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The isotopic composition of zircon and garnet: A record of the metamorphic history of Naxos, Greece

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Abstract

Growth of zircon with respect to that of garnet has been studied using a combination of petrography, U–Pb dating and oxygen isotope analysis. The aim is to document the mechanism and pressure–temperature conditions of zircon growth during metamorphism in order to better constrain the Tertiary metamorphic history of Naxos, Greece. Two metamorphisms are recognised: (1) an Eocene Franciscan metamorphism (M1) and (2) a widespread Miocene Barrovian metamorphism (M2) that increases from greenschist facies up to partial melting. An amphibolite sample contains zircon crystals characterised by a magmatic core and two metamorphic rims, denoted as A and B, dated at 200–270, 42–69, and 14–19 Ma, respectively. The first metamorphic rim A ($\delta^{18}O = 7 \pm 1‰$) preserves the $\delta^{18}O$ value of the magmatic core ($6.2 \pm 0.8‰$), whereas rim B is characterised by higher $\delta^{18}O$ values ($7.8 \pm 1.8‰$). These observations indicate the formation of A rims by solid-state recrystallisation in a closed system with regard to oxygen and those of B in an open system. Compositional zoning in garnet is interpreted as the result of decompressional heating. Zircon B rims and garnet rims display similar $\delta^{18}O$ values which indicates a contemporaneous growth of garnet and zircon rims during the Miocene Barrovian event (M2). Calcic gneiss and metapelite samples contain zircon crystals with single metamorphic overgrowths aged 41–57 Ma. $\delta^{18}O$ values measured in zircon overgrowths ($11.8 \pm 1.4‰$) from the calcic gneiss are similar to those measured in garnet rims ($11.4 \pm 1.1‰$) from the same rock. This suggests that garnet rims and zircon overgrowths grew during the high pressure–low temperature event in equilibrium with prograde fluids. In the metapelite sample, $\delta^{18}O$ values are similar in garnet cores ($14.8 \pm 0.2‰$) and in zircon metamorphic overgrowths ($14.2 \pm 0.5‰$). As zircon overgrowths have been dated at ca. 50 Ma by U–Pb, garnet cores and zircon overgrowths are interpreted to have grown during the high pressure event.

As demonstrated here for the island of Naxos, correlating the crystallisation of zircon with that of metamorphic index minerals such as garnet using stable isotope composition and U–Pb determination is a powerful tool for deciphering the mechanism of zircon growth and pin-pointing zircon crystallisation within the metamorphic history of a terrain. This approach is potentially hampered by an inability to verify the degree of textural equilibrium of zircon with other mineral phases, and the possible preservation (in metamorphic rims) of isotopic signatures from pre-existing zircon when they form by recrystallisation.

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Nevertheless, this study illustrates the application of this approach in providing key constraints on the timing and mechanism of growth of minerals important to understanding metamorphic petrogenesis.

Keywords: U/Pb; Absolute age; O-18/O-16; Garnet; Zircon; Naxos

1. Introduction

Constraint on the timing of a metamorphic event is nowadays often accomplished by U–Pb isotopic dating of zircon. Lee et al. (1997), and Cherniak and Watson (2000) experimentally determined that the closure temperature of the U–Th–Pb isotopic system in zircon is greater than 900 °C and that Pb isotope ratios will not be altered by volume diffusion under most geologic conditions. Consequently, zircon is able to preserve multistage magmatic and metamorphic histories (e.g., Zeck and Whitehouse, 1999; Möller et al., 2002). Metamorphic zircon growth occurs as thin overgrowths or rims around relict cores or as small equant grains (Hoskin and Schaltegger, 2003) from which U–Pb ages can be determined using high mass resolution ion microprobes (Ireland, 1995). However, Rizvanova et al. (2000) showed that the U–Th–Pb system can be disturbed at temperatures lower than 900 °C in the presence of fluids. Additionally, neither the mechanisms of growth nor the stability field of zircon during metamorphism are well constrained. Previous studies have shown that zircon can grow (i) in closed system at the rock scale by solid-state recrystallisation of protolith zircon (Hoskin and Black, 2000), by dissolution–recrystallisation (Pidgeon, 1992; Pan, 1997), or by destabilisation of Zr-bearing accessory (e.g., ilmenite; Bingen et al., 2001) and major minerals (e.g., amphibole and garnet; Fraser et al., 1997), and (ii) in open systems, during partial melting (Roberts and Finger, 1997) or fluid circulation (Williams et al., 1996).

In order to recover pressure–temperature conditions of zircon crystallisation, several attempts have been made to link zircon growth to an index mineral of metamorphism. (1) Net transfer reactions involving the breakdown or crystallisation of a Zr-bearing phase such as hornblende or garnet have been identified (Fraser et al., 1997). (2) Mineral inclusions preserved in zircon can provide direct information of a mineral assemblage before and during zircon growth (Gebauer et al., 1997; Hermann et al., 2001). However, as pointed out by Rubatto (2002) such inclusions are rare. (3) The comparison of trace element patterns in zircon and other minerals such as garnet or feldspar can be used to assess their concurrent growth (Peucat et al., 1995; Schaltegger et al., 1999; Rubatto, 2002). This method has to be used with caution because of the wide range of possible zircon trace element compositions (Hoskin and Ireland, 2000; Rubatto, 2002), the possible existence of an inherited component when solid-state recrystallisation of protolith zircon occurs (Hoskin and Black, 2000), and because the partitioning of trace elements between zircon and other phases is not well quantified. In this respect, the evaluation of trace element partitioning coefficients between garnet and zircon in equilibrium at granulite facies grade (Rubatto, 2002) appears to be a potential tool to link zircon to garnet growth (Whitehouse and Platt, 2003).

Another way to correlate metamorphic zircon rims with garnet growth that has, to our knowledge, not previously been investigated is via oxygen isotope compositions. On the one hand, oxygen isotope provide information on the closure of the system with respect to fluids; and on the other hand, they are good tracers of concomitant growth of garnet and zircon as there is no fractionation of oxygen isotope at equilibrium between them (Zheng, 1993; Valley et al., 1994).

In this study, the oxygen isotope composition of zircon and garnet are measured for a suite of samples from Naxos, Greece, in order to first investigate zircon growth mechanisms and second to discuss the geological significance of zircon U–Pb ages. Naxos lies in the Aegean region, at the north of the Hellenic subduction zone (Fig. 1A). Naxos displays a migmatite dome forms rimmed by a metasedimentary sequence (marble and schist, “Middle unit”, Fig. 1B). Metabasites locally cross-cut the metasedimen-