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Grain size matters: Implications for element and isotopic mobility in titanite

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ABSTRACT

The U–Pb isotopic signature of titanite collected across an exhumed refractory lower crustal block within the Albany–Fraser Orogen, Australia, records thermal overprints not apparent in a suite of other U–Pb chronometers. This helps to reconcile a dichotomy within the geochronological record of two adjacent zones within the orogen. The zircon U–Pb record for the older Biranup Zone preserves widespread overprinting at 1225–1140 Ma (Stage II), whereas the younger Fraser Zone records an older 1330–1260 Ma (Stage I) tectonothermal event. Titanite in the Fraser Zone also predominantly records a U–Pb age of 1299 ± 14 Ma, reflecting the interval of closure to radiogenic Pb mobility. Nonetheless, small titanite grains reveal subsequent overprinting with a mean reset age of 1205 ± 16 Ma. By contrast, titanite from metasedimentary rocks within the adjacent Biranup Zone principally record U–Pb ages of 1200–1150 Ma, interpreted as dating cooling after prolonged Stage II metamorphism. Interestingly, titanite also preserves domains with old apparent ages. These domains have a statistically significant association with lower U content and also indicate reduced Sm/Yb ratios and are interpreted to have lost U but acquired HREE (e.g. Yb) more rapidly than MREE (e.g. Sm). The old apparent ages are interpreted as artefacts of a Stage II U redistribution process, leading to unsupported radiogenic Pb. In addition, titanite grain size has a strong effect on the preservation or resetting of metamorphic U–Pb ages. Thermochronological modelling based on apparent age versus grain size relationships indicates that complete resetting of small titanite grains requires overprinting temperatures of 695–725 °C during Stage II in the Fraser Zone. This result is similar to estimates from the Biranup Zone based on phase equilibrium modelling that indicates pressures and temperatures of 6.5–8.5 kbar and 675–725 °C. An in situ U–Pb analysis strategy for titanite that targets a range of grain sizes has the potential to reveal differential resetting and place important controls on thermal history.

1. Introduction

Titanite $CaTi[SiO_4](O,OH,F)$ is a calcium–titanium neosilicate with trace quantities of iron and rare earth elements, uranium, and thorium. It is a common accessory phase in alkaline igneous rocks and many metamorphic rocks, particularly metamorphosed calc-silicates, and occurs as a detrital mineral in most clastic sediments. Titanite is more reactive than many other minerals useful for geochronology and commonly recrystallizes in whole or in part dependent upon the duration and magnitude of the thermal perturbation (Bonamici et al., 2015). Thus, titanite provides additional age information that complements data derived from other mineral geochronometers (Aleinikoff et al., 2002; Hermansson et al., 2008; Jung and Hellebrand, 2007; Kylander-Clark et al., 2008; McAteer et al., 2010; Rasmussen et al., 2013; Spencer et al., 2013), in which titanite U–Pb dates are generally interpreted to reflect the time of metamorphism, deformation, fluid infiltration, and/or cooling (Kylander-Clark et al., 2008; Lawley et al., 2014; Mohan et al., 2014; Rasmussen et al., 2013; Spencer et al., 2013).

Pb diffusion in titanite is a key process responsible for the redistribution of radiogenic Pb and resetting of isotopic information.

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Hence, titanite dates are commonly interpreted to indicate the time of cooling of the host rock below a certain 'closure' temperature (Mezger et al., 1991). However, the thermal interval over which this closure to radiogenic Pb mobility occurs is likely dependant on a number of factors including grain shape and size, chemical composition, proximity to fast fluid pathways and thermal gradients (Stearns et al., 2015). Cited titanite closure temperatures range between ∼500 and 800 °C for most geological cooling rates (Cherniak, 1993; Schärer et al., 1994; Scott and St-Onge, 1995; Spencer et al., 2013; Stearns et al., 2015). However, in many cases it remains unclear to what extent the U–Pb systematics of titanite were affected by diffusive Pb loss or, potentially, mobility of U. Consequently, the extent to which initial U–Pb titanite dates reflect formation ages, partially or wholly reset ages, or the age of later metamorphic growth may be ambiguous.

Dates determined from titanite grains that have experienced Pb diffusion may not reflect the age of a specific geological process (Rubatto and Hermann, 2001). Nonetheless, these apparent ages are a function of the time–temperature path followed by the host rock. Additionally, the apparent age recorded within titanite from a sample that has undergone detectable Pb diffusion should be characteristic of some specific aspect(s) of that process. A process where diffusive Pb loss has occurred due to the effect of a younger metamorphic event in which titanite grew cannot be readily distinguished from an episodic or prolonged growth event without recourse to additional chemical (and textural) information. Thus, on the basis of the distribution of data on a Concordia plot, episodic titanite growth relative to diffusive radiogenic Pb loss cannot always be readily differentiated.

Diffusive radiogenic Pb loss is prevalent in metamict minerals that are formed when alpha particles are emitted by radiogenic atoms such as U or Th. These atoms undergo recoil during the emission and damage the surrounding crystal matrix, which becomes amorphous (Beirau et al., 2012). Salje et al. (2012) found that damage generation in titanite is very similar to that in zircon, with a similar temperature scale for recrystallization although the structural pathways of the thermal annealing differ significantly. As with zircon, it may be expected that greater crystal damage of titanite is manifest in enhanced diffusive Pb loss and crystal dissolution (Meldrum et al., 1998).

We present the results of titanite and zircon geochronology from the Albany–Fraser Orogen in Western Australia in order to elucidate the timescale and process of exhumation of lithotectonic blocks within the orogen. In addition, the dataset provides important information on key factors affecting radiogenic Pb and U mobility in titanite over a range of geological and thermal settings.

2. Geological background

The Albany–Fraser Orogen (Fig. 1) is a component of the West Australian Craton, located along the southern and southeastern margins of the Archean Yilgarn Craton in Western Australia (Spaggiari and Tyler, 2014; Spaggiari et al., 2011). It comprises a range of Paleoproterozoic to Mesoproterozoic igneous and metamorphic rocks formed through a series of events, involving variable crustal reworking of existing Archean crust and periods of crustal refertilisation through input of a mantle-derived magma (Smithies et al., 2015). Two major basin systems are also part of the orogen. The older Barren Basin (1815–1600 Ma) reflects extensional processes providing accommodation space within the Yilgarn Craton; the younger Arid Basin (1455–1305 Ma) records the arrival of exotic outboard elements and their denuded remains that were recycled into a foreland basin (Spaggiari et al., 2015) or back-arc system (Kirkland et al., 2011a; Clark et al., 2014). The eastern margin of the Albany–Fraser Orogen is covered by the Bight and Eucla Basins, but is inferred to extend to the Rodona Shear Zone (Spaggiari et al., 2012). On the eastern side of this structure, the orogen is in contact with the Madura Province, which comprises juvenile c. 1410 Ma tonalites and gabbros (Kirkland et al., 2014) that were derived from low- to medium-K tholeiitic parental magmas of the Loongana Arc (Spaggiari et al., 2015).

The tectonothermal evolution of the Albany–Fraser Orogen is cryptic, consisting of many events. Two of particular significance to this work are Stage I (1330–1260 Ma) and Stage II (1225–1140 Ma) (Clark et al., 2000; Smithies et al., 2015). Stage I tectonism, has been attributed to convergence and collision of two lithospheric blocks, one comprising the West Australian and North Australian Cratons and the other the combined Mawson and South Australian Cratons (Fitzsimons, 2003). However, Stage I has also been regarded as the product of oceanic arc accretion and resultant magmatism (Spaggiari et al., 2015; Smithies et al., 2015). Stage II may reflect prolonged intracontinental reworking of the orogen over approximately 85 Ma. In any case, the structure of the orogen was significantly modified during Stage II, which produced a large-scale, northwest-vergent fold and thrust architecture that characterises the orogen (Spaggiari et al., 2011).

Granitic magmatism and metamorphism were widespread during both Stage I and II, although there are distinctive spatial trends in both (Smithies et al., 2015). Granites of the Recherche Supersuite, which crystallized during Stage I, have been considered in terms of two separate suites. One, concentrated around the Fraser Zone, is highly silicic and reflects partial melting of supracrustal packages, including juvenile material from the Madura Province to the east (Spaggiari et al., 2011). The second suite is dominantly calc-alkaline and weakly ferroan, and includes both crustal and mantle sources. Granites that formed during Stage II of the Albany–Fraser Orogeny (Esperance Supersuite) have also been discussed in terms of two suites (Smithies et al., 2015). One suite represents low-degree partial melts of local lithologies with melting associated with major shear zones. The second suite is ferroan with a strong enrichment in incompatible trace elements, characteristic of A-type magmatism that likely formed through high-temperature melting of anhydrous lower crust with a significant mantle input (Smithies et al., 2015).

The Kepa Kurl Booya Province is the crystalline basement of the Albany–Fraser Orogen (Spaggiari et al., 2011), and lies immediately to the south and east of the Yilgarn Craton (Fig. 1). The Kepa Kurl Booya Province can be considered as comprising several fault-bounded lithotectonic zones, including the Biranup, Fraser, and Nornalup zones. Although each of these zones contains rocks with variable protolith ages, they are characterised by coeval metamorphism and/or intrusion by younger mafic and felsic magmas. This study concentrates on rocks from the Biranup and Fraser zones.

2.1. Biranup Zone

The Biranup Zone comprises largely mid-crustal rocks, including granitic gneiss and metagabbro with ages of c. 1815–1625 Ma (Spaggiari et al., 2011). The earliest magmatic pulse in this zone occurred during the Salmon Gums Event (1815–1800 Ma) and was followed by the Ngadju Event (1780–1760 Ma). The bulk of the magmas within the Biranup Zone were emplaced during the Biranup Orogeny (1710–1650 Ma). A younger suite of metamorphosed granitic and gabbroic rocks, which exhibit distinct mingling and local hybridization textures, are dated at 1665 ± 4 Ma (Kirkland et al., 2011a). The youngest Biranup Zone magmatic rock (excluding Stage I and II granite injections) is a metasyenogranite with a U–Pb zircon crystallization age of 1627 ± 4 Ma (Spaggiari et al., 2011; Spaggiari et al., 2015). Nd and Hf isotopic datasets have shown that the Biranup Zone probably formed autochthonously along the margin of the Yilgarn Craton (Kirkland et al., 2011a; Spaggiari et al., 2011), consistent with the