Zr–LREE rich minerals in residual peraluminous granulites, another factor in the origin of low Zr–LREE granitic melts?

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Abstract

There is a significant enrichment in some trace elements in the major residual minerals of peraluminous granulite xenoliths from the lower crust. Those trace elements are released from the breakdown of accessory phases at high-T granulite-facies conditions (>850 °C). Around 10–35% of Zr is hosted in granulite rutile and garnet, whereas, the entire LREE–Eu budget is controlled by feldspar. The Zr- and REE-compatible behaviour of the major granulite phases, combined with the scarcity of accessory phases, which are mostly included in major granulite minerals, leads to a disequilibrium in accessory dissolution in the peraluminous partial melts. Thus the melt extracts less Zr and LREE and, consequently, generates the false impression of having lower-T when applying current accessory phase dissolution models.
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1. Introduction

Very little is known about the redistribution of REE, Zr and other trace elements during fluid-absent melting under granulite facies conditions, but according to the results of Bea (1996) equilibrium partitioning is rarely attained. Scarce data is available on the trace-element composition of major minerals from granulite facies terranes (e.g. Bea et al., 1994; Fraser et al., 1997) and lower crustal xenoliths (Reid, 1990; Villaseca et al., 2003). Moreover, there has been recent discussion on the apparent existence of low-temperature granitic melts, as indicated by their Zr (and LREE) contents (Miller et al., 2003; Chappell et al., 2004), based on the dependence of zircon (and monazite) solubility on tem-

perature and melt composition during partial melting. This study of the trace-element geochemistry of granulite residua left after the expulsion of granitic melt is designed to move this discussion forward.

We examine the trace-element chemistry of major phases in peraluminous granulite xenoliths from central Spain. They show marked decreases in the abundance of accessory phases with no concomitant depletion in Zr and REE concentrations when compared to equivalent rocks from shallower depths (Villaseca et al., 2001). These lower crustal xenoliths have been interpreted as being the residual keel of the Hercynian peraluminous Spanish Central System (SCS) batholith (Villaseca et al., 1999).

2. Geological setting

Felsic meta-igneous granulites from the SCS have low abundances of the accessory minerals apatite, zircon

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and monazite (Villaseca et al., 2003). Most of these granulites also have unzoned almandine-pyrope garnets (Alm_{45-50}–Pyr_{45-55}) (Villaseca et al., 1999). Feldspars show significant ternary solid solution, indicative of high temperature equilibration. Conditions of metamorphism have been estimated at between 850 and 1000 °C, 0.8 to 1.1 GPa, with highly reduced conditions (graphite is common) and very low H_2O partial pressures (Villaseca et al., 1999). Detailed major- and trace-element modelling, combined with isotope (Sr, Nd, O) data, is consistent with the hypothesis that the SCS Hercynian granites were felsic melts in equilibrium with residual granulites of similar composition to the lower crustal xenoliths (Villaseca et al., 1999; Villaseca and Herreros, 2000). Moreover, a recent U–Pb geochronological study on granulite zircons yields an age range of 277 to 312 Ma as the dominant age group, which mainly overlaps with the age of the SCS granite batholith, reinforcing this granulite–granite connection (Fernández Suárez et al., 2006).

Samples from two migmatite terranes have also been included for comparison in this study (100560: a cordierite-bearing anatectic granite from Sotosalbos area, in the SCS, and 93198: a garnet–cordierite-bearing migmatite from the Anatectic Complex of Toledo) (see Villaseca et al., 2001, for further details of the petrography). These are equivalent peraluminous granulite lithotypes to the granulite xenoliths, but represent shallower crustal levels and lower temperatures and pressures of equilibration ($T \leq 800$ °C and $P \leq 0.6$ GPa) (Villaseca et al., 2001).

3. Analytical methods

Concentrations of 24 trace elements (REE, Ba, Rb, Th, U, Nb, Ta, Sr, Zr, Hf and Y) in mineral phases were determined *in situ* on >130 µm thick polished sections by laser ablation ICP-MS (LA-ICP-MS) at the *Department of Earth Sciences* (University of Bristol) using a VG LaserProbe II (266 nm frequency-quadrupled Nd-YAG laser) coupled to a VG Elemental PlasmaQuad 3 ICP-MS. The diameter of the laser spots was approximately 20–30 µm. The counting time for each analysis was typically 100 s (40 s measuring gas blank to establish the background and 60 s for the remainder of the analysis). The NIST 610 and 612 glass standards were used to calibrate relative element sensitivities for the analyses of the silicate minerals. Each laser analysis used Si (or Ca) as an internal standard, with concentrations determined by electron microprobe. Ti was the internal standard for rutile analyses.

Major element mineral compositions were determined at the *Centro de Microscopía Electrónica "Luis Bru"* (Complutense University of Madrid) using a JEOL JXA-8900M electron microprobe with four wavelength dispersive spectrometers. Analyses were performed with an accelerating voltage of 15 kV and an electron beam current of 20 nA, with a beam diameter of 5 µm. Elements were counted for 10 s on the peak and 5 s on each of two background positions. Corrections were made using the ZAF method.

4. Zr-rich rutiles and garnets

Tables 1 and 2 list averaged trace-elements contents of rutile and garnet, respectively, and chondrite-normalized REE patterns for garnet are given in Fig. 1a.

Rutile is the main Ti-bearing phase in SCS granulite xenoliths, which are essentially composed of anhydrous high-T minerals, with Al–Ti-rich phlogopite being scarce or absent (Villaseca et al., 1999). Rutile (modal proportion 1 to 3 vol.%) is an important carrier of Cr and V (up to 4800 ppm and 5400 ppm, respectively) and

Table 1

Average trace element composition of rutile from SCS granulite xenoliths

Sample	U49	105796	95153	U28
	(n=3)	(n=3)	(n=1)	(n=2)
P	123.23	167.47	112.5	113.72
Sc	4.53	50.64	4.84	29.33
V	5422	4163	3084	2285
Cr	1097	1130	593.3	4824
Y	0.29	0.93	b.d.l.	b.d.l.
Zr	3338	878	6860	4042
Nb	1228	496	615	1255
La	0.11	0.23	b.d.l.	1.13
Ce	1.14	0.19	b.d.l.	2.08
Pr	b.d.l.	b.d.l.	b.d.l.	0.16
Nd	b.d.l.	0.71	b.d.l.	0.8
Sm	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Eu	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Gd	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Tb	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Dy	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Ho	0.04	b.d.l.	b.d.l.	b.d.l.
Er	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Tm	b.d.l.	0.13	b.d.l.	b.d.l.
Yb	b.d.l.	0.56	b.d.l.	0.65
Lu	b.d.l.	b.d.l.	b.d.l.	0.07
Hf	127.33	34.24	244.2	103
Ta	69.43	23.23	11.08	51.61
Pb	0.26	b.d.l.	b.d.l.	0.4
Th	b.d.l.	b.d.l.	b.d.l.	b.d.l.
U	59.68	b.d.l.	33.35	7.37

b.d.l. = below detection limits.