Melts and Residua Geochemistry in a Low-To-Mid Crustal Section (Central Spain)

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Abstract. Granulite terranes from Central Spain are Hercynian anatectic areas of mid-crustal levels (P-T conditions: 750-800° C and 4-6 kb). The granulite xenolith suite of the same sector comes from the lower crust as deduced from their P-T estimates (850-950° C and 8-11 kb). Chemical differences between granulites from terranes and those from xenoliths are less marked in Central Spain than in other places as this xenolith suite lack mafic lithologies. Granulitic xenoliths show U and Rb depletion, and occasionally a subtle enrichment in Ba, Fe, Mg, Ti, (V) and HREE. Contents in Zr, Th, Y, and REE in both granulite types might be explained as a consequence of the minor role of accessory phases in controlling the geochemistry of the residual rocks in the lower crust. Migmatitic leucosomes and other felsic anatectic melts show the same trend of Rb and K enrichment and Fe, Mg, Ti, Cr, Ni, V and Th, Y, Zr, Nb, REE impoverishment (compared to protoliths) than granitic plutons. Although plutonic granites show higher Ca (Na), Fe and Mg contents a genetic link with anatectic melts is suggested. Isotopic differences (Sr, O) between granitic plutons and anatectic melts might be a reflection of their derivation from a different crustal level in an isotopically stratified crust.

1 Introduction

Relationships between anatectic magmas formed in the deeper crust and granitic magmas emplaced in the upper crust are rather poorly established, because few crustal sections are continuous from a partially melted deeper source to an upper-crustal plutonic emplacement level. Most granitic magmas that crystallized close to their sources in migmatitic terranes appear to contain a large residuum component, whereas allochthonous upper-crustal plutonic rocks are residuum depleted (e.g. Barbero & Villaseca, 1992; Jung et al., 1999). Where and how this separation occurs is also poorly known (Sawyer, 1998). Studies of migmatitic complexes are crucial in understanding the generation of larger-scale granitic bodies, although most of them represent an early (or arrested) stage of granite development. During the Hercynian collision, the continental crust of Central Spain evolved from intermediate P-T towards low-P/high-T reaching granulite-facies conditions in wide zones of the middle crust with consequent anatexis.

Two areas are representative of these migmatitic terranes in Central Spain: i) An anatectic area in the eastern side of the Spanish Central System (SCS) (Sotosalbos area in Guadarrama) where meta-igneous augen-gneisses are variably migmatized. Their metamorphic peak conditions have been estimated to be around 750°C and 4-5 kb (Martín Romera et al., 1999) leading to the formation of cordierite-bearing migmatites and anatectic granites. U-Pb monazite ages from orthogneissic rocks give 337 ± 2 Ma as a probable age of the metamorphic peak in the Guadarrama sector (Escuder Viruete et al., 1998). ii) The second area is the Anatectic Complex of Toledo (ACT) where the intrusion of calcalkaline granitoids and coeval gabbros is related to the development of anatectic granites in a metasedimentary and meta-igneous sequence (Barbero et al., 1995). Metamorphic peak conditions in the ACT have been estimated to be around 800°C and 4-6 kb (Barbero et al., 1995). U-Pb monazite ages from anatectic granitoids give 310 ± 1 Ma as the most reliable age for the metamorphic peak of the ACT (Barbero & Rogers, 1999). Hence, a significant diachronism for the age of the metamorphic climax in Central Spain is suggested.

These granulitic terranes represent a transient feature reached during Hercynian times because late granitic plutons (the SCS batholith) intruded when these terranes were partially exhumed and promoted contact-aureole metamorphism (Villaseca et al., 1998). A granulitic xenolith suite, that appears as enclaves in a late-Permian alkaline lamprophyre dyke swarm, is genetically related to this peraluminous SCS batholith and is interpreted as samples of the deeper lower crust as it existed at the end of the Hercynian orogeny (Villaseca et al., 1999). P-T estimates give granulite facies conditions around 850-950°C

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and 8-11 kb. Detailed major and trace element modeling, combined with isotopic data, is consistent with the hypothesis that the late-Hercynian plutonic granites are silicate liquids in equilibrium with residual granulites of similar composition to these lower-crustal xenoliths (Villaseca et al., 1999).

The geochemical comparison between residual granulites (derived from equivalent lithotypes: metapelites and orthogneisses) and their derivative granitic melts in this crustal section is the main objective of this work. This is also important for understanding chemical segregation of the continental crust during a collisional orogenic cycle.

2 Petrographic features of migmatites, granulites and related granites

Petrographic characteristics of all the materials considered in this work can be found in several previous papers (Barbero & Villaseca, 1992; Barbero et al., 1995; Villaseca et al., 1998; Villaseca et al., 1999; Martín Romera et al., 1999). Nevertheless, a brief summary is given here. Migmatites from the Guadarrama sector were sampled from a parautochthonous cordierite-bearing granite massif (Sotosalbos granite) which shows a gradual transition to partially migmatized orthogneisses. The migmatization produced a range of textural varieties, the first formed variety occurs as cordierite-bearing mafic nodules rimmed by leucocratic haloes of a few centimeters across and deleting the host-rock gneissic foliation. As migmatization advanced these nodules define nodular veinlets which are sometimes in narrow shear zones and are evidence that melt segregation occurred. Typical melanosome-leucosome pairs are rare, as are mafic selvedges. In general, *in situ* residual granulitic material is difficult to find in the Guadarrama sector. *Leucosomes* in the migmatites consist of quartz, K-feldspar and minor plagioclase, with biotite and some cordierite. Tourmaline is locally present and occurs interstitially or defines nodules. The *Sotosalbos granite* is a medium-grained equigranular rock consisting of quartz, plagioclase, K-feldspar, biotite and cordierite with accessory tourmaline. Cordierite is euhedral and contain minor inclusions of biotite and sillimanite; K-feldspar also contain needles of sillimanite. The granite contains scarce *biotite-rich enclaves* which resemble the biotite-rich folia present in the gneisses.

In the ACT most of the metapelitic material exhibits a stromatic migmatitic structure. The *melanosomes* are composed of cordierite, sillimanite, and garnet, with minor biotite, plagioclase, spinel and ilmenite. Biotite is very scarce, and is usually interstitial to cordierite crystals, suggesting that biotite dehydration melting reactions had run almost to completion. The *leucosomes* occur as layers of variable width from 1-2 cm to >10cm, and are essentially composed of K-feldspar and quartz, with subordinate proportions of plagioclase. The presence of large rounded garnet porphyroblasts (up to 7-8cm) is characteristic. Related anatectic leucogranites and restite-rich granitoids appear in the ACT (Barbero et al., 1995). The *Layos granite* is a restite-rich suite characterized by a high modal proportion of cordierite (up to 30%), and has been interpreted as resulting from a residuum unmixing processes, in which the residual end-members were represented by the melanosomes, and the melt end-member by the Cervatos leucogranites (Barbero & Villaseca, 1992). The *Cervatos leucogranites* have a modal eutectic composition with a centimetre-scale layering consisting of garnet-, cordierite- or very rare biotite-bearing leucogranites.

The granitic plutons define a big batholith (around 10 000 km^2 in the SCS), mainly of monzogranitic modal composition, and which formed during a time span of about 40 Ma (Villaseca et al., 1998). The region of partial melting from which the granites were produced must have been deeper crustal levels than that represented by the exhumed migmatite terranes (Sotosalbos, ACT) into which they were finally emplaced.

Villaseca et al. (1999) describe three types of lower crustal granulites from suites of xenoliths. They are: i) rare charnockites (< 0.01% in vol. of the xenolith suite), ii) metapelites (5% in vol.) and, iii) common felsic meta-igneous types (95% in vol.). These granulites all exhibit a banding marked by garnet-rich and felsic-rich layers, but clear migmatitic structures are not evident. The felsic meta-igneous granulites are garnet-bearing types, sometimes with accessory orthopyroxene, phlogopite or, with prismatic sillimanite.

3 Whole-rock geochemistry

The general chemical characteristics of most of the material involved in this discussion have been published in previous works on the Toledo migmatites (Barbero & Villaseca, 1992; Barbero et al., 1995), the Sotosalbos anatectic area (Martín Romera et al., 1999), the granulitic xenoliths (Villaseca et al., 1999) or the late-Hercynian granites (Villaseca et al., 1998). Metapelitic protoliths are believed to be involved in the genesis of anatectic granites and migmatites from Toledo area (Barbero et al., 1995), whereas, orthogneissic protoliths are involved in the genesis of the Sotosalbos anatectic area. Orthogneisses are also suggested to be the protoliths of the most common of the granulitic xenoliths (Villaseca et al., 1999), and their extracted granitic melts which formed the Hercynian Batholith of Central Spain.

Metapelites from Central Spain are similar in composition to the NASC values of Gromet et al. (1984), being slightly enriched in SiO_2, Al_2O_3 and Fe_2O_3 and depleted in CaO and Na_2O contents. Orthogneisses define a complex chemical suite of rocks, with the less felsic varieties (biotite-rich gneisses) being more suitable for partial melting. These meta-igneous rocks are richer in silica than the metapelites and also have higher CaO and Na_2O contents, being less peraluminous than metasediments. Nevertheless, contents in other elements are very similar in both types of protolith excepting the ferromagnesians Fe, Mg, Ti, Ni, V. For this reason the lithotype influence on migmatite composition in Central Spain is very limited in contrast to other anatectic terranes (e.g. Sawyer, 1998).

In general, migmatites, gneissic protoliths and restites (e.g. melanosomes, biotite-rich xenoliths) do not define simple unmixing lines in binary variation plots of major and trace elements. This is particularly evident in those elements controlled by feldspar minerals; CaO, Na_2O, K_2O, Ba and Sr (Table 1). The analyzed leucosomes (Toledo and Guadarrama) show higher LILE (K, Rb, Ba, Sr) contents not only than their suggested protoliths and their restitic counterparts, but also than the related anatectic granites (Layos, Cervatos, Sotosalbos) (Fig. 1, Table 1). Similar relationships are found when considering the transition metals (Cr, Ni, Sc, V) for which some anatectic granites show higher contents than the melanosomes, or when considering Th-REE, for which some leucosomes show very high concentrations (Fig. 2).

	1	2	3	4	5	6	7	8	9
SiO_2	69 03	70.82	60.96	43.19	66.41	68.92	69.06	58.19	72.01
Al_2O_3	16.09	15.81	18.53	27.65	15.19	16.91	15.21	19.43	14.95
TiO_2	0.33	0.12	0.8	1 81	0.78	0.13	0.64	1.12	0.1
Fe_2O_3	4.07	1.31	8.12	13.57	6.17	1.56	3.65	8.89	1.2
MnO	0.06	0.02	0.08	0.07	0.05	0.01	0.02	0.08	0.01
MgO	1.6	0.31	2.58	3.44	2.12	0.48	1.12	3.4	0.31
CaO	1.11	0.57	1.66	0.65	1.1	1.31	1.31	1.52	0.79
Na_2O	2.43	2 59	2.34	1.38	2.61	2.75	1.93	1.82	3.5
K_2O	3.65	7 88	3.1	6.54	3.02	6.5	5.47	3.65	5.44
P_2O_5	0.29	0.19	0.5	0 1	0.24	0.3	0.15	0.14	0.14
LOI	1.29	0.87	1.58	1.56	2.08	0.76	1.09	1 42	1.35
Total	**99.95**	**100.49**	**100.25**	**99.96**	**99.77**	**99.62**	**99.65**	**99.66**	**99.79**
Ba	596	1159	191	536	532	1341	1265	898	437
Rb	151	261	279	501	121	236	162	142	164
Sr	122	139	88	79	127	276	292	248	121
Y	34	12	66	24	39	11	14	25	12
Zr	154	41	296	406	248	48	184	219	60
Nb	6	4	16	39	12	5	13	21	2
Th	11	4	25	19	14	5	27	23	7
U	6	3	5	6	5	nd	nd	nd	1
V	48	15	107	268	115	14	37	139	17
Cr	340	60	607	249	95	6	34	137	322
Ni	28	5	51	99	47	5	17	54	21
La	25.72	8.57	53.7	60.51	37 63	23.15	69.66	67.39	17.03
Ce	54.23	17 02	113.03	129 81	80.51	43.79	141.29	131 76	36.12
Nd	25.81	7.56	58.4	65.45	38.43	21 5	57.97	54.17	15.46
Sm	6.15	1 78	13.18	12.87	7.76	5.34	11.3	10.88	3.53
Eu	1.05	1.38	0.85	1.21	1.34	2.21	2.57	2 09	0.92
1°	5.38	1.62	12.12	8.63	6.74	4.62	7.87	8.24	2.74
Dy	5.77	1.96	11.86	5.28	6.53	3.36	3.86	6.37	2.23
Er	3.11	1.01	5.48	2 27	3.58	1.5	2.28	3.37	1,00
Yb	3.21	1 03	5.47	2.1	3.31	1.27	2.22	3.03	0.86
Lu	0.47	0 14	0.71	0.35	0.53	0.23	0.39	0.58	0.11

Table 1. Representative major and trace element compositions of migmatitic rocks from granulite terranes of Central Spain. 1) Sotosalbos granite. 2) N-Leucosome from Sotosalbos area. 3) Melanosome from Sotosalbos area. 4) Biotite-rich enclave in Sotosalbos granite. 5) Layos granite. 6) N-Leucosome from the ACT. 7) E-Leucosome from the ACT 8) Melanosome pair of the E-Leucosome from the ACT. 9) Cervatos leucogranite from the ACT

Leucosomes usually have SiO_2 contents in the range of 68-71wt.% whereas related anatectic leucogranites reach up to 75 wt.%. In the Q-Ab-Or diagram, leucosomes plot outside the experimental "minimum solidus" compositions, usually on the Qtz-Or cotectic line, whereas anatectic leucogranites plot as minimum melts. The shift of leucosomes towards less Ab component is typical of water-undersaturated melts (Johannes & Holtz, 1996) but also could be a consequence of feldspar accumulation. Two types of leucosomes are present in these anatectic areas; a low-REE (and Th-Y-Zr) leucosome with a positive chondrite-normalized Eu anomaly (normal or N-type), and a high-REE leucosome (enriched or E-type) with negative Eu anomaly (Table 1). This second type is also higher in ferromagnesian and transition metal contents (Fe, Mg, Ti, Cr, Ni, V), being similar in LILE and other major elements respect to the N-type leucosomes (Fig. 1, Table 1). In the

Guadarrama sector only the first type of leucosomes (N-type) has been recognized.

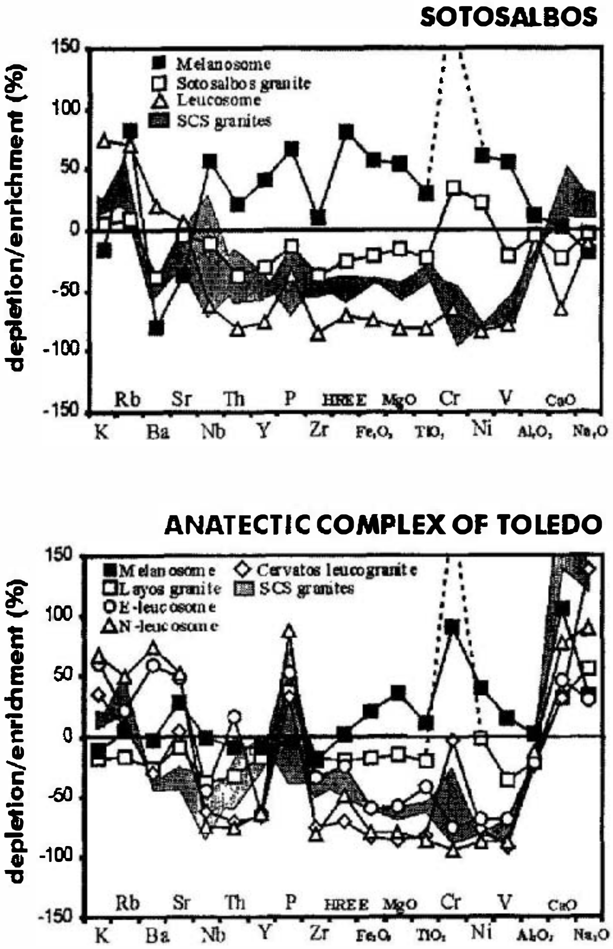

Fig. 1 Graphical illustration of the enrichment and depletion of selected major and trace elements in the residuum-rich (e.g. melanosomes, biotite-rich enclaves) and the melt-rich (e.g. leucosomes, anatectic granites) migmatites relative to an averaged protolith composition (orthogneiss in Sotosalbos area, metapelite in ACT). A compositional range field for monzogranitic magmas of the SCS batholith (shaded) are also included.

3.1 Melt-residuum segregation in granulitic terranes

The migmatitic samples display a wide compositional range because of the complexity of the partial melting process. In general, residual melanosomes and biotite-rich enclaves are enriched in compatible elements (TiO_2, FeO, MgO, Cr, Ni and V) relative to their suggested protolith, and in the majority of trace elements (Th-Y-Zr-REE) controlled by accessory phases (Fig. 2). So, the principal vectors controlling migmatite composition are the major minerals (quartz, plagioclase, biotite, K-feldspar), the amount of melt fraction and the accessory mineralogy. Figure 3 shows that N-type leucosomes and Cervatos leucogranites are enriched in the melt component, as previously suggested (Barbero & Villaseca, 1992). Some N-type leucosomes show a K-feldspar enrichment. Residuum component is concentrated in the melanosomes and particularly in the biotite-rich enclaves. Mafic minerals, sillimanite and some minor phases seem to be in excess (or concentrated) in the residuum during the melting process. The broad distribution (not perfectly linear) of melt-rich and residuum-rich samples on opposite sides of the protolith field in several diagrams is consistent with closed-system (*in situ*) migmatization. The anatectic granites (Layos, Sotosalbos) plot between melt and residuum components with the Layos granites displaying the more residuum-rich character, in agreement with previous estimates of higher (25-68 wt.%) residual component (Barbero & Villaseca, 1992). Some heterogeneous diatexites from Guadarrama sector plot towards plagioclase component in accordance with their higher Al_2O_3 and Sr contents (Fig. 3).

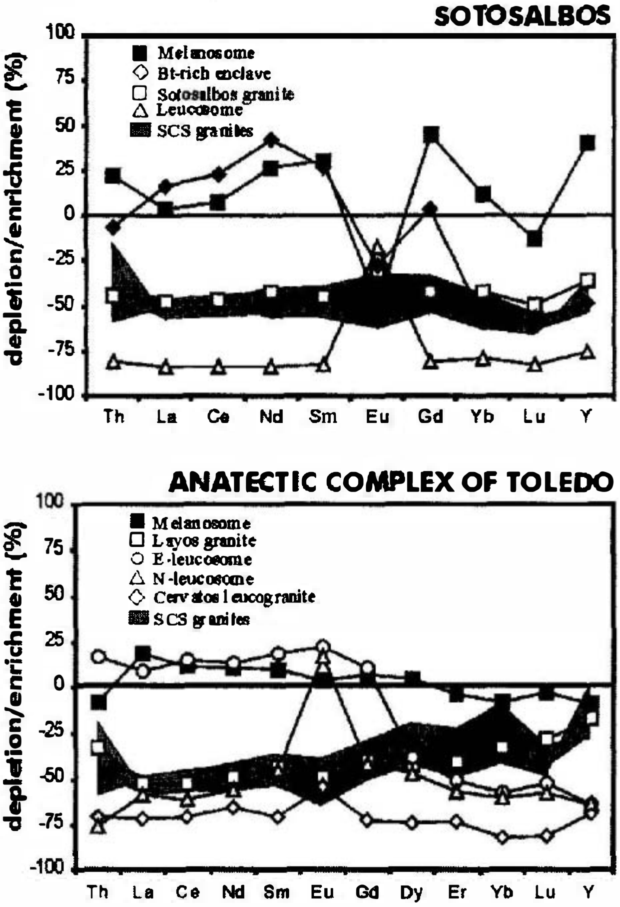

Fig. 2 Enrichment-depletion diagram of REE-Th-Y contents in the residuum-rich and the melt-rich migmatites (averaged values) relative to suggested protolith composition (see caption to figure 1). Shaded field is the compositional range of parental granites of the SCS batholith (SCS granites).

It is interesting to note that Th, Zr, Y and REE are highly enriched in the residual components of migmatites in agreement with the petrographic observation that accessory phases containing HFSE and REE (mainly zircon and monazite) are concentrated in the residuum and in the biotite-rich (folia) enclaves (Fig. 4). The E-type leucosomes show also a higher restitic component (and accessory phases inheritance) than other melt-rich migmatites.

3.2 Composition of melt-rich migmatites and granitic plutons

It has been argued that a significant portion of the melts generated in granulite-facies migmatitic terranes is unlikely to represent the precursors of the peraluminous granite plutons (e.g. Watt & Harley, 1993; Sawyer, 1996). This is generally supported by the highly leucocratic character of some metatexitic material (leucosomes) coupled with some bizarre trace element composition, e.g. low REE and HFSE contents associated with positive Eu anomalies. This geochemical contrast is considered a demonstration that these partial melts are not the source for plutonic granitic magmas.

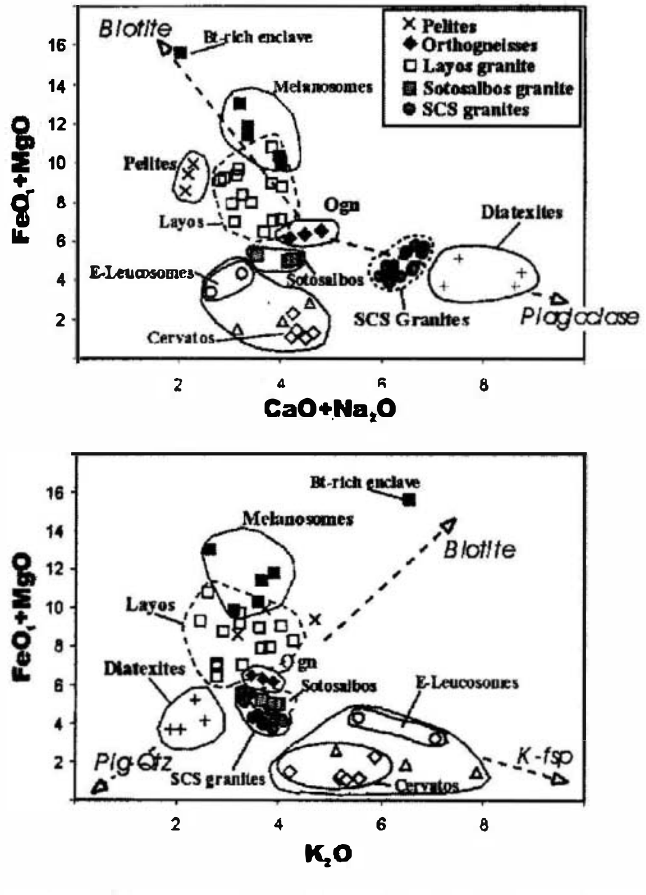

Fig. 3. Compositional relationships in the SCS migmatites. (FeO_t + MgO) vs (CaO + Na_2O) and (FeO_t + MgO) vs K_2O plots show mineral vectors based on electron microprobe compositions. Layos (open squares) and Sotosalbos (open circles) granitic fields are marked. Some regional metamorphic rocks (protoliths) are also plotted (Ogn=orthogneisses, full diamonds; pelites=X-shapes). Averaged compositional range of SCS batholith (SCS granites) is also shown for comparison.

In the region studied, the geochemical evolution of the different granitic melts when compared to their sources is broadly similar. When compared to protoliths, N-leucosomes show the same Rb and K enrichment and Fe, Mg, Ti, Cr, Ni, Sc, V, Nb, Th, Y, Zr, REE impoverishment as the granitic plutons (Fig. 1). This might imply a genetic link between migmatites and granites even not being comagmatic. The chemical similarity is greater when comparing the plutons with the anatectic granitoids of migmatitic terranes (Fig. 2). The SCS granitoids show similar ferromagnesian, LILE, HFSE and REE contents to the Sotosalbos granite, but the Layos granites are more mafic on average (Figs. 1 & 3). A major chemical difference between both groups of granites is the higher $CaO+Na_2O$ contents of SCS plutonic granites (markedly less peraluminous than anatectic granitoids) and their lower contents in transition metals (Cr, Ni, V). Another major difference between both groups of granites is their different isotopic signatures (Sr, O), that will be discussed later.

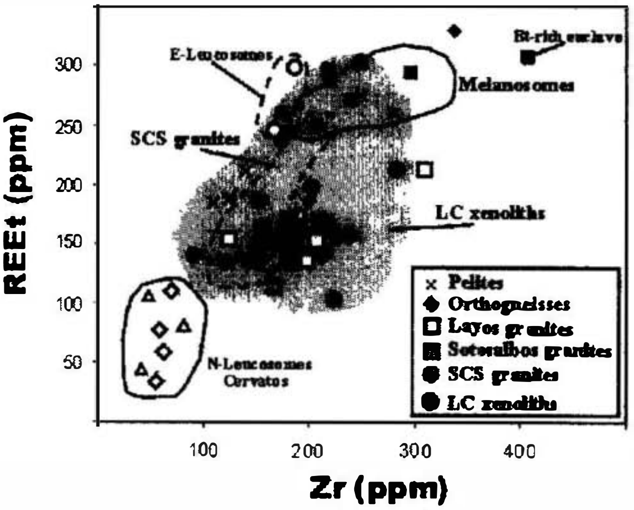

Fig. 4. REE_t vs Zr plot of migmatites, SCS granites and granulitic xenoliths. The compositional field of lower crustal granulitic xenoliths is outlined (shaded). Other symbols as in figure 3

3.3 Composition of the residual migmatites compared to granulitic xenoliths

Chemical differences between granulites from migmatitic terranes and those from lower crustal xenoliths are less marked in Central Spain, this is because the xenolith suite is devoid of mafic lithologies (Villaseca et al., 1999). Chemically there is a considerable overlap, for example, the Mg number is always in the range of 0.3 to 0.5 for all the granulite types studied. Nevertheless, some differences in the geochemistry of the granulitic xenoliths can be found. i) Xenoliths display a wider compositional range, in particular towards slightly higher ferromagnesian contents (Fe, Mg, Ti, Ni and V). ii) Xenoliths usually show lower LREE (and Th) contents than do granulites from the migmatitic terranes, in agreement with their much lower modal content of monazite; they have also lower LREE and Th contents than E-types leucosomes. iii) Xenoliths have lower Rb and U contents in spite of their felsic character; the U depletion is more marked than the Th depletion (Fig. 5). These elements have been depleted during the hercynian high-grade metamorphism. Monazite (with high Th/U ratios, mostly in the range of 10-20) is an extremely rare accessory mineral in these xenoliths (Villaseca et al., 1999).

3.4 Sr-Nd-O isotopes

Most of the isotopic data have been published previously (Barbero et al., 1995; Villaseca et al., 1998; Villaseca et al., 1999; Martín Romera et al., 1999, 2000) and is summarized and discussed below. Xenoliths from the lower crust are the granulite facies residuum with the lowest isotopic ratios of the SCS rocks. Felsic meta-igneous xenoliths have initial $^{87}Sr/^{86}Sr$ and $^{18}O/^{16}O$ ratios in the range of 0.70594 to 0.71300 and 8.3 to 9.3 $^0/_{00}$, respectively, whereas meta-igneous granulites from migmatitic terranes of Guadarrama have 0.71530 to 0.73500 and 10.1 to 10.9$^0/_{00}$, respectively. The initial εNd values are mostly in the range of –2.6 to –8.0 and is very constant for all the meta-igneous granulites (those from migmatitic terranes and those from the lower crustal xenoliths). A similar relationship is found when comparing metapelitic lithotypes. The granulite-facies metapelitic xenolithic samples have initial $^{87}Sr/^{86}Sr$ and $^{18}O/^{16}O$ ratios in the range of 0.70951 to 0.71746 and 9.1 to 9.6$^0/_{00}$, respectively, whereas the metapelites from migmatitic terranes have 0.72003 to 0.74084 and 9.2 to 11.4$^0/_{00}$, respectively. Initial εNd values in metapelites varies mostly in the range of –9.0 to –12.5.

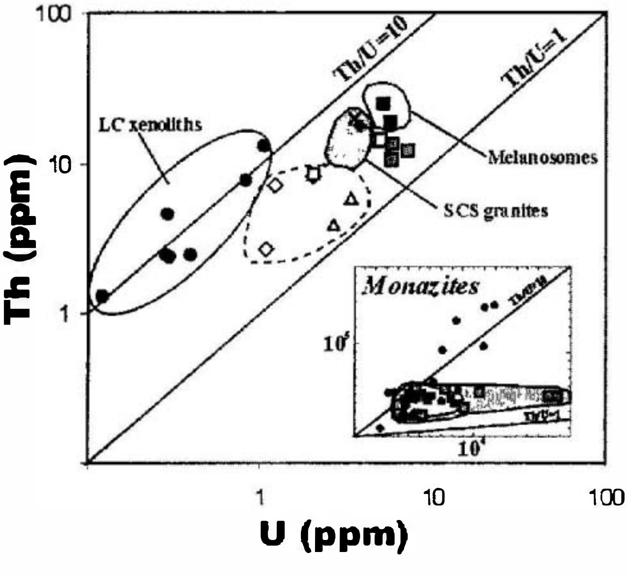

Fig. 5. Bilogarithmic Th vs U plot of migmatites, SCS granites and granulitic xenoliths. Also included a Th vs U plot of monazites from granulitic xenoliths (full circles) and from migmatites of granulitic terranes: Sotosalbos (shaded squares) and ACT (full squares). Monazites from xenoliths have higher Th/U ratios than monazites from granulitic terranes. Other symbols as in figure 3

The low-melt fractions (*in situ* leucosomes) are close to isotopic equilibrium with the granulitic residuum (melanosomes). However, the oxygen isotopes of leucosomes show slightly higher $\delta^{18}O$ values than their corresponding residuum (Martín Romera et al., 2000). A more complex situation is envisaged for the anatectic granitoids (leucogranites and restite-rich granites) because these granites show a wider isotopic composition, and, in some cases (ACT) a significant isotopic difference with respect to the surrounding migmatites occurs. This has been previously explained by isotopic disequilibrium during melting (Barbero et al., 1995). Nevertheless, in the migmatitic terranes of Guadarrama, anatectic granitoids have the same isotopic range as the related migmatites (Martín Romera et al., 1999). Finally, granitic plutons have Sr and O isotopic ratios that overlap those of the melt-rich migmatites of granulite terranes, although they tend to be slightly lower in averaged values. Their initial ratios are identical to those found in the granulitic xenoliths to which they are genetically related (Villaseca et al., 1999). Therefore, the isotopic difference between the granitic plutons and the granitic melts derived from migmatitic terranes might be a reflection of their derivation from different crustal levels of an isotopically stratified crust rather than of a marked difference in the source lithologies involved, as have been discussed in Villaseca et al. (1999).

4.Discussion

4.1 Mafic component of granitoids: a primary feature or restite entrainment?

When comparing the more mafic granitoids in migmatitic terranes (i.e. the Layos and Sotosalbos granites) with granite plutons the only significant differences found are in CaO, Na_2O and transition metal (Cr, Ni, Sc, V) contents. Some anatectic granites have been explained as the result of restite unmixing processes (e.g. the Layos granite, Barbero & Villaseca, 1992). The Sotosalbos granite is also rich in residua; megacrystic K-feldspars, biotite-rich enclaves, gneissic xenoliths and, especially, the cordierite crystals. In fact, the Sotosalbos granite is almost identical in composition to the surrounding orthogneisses (Martín Romera et al., 1999). A very limited extent of chemical (and physical) segregation between protoliths and restite-rich granitoids is, therefore, suggested. By contrast, the mafic character of the allochthonous granites (i.e. the SCS batholith) is not due to dissolution of the residuum during transport because these granites clearly have lower transition metal contents.

Experimental studies show that melts formed by partial melting of crustal material at T ≤ 800°C have relatively low FeO and MgO contents (Johannes & Holtz, 1996). Most crustal melts generated at these "low" temperature conditions (aH_2O and P have much less influence, Johannes & Holtz, 1996) have a leucogranitic composition, except for those granitic melts carrying residuum minerals. Experimental peraluminous melts generated at higher temperatures (T=850-950°C), have higher FeO, MgO and CaO contents reaching monzogranite/granodiorite composition, although this is dependent on the chemistry of the protolith. Felsic meta-igneous protoliths (e.g., orthogneisses, dacites) and greywackes constrain better the chemistry of the SCS granites; experimental results for these materials (e.g. Conrad et al., 1988; Singh & Johannes, 1996) give high-temperature melt fractions with a compositional range close to that shown by the parental granites of the SCS plutons (67.6-70.2 SiO_2, 1.8-3.2 CaO, 3.6-4.9 FeO+MgO, contents in wt.%)(Fig. 3). This scenario is clearly supported by the existence of a felsic residual granulite lower crust that is the geochemical counterpart to these granitic liquids (Villaseca et al., 1999).

4.2 Limited fractionation of REE (Th, Y, Zr) during partial melting

The absence of significant differences in some trace element (REE, Th, Y, Zr) contents between residual granulites and granitic melts in the area (Fig. 4) is remarkable. Granulitic xenoliths show an undepleted signature in these trace elements, whereas the SCS granites have been interpreted as undersaturated in those trace elements (Villaseca & Herreros, 2000). Granulitic xenoliths and granites share similar shape of REE patterns although those of xenoliths are less fractionated (La/Yb_N =4.5-12.2 in xenoliths, and 6.3-14.3 in granites) and with a less marked negative Eu anomaly (Eu/Eu*= 0.6-1.0 in xenoliths and 0.4-0.6 in granites). Therefore, a limited REE redistribution during anatexis is suggested, with LREE being slightly partitioned into the melt and HREE concentrated in the residuum. Nevertheless, there is no significant amount of residual lower crustal rocks with a positive Eu anomaly (see figure 9 in Villaseca et al., 1999) to balance the typical negative Eu anomaly shown by the granitic upper-middle crust of central Spain.

REE, Th, Y, and Zr behavior during crustal melting is usually controlled by accessory minerals which can either: i) dissolve into the melt, ii) react with other minerals, iii) be inert or refractory (e.g. Johannes et al., 1995). In the studied migmatitic terranes there is evidence for efficient fractionation of the trace elements at small-volume scale, represented by the analyzed melanosome-leucosome pairs, and the low-REE anatectic leucogranites (Fig. 4). Melanosomes and N-leucosomes show complementary REE (Th, U), and to a lesser extent, Zr, Y patterns, these trace elements being preferentially concentrated in the residuum. This is typical of an efficient separation of residual minerals with their population of trapped accessory phases, from quartz-feldspar-rich fractions (Johannes et al., 1995). Nevertheless, the low REE, Th and Zr contents in the melt-rich fraction of the migmatites (N-leucosomes and leucogranites) are much less than expected from solubility models. This indicates either: i) isolation of accessory phases in major minerals not decomposed, or, ii) melt segregation rates exceeding chemical equilibrium rates (Sawyer, 1991; Barbero et al., 1995 for ACT migmatites). E-leucosomes in which REE, Th, and Zr abundances are similar to those expected in saturated dissolution models are actually undersaturated melts since their higher trace element contents merely reflects their greater residuum component (see previous section).

In lower crustal melting scenarios, REE, Th, and Zr behavior is not controlled by the accessory minerals as these have almost disappeared after being consumed in melt-producing reactions (as well as biotite, the main host of accessory phases). The main mass of these trace elements, therefore, resides in major minerals of the granulitic xenoliths (Reid, 1990; Villaseca et al., in prep.). Residual feldspars and garnets are the main LREE- and HREE-Y-Zr-carriers, respectively, being U (and to a lesser extent Th) depleted in these xenoliths. Redistribution of REE and Zr between residual minerals and monzogranitic melts by the dissolution of accessory phases into the melt under extreme granulitic conditions is far from being well constrained. Partition coefficients in these granulite parageneses might be reasonably assumed to be different to the published REE partition coefficients for garnet and feldspars in granitic (dacitic) melts. In this sense, the few available data on peraluminous granulites (Bea et al., 1994) show a moderately compatible character for the REE into feldspars, making possible the generation of both, undepleted residue (when they are feldspar-rich) and an undersaturated granitic melt.

5 Conclusions

The more mafic character of SCS granite plutons is a primary feature, and resulted from their extraction from deeper crustal levels under more extreme granulitic conditions where higher melt fractions were generated, rather that being caused by an important change in the nature of source-rocks involved. This provenance also explains their more primitive isotopic composition in Sr and O ratios, although the exact process of isotopic crustal evolution is not considered here. The absence of residual component in the SCS plutons suggests a much more effective segregation of granitic melts from the high-T residual granulite left behind. In migmatite terranes, residuum-rich granites and leucogranitic “minimum or cotectic” melts are closely-related. Residuum-rich granites (crystal-rich mushes) have a limited probability to be segregated far away from their sources. Their compositions are similar to some extent with that of the SCS plutonics, which suggests either, a derivation from similar sources, and/or similar chemical differentiation processes when melting occurred.

The undersaturation in some trace elements (Th, Y, REE, Zr) in the SCS granitic melts may occur in several ways: i) isolation and armouring of the accessory phases in biotite crystals (as observed in the residual melanosomes and biotite-rich folia), ii) melt segregation rates exceeding chemical equilibrium rates, and iii) the progressive loss of accessory minerals importance in controlling the geochemistry of REE and HFSE during extreme granulite facies metamorphic conditions (Reid, 1990). Accessory minerals were consumed in dehydration-melting reactions (and also in other metamorphic reactions not involving melt), transferring their trace element components to the melt and/or to the residual solid minerals, preventing the possibility of saturation of these components in the granitic melts.

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