towards the hangingwall (Fig. 1b; see Scharf et al., 2013a and Schmid et al., 2013 for further details). The lower limit of this mylonite belt is defined by the transition from gneisses of the Venediger Nappe Complex below to a pervasive mylonitic fabric carrying a E to ESE-plunging stretching lineation within the KNF. The top of the KNF comprises 100–200 m of greenschist facies mylonite capped by cataclasites that also affect basal Austroalpine units along the eastern margin of the KNF (Fig. 1b; Scharf et al., 2013a).

2.2. Samples and their locations

Seven samples were collected from the KNF along the north-eastern margin of the Tauern Window (see Fig. 1b, Table 1 & Appendix S1 for exact locations, lithologies and tectonic units). The main foliation in these samples is oriented parallel to the macroscopic shearing plane of the KNF and is therefore assumed to have been active during orogen-parallel extensional exhumation. The protoliths of these samples comprise basement gneiss of the Venediger Nappe System and its cover, basement gneiss of the Modereck Nappe System, as well as calc-schists and metapelites of the Glockner Nappe System. Two additional samples, AS36 and AS63, are from above (hangingwall) and below (footwall) the KNF, respectively. The sample from below is a paragneiss of the post-Variscan cover from the Venediger Nappe System, whereas the sample from above is a paragneiss of the Radenthein Complex belonging to the Koralpe–Wölz Nappe System of the Upper Austroalpine Unit. The ages of the white-mica grains from the seven KNF samples are expected either to date cooling to below a grain-size dependent closure temperature, or alternatively, to date white-mica formation (see review of Villa, 2010).

3. Methods

3.1. Sample preparation for $^{40}Ar/^{39}Ar$ and Rb/Sr dating

The $^{40}Ar/^{39}Ar$ in-situ laser ablation technique (e.g., Kelley et al., 1994) was combined with micro-structural investigations of grain aggregates and single grains to constrain the tectono-thermal history of the eastern Tauern Window. Microprobe-quality polished samples 1 mm thick and with a diameter of 7 mm were drilled from the samples oriented parallel to the stretching lineation and perpendicular to the main foliation of the KNF.

Prior to laser ablation, samples were investigated with an electron microprobe (JEOL JXA-8200 at the Freie Universität Berlin) to