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Trace element fractionation during high-grade metamorphism and crustal melting—constraints from ion microprobe data of metapelitic, migmatitic and igneous garnets and implications for Sm–Nd garnet chronology

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Abstract

Rare earth element (REE) and other trace element (Y, Sr, Ti, Cr, V, Na) abundances in garnet from a garnet-bearing metapelite, a pelitic migmatite, a syn-tectonic granite and a post-tectonic leucogranite were measured by secondary ion mass spectrometry (SIMS) in order to identify the effective variables on the trace element distribution between garnet and the host rock. Garnet from the garnet-bearing metapelite, the pelitic migmatite and the syn-tectonic granite is zoned with respect to REE. The cores are enriched by a factor of 2–3 relative to the rims. For the garnets from the garnet-bearing metapelite equilibrium distribution following a simple Rayleigh fractionation is responsible for the decreasing concentrations in REE from core to rim. Garnet from the pelitic migmatite shows a more complex trace element pattern following distinct enrichment and depletion patterns for Ti, V, Cr and REE from core to rim. These features suggest disequilibrium between garnet and the associated melt in which the enrichment of trace elements probably correspond to a period of open-system behaviour in these rocks at a time when the garnet, originally nucleated in the metamorphic environment was incorporated into the melt. The garnet from the syn-tectonic granite shows stepwise decreasing concentrations in REE from core to rim: a REE-rich core can be distinguished from a broad REE-depleted rim. Notably, from core to rim an inflection of the Yb/Er and Yb/Dy ratios is visible. Whereas the decrease of HREE abundance in the core region of the garnet from the syn-tectonic granite may arise from equilibrium partitioning during garnet growth, the inflection can be interpreted as a result of partial melting. Garnet cores with high Yb/Er and Yb/Dy $>$ 1 nucleated in the metamorphic environment without the presence of a melt whereas the rims with lower Yb/Er and Yb/Dy $<$ 1 crystallized in the presence of a melt. Garnet from the leucogranite has lower REE abundances and is considered to be of igneous origin. In contrast to garnet from the other samples, its core has low trace element abundances, whereas its rim is significantly enriched in REE but depleted in Ti. These features suggest that only the outermost rim was in equilibrium with

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the melt. For this garnet, liquid diffusion controlled partitioning is more likely to explain the extreme trace element variation. An evaluation of Sm and Nd concentrations in garnet and a comparison of Sm–Nd and U–Pb garnet ages and U–Pb monazite ages form the terrane indicate that the observed LREE systematics in the different garnet species are a primary feature and are not homogenized by volume diffusion during high grade amphibolite facies conditions.

Keywords: Garnet group; Rare earths; Absolute age; Crystal zoning; Ion probe data; Damara orogeny

1. Introduction

The presence of garnet in a wide range of bulk compositions, pressure and temperature conditions justifies its importance as a probe of metamorphic processes. For this reason, the major element zoning of garnet has been widely used to investigate the *P–T* conditions of regional metamorphic terranes (Tracy, 1982; Spear and Selverstone, 1983; Spear et al., 1984). The chemical signatures of the early stages of regional metamorphism are often preserved up to the lower amphibolite facies due to the slow diffusivities of the major cations Fe, Mg, Mn and Ca. However, prograde chemical zoning is rare in higher grade garnet of amphibolite- to granulite-facies terranes (Martignole and Pouget, 1993), due to enhanced intracrystalline diffusion at higher temperatures (Spear and Florence, 1992). Prograde heating of crustal segments will ultimately result in fluid-absent partial melting of metasedimentary rocks, producing a granitic melt and an aluminous residue in which the restitic mineral assemblage will control the trace element concentration of the melt. The mineralogical composition of the residual assemblage is dependent on the nature of the melting reaction and the pressure at which melting occurs. Garnet is a common refractory mineral phase that may be present in the high-grade metasedimentary protolith or a product of an incongruent melting reaction at a higher metamorphic grade. A detailed knowledge of the distribution of trace elements between garnet, metamorphic host rock or melt is therefore critical for trace element modelling of anatectic crustal melts. It has been demonstrated that trace element zoning in garnet is often more pronounced than major element zoning (Hickmott et al., 1987; Hickmott and Shimizu, 1990; Hickmott and Spear, 1992; Spear and Kohn, 1996; Chernoff and Carlson, 1999; Otamendi et al., 2002). This implies that trace elements may potentially be more sensitive to chemical and thermobarometric changes in rocks than major elements. Therefore, accurate interpretation of major and trace element zoning in garnet leads to significantly improved understanding of *P–T* paths of metamorphism and hence of the tectonic evolution of mountain belts.

The conventional approach to date *P–T–t* paths in high grade metamorphic belts is to date U–Th rich accessory minerals (monazite, allanite, titanite, zircon) and link the obtained ages with petrographical, structural and thermobarometric results. Assigning ages to a given *P–T* path remains a challenge because it is uncertain whether these accessory minerals grew or equilibrated at the *P–T* conditions recorded by the mineral assemblage. Attention has also focused on the dating of major rock-forming minerals (e.g., garnet, staurolite; Mezger et al., 1989; Burton and O'Nions, 1991; Vance and O'Nions, 1990; Lanzirotti and Hanson, 1995, 1997; Jung and Mezger, 2001) that have recorded various aspects of their pressure and temperature history during their growth. Generally, garnet is the major mineral used for the reconstruction of *P–T* paths because it is involved in a number of reactions useful for thermobarometry (e.g., Essene, 1989), and the ability to date the growth of garnet is a powerful tool to assign precise ages on a given *P–T* path. In order to identify the effective variables on the trace element distribution between garnet and the host rock, this study presents trace element data on garnet measured by SIMS from different lithologies from the Damara Orogen (Namibia). We examine whether trace element variation during garnet growth on the prograde path of metamorphism can provide additional constraints on the garnet-forming process. Additionally, we present one new Sm–Nd garnet–whole rock age from a garnet-bearing metapelite in order to provide complete geochronological data for all investigated samples. This age is discussed with previously published U–Pb monazite ages and Sm–Nd garnet–