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U–Pb ages of apatite in the western Tauern Window (Eastern Alps): Tracing the onset of collision-related exhumation in the European plate

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ABSTRACT

We performed single spot U–Pb analyses of zircons and apatites from eighteen samples distributed along three sections crossing the western Tauern Window (Eastern Alps). Zircon analyses yield concordant ages of ∼295 Ma dating the Variscan emplacement of the Zentralgneiss batholith. Common Pb-corrected apatite U–Pb ages show two age groups; the first is characterized by apparent $^{206}\text{Pb}/^{238}\text{U}$ ages scattering between ∼300 and 40 Ma and a second having a relatively uniform cluster of age values around 30 Ma. We applied an age extractor algorithm (TuffZirc ISOPLOT) to all apatite analyses of each sample to calculate median ages from the younger age cluster and asymmetric 2σ errors as their uncertainties, which are mostly in the range of ∼10%. These median ages are interpreted to date cooling below ∼450–500 °C during Alpine orogeny after the thermal climax of Barrovian metamorphism in the western Tauern Window. Cooling ages give a consistent pattern over the study area of ∼31–29 Ma. Along each section younger cooling ages were obtained in the center compared to its margins. The eastern section shows older cooling ages of ∼36–34 Ma whereas the western section younger cooling ages of ∼26–25 Ma. The reliability of both age trends, (1) younging towards the centers of the sections and (2) younging towards the west across all three sections were verified by six independent two-sample Student's t-tests. Spatially the cooling age pattern resembles those observed from geochronometers having lower closure temperatures (∼375–110 °C), that are largely related to doming of the Tauern Window. Cooling rates of five samples, where additional fission track ages are available, yielded uniform results and were averaged to 15.3 ± 1.9 K/Myr (2σ). Linear extrapolation using the specific cooling rates and the estimated maximum temperature (T_{max}) indicates a time range of ∼37–34 Ma, interpreted to date the thermal climax of Barrovian metamorphism in the western Tauern Window.

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1. Introduction

Apatites contain a moderately high concentration of lattice-bound uranium (∼5–50 ppm), hence they are suitable for U–Th–Pb chronology (Harrison et al., 2002; Willigers et al., 2002; Chew et al., 2011). Apatite is stable at epidote–amphibolite-facies conditions and largely inert to recrystallization during metamorphism, i.e. at temperatures that are typically higher than the apatite closure temperature for Pb diffusion (∼500 °C, Cherniak et al., 1991). Therefore, apatite U–Pb systematics are controlled by diffusion rather than growth or recrystallization (Willigers et al., 2002). They showed that the formerly assumed closure temperature of ∼620 °C for U–Pb apatite was overestimated, because K/Ar hornblende ages of the same samples and areas are consistently older than U–Pb ages of apatite. Based on these results the authors calculated a closure temperature of ∼500 °C for U–Pb apatite. Chamberlain and Bowring (2000) showed that U–Pb of apatite and cogenetic feldspar is a mid-range (∼450 °C), diffusion-controlled system, reliable for constraining cooling and exhumation histories from both igneous and metamorphic rocks. Closure temperatures for Pb diffusion in apatite of 450 ± 50 °C for typical diffusive diameters and cooling rates based on experimental and empirical estimates and are valid for both, rapidly and slow cooling regions (Willigers et al., 2002).

Nowadays dating metamorphic cooling is ideally achieved by applying multiple geochronometers covering a wide range of closure temperatures to a single sample (e.g., Willigers et al., 2002). If multiple geochronometers are applied to several samples covering the area of interest a refined cooling pattern might be obtained. From such a cooling pattern spatial variations of cooling- and exhumation rates might be calculated and structures like folds, shear zones and faults might be dated (e.g., Borsi et al., 1978). Whereas the absolute closure temperatures of geochronometers are still debated, and generally show large uncertainties ∼10–20% the relative difference of closure temperatures of diverse geochronometers seems to be well established. The major advantage applying multiple geochronometers is to minimize the possibly complex cooling history of the working area to the dimension of the hand specimen and to calculate sample-specific cooling rates. Spatial interpolations of ages and temperatures between several, spatially-separated samples can be avoided by this approach.

U–Pb ages of apatite can be obtained by different analytical approaches such as TIMS (Thermal Ionization Mass Spectrometry) analyses after chemical dissolution, non-destructive ion-microprobe analyses using SHRIMP (Sensitive High Resolution Ion Microprobe) or SIMS (Secondary Ion Mass Spectrometry), where the textural control matters, or by LA-ICPMS (Laser Ablation Inductively Coupled Mass Spectrometry) analyses (Chew et al., 2011; Thomson et al., 2012; Chew et al., 2014). The present study applies the U–Pb apatite geochronometer performed with by LA-ICPMS analyses for the first time to samples of the Alps, i.e. the western Tauern Window, to unravel its cooling history. Cooling ages derived from Rb/Sr biotite, K/Ar biotite, zircon and apatite fission track (ZFT, AFT) analyses in the western Tauern Window (Eastern Alps) all show a similar and systematic age pattern in map view, consisting of elongate and concentric isochrons, progressively younging toward the center of the Tauern Window. The closure temperature of U–Pb apatite is generally higher compared to available cooling ages of the working area (Luth and Willingshofer, 2008; Bertrand, 2013). Hence, U–Pb apatite ages from the same area will yield the opportunity of testing this geochronometer with respect to four others inferred to have lower closure temperatures, and to assess for the first time the spatial distribution of cooling ages for the Cenozoic high-temperature (>400 °C) history of the Eastern Alps. We calculated six sample-specific cooling rates from samples where additional fission track ages were available (Bertrand, 2013).

2. Geological setting

The Tauern Window forms a structural and metamorphic dome. It exposes lower plate (European- and ocean-derived) units of the Alpine orogen and it is surrounded by upper plate (Adria-derived) rocks (Fig. 1a). The European-derived rocks (Fig. 1a, Venediger Duplex) consist of post-collisional (Variscan) calc-alkaline, epizonal I-type granitoids (∼310–290 Ma) forming the Zentralgneiss batholith (Finger et al., 1997) and its country rocks. Additionally, in the central Tauern Window Early Carboniferous, deformed S-type granites/migmatites of ∼340 Ma occur (Finger et al., 1997). Veselá et al. (2011) presented new and compiled U–Pb zircon ages of the western Tauern Window that vary between 342–279 Ma.

During Alpine orogeny two metamorphic events overprinted the rocks of the Tauern Window (Fig. 1b). First subduction-related metamorphism as observed in the ocean-derived rocks is mostly in the range of 0.9–1.3 GPa and 350–550 °C (e.g., Selverstone, 1985, von Bousquet at al., 2008). Remnants of the pressure climax (1.9–2.6 GPa, 550–590 °C) can be found in the Eclogite Zone in the southern central Tauern Window (e.g., Spear and Franz, 1986; Smye et al., 2011). Second, a high-temperature collision-related metamorphism occurred, associated to the imbrications of the Venediger duplex, hence continental thickening (Schmid et al., 2013). The so called "Tauern crystallization" caused greenschist- and amphibolite-facies metamorphism (Barrovian) overprint in the entire dome (Genser et al., 1996; Bousquet et al., 2008), some authors argue for radioactive decay that enhanced the heat production in the Venediger duplex (e.g., Clark and Jäger, 1969). Others argue for slab breakoff followed by asthenospheric heat input (e.g., von Blanckenburg and Davies, 1995; Ratschbacher et al., 2004). Smye et al. (2011) argue for a maximum duration of 10 Ma (28–38 Ma) for juxtaposition of Alpine upper-plate and European basement units and subsequent conductive heating thought to have driven regional Barrovian metamorphism. 2D numerical models of the Eastern Alps argue for a two-stage cycle of orogenic stacking, subduction and underthrusting (Genser et al., 1996). Similar models of the Andes suggest convective heat and mass transfer by partially molten lower crust which itself was heated by enhanced mantle heat flow, possibly associated with delamination of the mantle lithosphere during tectonic shortening (Babeyko et al., 2002).

Oxygen isotope thermometry in the western TW (Fig. 1b; Hoernes and Friedrichsen, 1974) shows an ENE–WSW elongate, concentric pattern with decreasing temperatures from the core (630 °C) to the margins (405 °C). These isograds strike subparallel to those defined by mapping of garnet (Höck, 1980; Selverstone, 1985) and biotite occurrences, and the anorthite component in plagioclase (Höck, 1980). These field-isograds point to higher, amphibolite-facies conditions in the center of the dome, as also supported by kyanite-, staurolite-, and silimanite occurrences, grading into lower, greenschist-facies conditions at the margins of the western subdome (Fig. 1b, Grundmann and Morteani, 1985). The peak metamorphic area coincides with the hinge of the Tauern Window (Fig. 1b).

The formation, the shape and the structure of the Tauern Window is largely controlled by the northward motion of the Dolomites Indenter, that triangular part of the Southern Alps bordered by the Giudicarie Belt in the west and the Pustertal-Gailtal Fault in the north (Fig. 1a). The window coincides with an arcuate dome structure that can be subdivided into a western, a central and an eastern subdome (Schmid et al., 2013). These subdomes have a common (i.e., doming), and a different (i.e., tight folding and shear zone localization) exhumation history. The central and eastern subdomes are characterized by broad and open folds that refold an early Alpine foliation caused by nappe stacking (Schmid et al., 2013). Localized mylonitic deformation is